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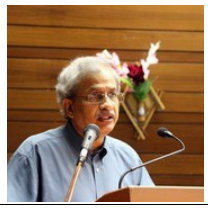

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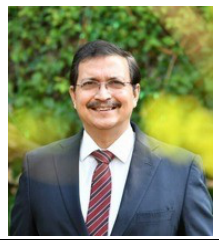

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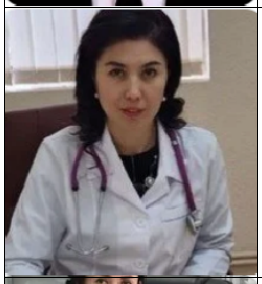

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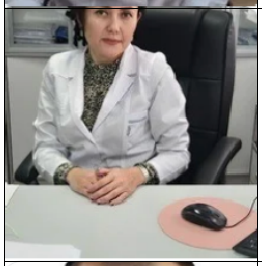

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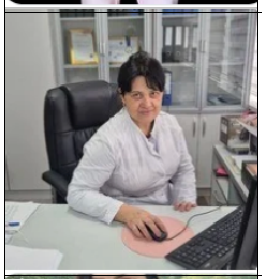

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RESEARCH ARTICLE

Reclaiming Selfhood: Identity Formation And Cultural Heritage In Alice Walker's *The Color Purple* And *Possessing The Secret Of Joy*

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ABSTRACT

Afro-American literature has long grappled with questions of identity, cultural belonging, and its place within the broader canon of Western literature. While numerous studies have examined Black identity and feminist discourse, comparatively little attention has been paid to the historiography of Afro-American female identity through the lens of the female *Bildungsroman* and its relationship to cultural heritage. Addressing this gap, the present study investigates the representation of Afro-American female selfhood in Alice Walker's *The Color Purple* and *Possessing the Secret of Joy*. The study adopts a qualitative research approach based on textual analysis, drawing on Black feminist theory as its primary theoretical framework. The findings demonstrate that Walker reconfigures the traditional *Bildungsroman* by portraying identity formation as a collective, cyclical, and culturally grounded process rather than a linear journey toward social integration. Through the protagonists' struggles with racial discrimination, patriarchal violence, cultural displacement, bodily autonomy, and psychological trauma, Walker foregrounds the interconnected roles of cultural heritage, female consciousness, and communal memory in the construction of Black female subjectivity. Celie's transformation in *The Color Purple* from objectification to self-articulation and Tashi's struggle with identity, tradition, and bodily autonomy in *Possessing the Secret of Joy* reveal how Walker challenges Eurocentric models of development while emphasizing the intersections of race, class, gender, sexuality, and cultural belonging.

***Keywords**: Bildungsroman, Black feminism, Identity formation, Cultural heritage, Afro-American women's literature, Self-formation, Identity*

INTRODUCTION: THE FEMALE BILDUNGSROMAN AND BLACK FEMINIST INTERVENTIONS

The *Bildungsroman*, or novel of formation, has long occupied a central place in Western literary tradition, tracing the protagonist's journey from youth to maturity, from innocence to experience, and ultimately toward social integration and self-realization. Originating in eighteenth-century Germany with Goethe's Wilhelm Meister's Apprenticeship (1795-96), the genre has traditionally focused on male protagonists navigating public spheres of education, vocation,

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and civic participation. The female Bildungsroman emerged as a distinct subgenre, yet even these narratives often culminated in marriage or domesticity, reflecting patriarchal constraints on women's development and agency. Although the Bildungsroman is an integral part of the Western literary tradition, it has typically followed a path for young people as they move from childhood to adulthood, from innocence to experience, and ultimately into society and self-realization. Although it was originally developed by Goethe in late 18th-century Germany (Wilhelm Meister's Apprenticeship), it has traditionally dealt with men who are traveling through the educational, vocational, and political spheres.

The *Bildungsroman* reflects the interplay between individual growth and societal forces. Wilhelm Dilthey's concept of *Erlebnis* (lived experience) frames this development as historically grounded and subjectively lived, unfolding through stages of increasing self-awareness and purpose. In *Wilhelm Meister's Apprenticeship*, this journey involves reconciling internal aspirations with societal expectations. Specifically, when delving into the Female *Bildungsroman*, Dilthey's ideas underscore how restrictive gender norms shape women's self-realization. Feminist critics argue that these narratives challenge traditional models by foregrounding struggles for agency and identity. Thus, Dilthey's framework reveals how culture and history intimately shape the evolving self, regardless of gender, but especially under patriarchal constraints.

"The *Bildungsroman* traditionally maps a male protagonist's journey to selfhood, yet when women undertake this journey, their paths are fraught with additional societal constraints," in Sarah Graham's work *A History of Bildungsroman* (2009). The *Bildungsroman* genre has typically focused on male characters, so it's not surprising that there are fewer works featuring female protagonists. For those who do, they often highlight how gender-specific challenges shape the coming-of-age experience. This aligns with the key arguments of the pioneering study on the female *Bildungsroman*. In female *Bildungsroman*, the protagonist's loss of self typically takes the stage. One attempts to gain control over one's thoughts and achieve liberation from bondage. Their primary focus switches to personal development and self-realization. Unlike male heroes, female heroes must reclaim the identity they lost during their young days. Female heroes must get freedom in order to mature psychologically and physically. Female Bildungsroman novels reveal how patriarchal structures and the society suppress women's creativity, growth and identity. These narratives depict female protagonists striving for self-discovery despite the psychological tolls imposed by socioeconomic and gender-based constraints. Maya Angelou's, *I Know Why the Caged Bird Sings* reflects this journey, particularly for Black women. She writes, "If growing up is painful for the southern Black girl, being aware of her displacement is the rust on the razor that threatens the throat" (6), capturing how awareness deepens suffering. Feminist scholars such as Susan Fraiman and Elizabeth Abel reframe Dilthey's theories to emphasize that women's paths to selfhood diverge from traditional male-centred models. Carol Lazzaro-Weis argues that identity is shaped by gendered social realities rather than by a fixed essence. She writes that the subject is "divided" and formed by psychological and political constraints. Simone de Beauvoir emphasizes how societal systems construct femininity. These critics expose how power structures shape and complicate female identity.

Afro-American women writers have radically challenged the *Bildungsroman* tradition and turned this story form into a means of interrogation of the complexities of Black women's identity formation in a world of racial, gender, and class oppression. One such transformative intervention can be seen in the works of Alice Walker, such as *The Color Purple* and *Possessing the Secret of Joy*. These novels do not just accommodate the black female experience, but they in fact radically redefine the notions of growth, maturity, and self in Afro-diasporic settings, which the study structures as the study of *Bildungsroman*. Walker's protagonists, Celie in *The Color Purple* and Tashi in *Possessing the Secret of Joy* embark on journeys of self-formation that challenge linear narratives of progress. They are being shaped not by assimilation into dominant culture, but by opposition to the dehumanizing framework of dominant culture, by reclaiming cultural heritage, by fostering radical self-love. This article explores how Walker employs the *Bildungsroman* form to articulate specifically Black feminist concepts of self-making: where identity is forged through community, memory, and through the brave facing of past and present trauma.

The analysis begins with the premise that Black feminist theory offers critical tools and frameworks through which one can examine Walker's literary innovations. Patricia Hill Collins, bell hooks, Kimberlé Crenshaw, and Barbara Smith, among others have expressed the idea that the oppression of Black women is not just race or gender oppression, but a combination of both. Rather, these scholars emphasise on intersectionality, the understanding that multiple systems of domination operate simultaneously and produce unique forms of marginalization. As Pragya Rawat et.al. are of the view,

"the process of identity formation for Afro-American women, making a significant contribution to study of the *Bildungsroman*, Afro-American literary history, and the broader collective history of the United States. The study, therefore, aims to the textual construction of identity by ethnic Afro-American women writers in contemporary *Bildungsroman* and describe the challenging *Bildung* of minority women in a culture where sex and gender oppression, racism, and classicism are all prevalent."

As Walker's novels explore these intersections, her main characters' explorations of self inevitably take place in the context of racism, sexism, economic grievance and cultural displacement. Moreover, Walker's work dwells deeply on the question of cultural heritage and connection to the ancestors. Both novels involve protagonists who have to deal with the negotiation of tradition in diasporic contexts, as well as with African cultural practices and colonial violence. It is a cultural dimension that differentiates Walker's *Bildungsroman* from the traditional European models and from many white feminist productions that assume specifically white epistemologies and communal ethics in the construction of identity formation.

THEORETICAL FRAMEWORK: FEMINISM, BLACK FEMINISM AND THE FORMATION OF SELF

Women's Development from A Feminist Perspective

Feminist theorists have long critiqued classical *Bildungsroman* narratives for their underlying androcentric assumptions. The essence of Simone de Beauvoir's revolutionary thought was that "one is not born, but rather becomes, a woman." Such an understanding is a direct assault on the convention of the *Bildungsroman*, which makes women's confinement to a domestic sphere and to reproductive roles seem natural.

Second-wave feminist critics, including Rachel Blau DuPlessis and Marianne Hirsch, have analysed how female *Bildungsroman* navigate the contradiction between personal development and patriarchal socialization. DuPlessis argues that traditional female *Bildungsroman* often conclude with the protagonist's death or renunciation of ambition, reflecting patriarchy's incompatibility with female self-actualization. Walker's novels are not these constrained possibilities, but rather a series of radical possibilities in which women take control of their own lives, bodies, and stories.

Black Feminist Theory and Intersectionality

Black feminism centres on the unique occurrences of woman of African descent in their fight for equality and justice. It arose as a response to the shortcomings of white feminism in the 19th and 20th centuries, which often centred on the issues faced by white women while overlooking the intersectional struggles of racism, sexism and classism that women of African descent face. The experiences of sexism within the Abolitionist movement in 1920 and the Civil Rights Movement (1954-1968), combined with the racial exclusion felt in the mainstream movement, prompted Black women to establish their own feminist organization. Black Literature emphasizes the plight of women of color, particularly from a sexual, cultural, racial and social point of view. These Black women were dominated by upper-class people, by white and even by patriarchal rule. This gained additional momentum addressing feminism and the sexual exploitation of black women inside white society. Black literature differs from the traditional European version. The Black feminist talks about race, class, gender and socio-political oppression in the journey of the protagonist to self-formation; therefore, a significant branch under the broader term of Feminism. The Black female challenges and rejects the dominant narratives that were imposed on marginalized Black women's voices. It also focuses on how the character forms their identity, fights against oppression and reaches their greatest potential. Bell Hooks, in *Ain't a Woman? Black Women and Feminism* (1981) and *Bone Black: Memories of Girlhood* (1996) argue that Black women's identity is structured by racism, sexism and classism. Where the main character achieves autonomy through social assimilation and education, Hooks, in her works, emphasizes the importance of resistance and self-recovery among the characters. In her works, she asserts that the growth of Black women is a continuous negotiation with white supremacist ideologies and patriarchal ideologies that seek to erase their subjectivity. The works of Bell Hooks give us a framework that allows us to examine how female protagonists move toward a radical self-definition through struggle, trauma and self-awareness.

Black female is included in mainstream feminist discourse, but it has been confined to the sidelines due to their unique yet essential concerns around racism and classism. Black female writers have delineated the distinction between black feminism and mainstream white feminism by depicting characters that interrogate the tenets and methodologies of white feminism, situating them within a framework of ethnic and economic disparity to emphasize the significance of the marginalized perspective. Francis Beal, in her essay *Double Jeopardy: To Be Black and Female* (1970), criticizes the white women's movement for its restricted perspective. She ascribes, "[a]ny white group that does not have an anti-imperialist

and anti-racist ideology has absolutely nothing in common with the Black Women's struggle" (351). Thus, the experiences of oppression faced by black women in social and patriarchal contexts cannot be equated with those of white middle-class women, as the latter embody an intrinsic dialectic concerning their dual function as both oppressor and oppressed. In a patriarchal culture, their status is that of the oppressed, whereas the same white women function in the role of oppressor in the lives of black women. Blacks, especially women, are also addressed by the triple marginalization of race, gender and class. Their work foregrounds how black female protagonists in literature not only struggle against patriarchal constraints but also confront racialized and systemic oppression, making their journey of self-formation even more complex than that of other female characters. This socio-economic, political and racial phenomenon illustrates the status of white women through the notion of pharmakon. Kimberlé Crenshaw, an Afro-American legal theorist asserts "In a society where race, gender and class are viewed as separate categories, it is difficult to address how these categories overlap and shape the lived experiences of those who are multiply marginalized." Thus, shows how women of colour endure a 'triple marginalisation' based on their ethnicity, gender and often their class, therefore defining their experiences from those of white women or men of colour. As a result, their writing often speaks to the interconnected fight against both racial and gender-based injustice. For Black women, their engagement with feminism tends to be more collective than individualistic, more cultural than political. The evolution of Afro-American women's fiction reflects the profound interplay between sexism and racism in America. A persistent challenge in the oeuvre of these writers from the nineteenth century to the present lies in their attempt to utilize the full spectrum of one's voice and to convey each aspect of the 'Self.' As Veerendra Kumar Mishra in his work, *Modern Novel and Poetics of Self,* ascribes, the idea of feminism that has evolved over a period of time not only focuses on oppression but also looks for ways in which women can take control of their own lives and identities. A liberal feminist, Betty Friend, in her *The Feminine Mystique* (1963), has strongly argued that giving women full legal equality can empower them and improve their status by removing their inferior place in society. Many Black women writers use the term 'womanist,' coined by Alice Walker, to describe the special challenges they face in today's society; thus, 'womanist' is an alternative term to 'feminism' for Black women. Womanists have questioned how information is transmitted and how language, tradition and history have been suppressed along with women's voices by the dominant white society. As they have struggled to hear the women's harmony by means of their literature, Afro-American authors such as Alice Walker, Toni Morrison, Maya Angelou, Zora Neale Hurston, Gloria Anzaldua and others have recovered their African heritage as individual 'self' within slavery.

Womanism and Cultural Heritage

Walker's theoretical contribution, 'womanism', constitutes a pivotal framework for this investigation. In her book *In Search of Our Mothers' Gardens* (1983), Walker defined a womanist as someone who is "committed to the survival and wholeness of all people, both men and women." Womanism rejects the individualism that is often associated with white liberal feminism and instead emphasizes the connection between personal freedom and the welfare of the collective. In Walker's stories, the main characters discover themselves by engaging with other women and returning to cultural traditions rather than remaining isolated. Walker's womanist viewpoint underscores the significance of deriving knowledge from one's ancestors and cultural heritage. Walker's *Bildungsroman* asserts that engagement with African and African American cultural traditions is crucial for genuine self-formation, countering assimilationist narratives that necessitate protagonists to forfeit ethnic particularity. This is an effort to revalue cultural heritage that both devalues African cultures by white people, and elements of western feminism that devalue non-western cultures as inherently oppressive.

The Formation of Self in Black Feminist Thought

Black feminist theorists challenge the idea of selfhood itself, beyond the Enlightenment, individualistic conception. Hortense Spiller's explicates in her essay, "Mama's Baby, Papa's Maybe" the ways violence and trauma wrought by slavery undermined African families and challenged black subjectivity. Spillers's argument is that slaves were treated as 'flesh' and denied the status of 'body' that would grant them full humanity and kinship recognition. This historical trauma requires unique ways of self-forming for Afro-Americans. Rather than assuming a stable, pre-existing self that simply requires development, Black feminist approaches recognize selfhood as something that must be actively constructed against systems designed to negate Black humanity. Identity formation is thus a process of resistance, creativity, and radical imagination.

ASPECTS OF THE FEMALE *BILDUNGSROMAN* IN ALICE WALKER'S NOVELS

Reconceptualizing Development and Maturity

The conventional trajectory of the *Bildungsroman* is reversed in Walker's novel. Instead of innocence to experience, her protagonists embark on cyclical journeys, in which they repeatedly die and rise again, following a progression from social isolation to social integration. *The Color Purple* is a series of awakening experiences for Celie: discovering her own voice through letters, her ability to love through Shug Avery, economic independence through sewing, and finally spiritual wholeness. Likewise, Tashi in *Possessing the Secret of Joy* undergoes several metamorphoses an Olinka girl becomes an American expatriate, a faithful wife becomes a traumatized survivor, silence becomes testimony. This cyclical pattern is a reflection of the time and development concept held by Africans and African Americans which is different from the linear concept of the west. Walker's use of African cosmologies, which view life as circular rather than linear, is a focus on return and renewal as well as progress.

Community and Relationality

Walker's novels differ from traditional *Bildungsroman* in that they focus on the community as the locus of the self-formation, rather than individual achievement. The development of Celie in *The Color Purple,* is very much rooted in the relationships he has with other women, especially Shug Avery, Sofia, and finally Nettie. These connections serve as mirrors to help people recognize themselves, models for resistance and space for affirmation that are not found in the gender patriarchy. In *Possessing the Secret of Joy*, Tashi's path to selfhood is also one of relationships with women from different cultures, first with Olivia, the daughter of an American missionary; then with Lisette, her European therapist; and finally with Mzee, an Olinka woman who performed her genital mutilation. Different relationships can help with different parts of the process of understanding and healing oneself. Such a communal focus stems from Black feminist ethics that hold connection rather than separation as dearly as the value of a relational rather than an atomistic identity as Collins contends. Walker's protagonists are not self-created entities, but they are aware of themselves in relation to others, in relation to kin.

Voice, Narrative, and Self-Authorship

Voice and narrative authority are the central themes of both novels. The epistolary structure follows Celie's path of writing letters to God (a figure she originally pictures as white and male) and writing to Nettie, and eventually to telling her own story. When Celie starts referring to the audience as 'she,' having previously referred to God, she has come to understand that the audience doesn't have to be outside, criticizing and judging, but one that is equal, loved, and inside. Devendra Kumar et.al. are of the view that "Language is a power which decides the reality of standard, which becomes a linguistic benchmark for the speaker", which can be derived through the character of Celie. In *Possessing the Secret of Joy* Tashi's journey to selfhood also progresses through her relationships with women from different cultures, including Olivia, the American missionary's daughter who becomes her sister-in-law; Lisette, her European therapist; and finally Mzee, the Olinka woman who performed her genital mutilation. Every relationship teaches you something new about yourself and helps you heal differently. Collins says that Black feminist principles stress connection over separation and see identity as something that comes from relationships rather than being separate. This focus on community is in line with those principles. The main characters in Walker's books don't become themselves by separating themselves from others. Instead, they do so by seeing themselves in their relationships and family ties.

THE COLOR PURPLE: CELIE'S TRANSFORMATION FROM OBJECTIFICATION TO SELF-ACTUALIZATION

Epistolary Form and Narrative Development

The Color Purple starts with Celie, a 14-year-old girl, who writes to God after being raped by the man she believes to be her father. "You better not tell anybody but God," she says. It would endanger your mom's life. The terribly silent tone establishes the theme of the book: voice, testimony, and self-expression. The epistolary format allows readers to see how Celie's mind evolves through the years as she slowly evolves from being an object to a person with an identity. Initially, Celie's letters indicate that she does not believe she is useful. Violence towards women is what Celie sees herself in. She has been raped numerous times, her children taken away, and married off to 'Mister' (Albert), who treats her like he owns her and her sex. In her early letters, she doesn't seem to have many words or a sense of identity. This was because she did not attend school or was not told she was a smart person. Epistolary is a form that is used to resist and remain safe, however. So, Celie writes to God and tells Him that her experience counts and that she is a person and not an object. This is a subjective statement, which is not very strong, but it is the basis for development in the future.

Shug Avery: Catalyst for Self-Discovery

Transformation of Celie accelerates when Shug Avery comes to town. She was glamorous and a former lover of Albert, Shug embodies everything Celie has never been granted: sexual freedom, self-expression, financial independence, and self-love. Their relationship becomes one from Celie's care of Shug when she was ill, to that of deep friendship to erotic love. Shug teaches Celie to enjoy her own body and pleasure directly challenging the issues of sexual violence that have been the experience of Celie's body. Despite Celie's sexual history with men, Shug says to her, "You still a virgin" while transforming the definitions of sexuality from penetration and violation to pleasure and consent. This is an important moment in Celie's self-formation, because she has come to realize that she can enjoy pleasure and be tender with herself. In addition, Shug brings Celie to other spiritual notions. Shug rejects conventional Christian belief in God, and suggests instead that she believes there is a spirituality in nature, beauty, and love that is God. As Celie confesses her growing anger at God for allowing her to suffer, Shug counters by rejecting the white, male-dominated God of traditional Christianity and proposing a pantheistic belief system in which the world, beauty, and love are all god. In this theological reworking, Celie can unleash her anger and can imagine herself in a universe that not only does not condemn her but also celebrates her.

Economic Independence and Creative Expression

Another significant characteristic of self-formation is economic independence as Celie in the novel makes her own pants and stitches clothes. Making pants for women is a source of income and an expression of creativity, as it gives women the freedom to move and the opportunity to defy gender norms. The business enables Celie to provide for herself, to have value other than unpaid domestic service. But the symbolism of sewing pants should not be underestimated. Clothes that liberate women from the limitations of femininity, Celie is participating in collective liberation while gaining her own. Her creative work brings material independence and psychic satisfaction, and she can satisfy her drives to self-expression and to useful work.

Reconciliation and Wholeness

At the end of the novel, the novel's protagonist Celie is reunited with her sister Nettie, her children, and Albert is presiding over a multi-generational household on her inherited property. This ending has led to some of the most severe criticism from readers, as they find it too worthy of redemption, and believe that it downplays the long-term impact of trauma. But, from a womanist point of view, the ending is a confirmation of the potential for healing, wholeness, and chosen family.

The last letter that Celie writes start with the phrase "Dear God" but then goes on to say "Dear God. Dear stars, dear trees, dear sky, dear peoples. Dear Everything." This cosmic address is an indicator of a level of self-actualization, of wholeness that is able to include the divine and the earthly, the spiritual and the material, the individual and the communal. Beginning to speak to an absent and a male God, then talking to all creation, reveals Celie's growth into the complete, integrated being.

Cultural Heritage and African Connection

Walker raises issues of cultural identity and pan-African awareness via the letters that Nettie writes while in Africa. Nettie's descriptions of the Olinka people give Celie (and the reader) pictures of African life, but they are not stereotypical and rather they tell the truth about the ravages of colonialism. By locating the history of the killing of Celie's and Nettie's real father because of his economic success, the reader is also exposed to a history of white supremacist violence against Black achievement. Nettie's letters serve as a bridge to this African connection that provides Celie with a broader sense of cultural identity. She does not physically go to Africa, but learning about the cultures of Africa and the way that she is a part of this culture helps her to understand herself as a member of an international African diaspora.

POSSESSING THE SECRET OF JOY: TASHI'S QUEST FOR CULTURAL IDENTITY AND BODILY AUTONOMY

Culture, Trauma and Identity

Possessing the Secret of Joy confronts readers with one of the most controversial subjects in contemporary feminism: female genital mutilation (FGM). Tashi, a minor character in *The Color Purple*, experiences genital cutting as an adult, in an attempt to define herself as Olinka and to question the cultural imperialism of the West. This decision is supposed to mean that Tashi culturally belongs, but instead leaves her in psychological and physical pain throughout her life. Walker's approach to this subject demonstrates the complexity of her womanist vision. She refuses to present a simplistic narrative that either condemns African traditions wholesale or romanticizes them uncritically. Instead, the novel raises issues about the impact of colonialism, of patriarchy, of internal oppression on cultural practices and people's relationship to tradition.

Circumcision takes place during adolescence in Tashi's case, as a means of nationalist fervour, in the resistance against colonial domination by the Olinka. She sees the ritual as a symbolic statement

of her African identity against the influence of Westerners, such as Olivia's parents, missionaries. But as the novel reveals, this is a 'traditional' practice that is designed to control Olinka women's sexuality, and many of them, like Tashi's mother and sister, resist it. The mutilation robs Tashi of her sexuality, causes chronic pain, leads to obstetric complications which cause damage to her son's brain, and leads to extreme psychological trauma, such as fugue states and violent impulses. Walker does not represent FGM as it would be represented by cultural relativism as a neutral 'other' as 'different' as it were but as a violence against women which should be faced and stopped.

The fractured Selfhood and Multiple Voices.

The novel's types of organization are a result of Tashi's split personality. Chapters switch between several narrators, such as Tashi herself as well as her husband Adam, son Benny, therapists, and more. This polyphony implies that Tashi is a self in disarray, fragmented among the various perspectives, and therefore not centred in a single and unified subjectivity.

Tashi's psychological split is evident in the alternate personalities she develops, such as "the woman with the parrot on her head", which embodies her suppressed rage and knowledge. The dissociative symptoms in this presentation are similar to those of current thinking on complex PTSD, demonstrating the very deep levels of disruption to identity formation that can be caused by severe trauma and the length of therapeutic engagement needed to achieve identity integration. The multiple narrators also take the edge off any one point of view, which you would expect to be an effect of Walker's desire to show multiple truths from a variety of angles. This method does not assume the colonizing position of 'knowing' and 'representing' the other totally, but instead recognizes the boundaries of any one perspective.

Therapeutic Journey and Historical Reckoning

Throughout the novel, Tashi's lengthy treatment by the European and American analysts is described. These sessions enable exploration of how colonial history, gender oppression and cultural dislocation intersect to create Tashi's trauma. Her therapists help her see that her suffering is not a pathology of her own, but rather it's a reaction to collective violence against women, perpetrated over generations. A crucial moment occurs when Tashi comes to understand that genital mutilation was conducted in Europe and America well into the 20th century as a 'cure' for female sexuality and masturbation. This historical disclosure undermines easy dichotomies of 'backward' African culture versus 'civilized' Western culture, showing the issue of patriarchal violence against women as a worldwide one that manifests in culturally different ways. The recovery of Tashi will take more than just psychological understanding, but concrete action. Eventually she faces and kills off Mzee, the tsunga (circumciser) who cut her, as the only justice for countless mutilated girls and women. The killings and the imprisonment and eventual execution of Tashi constitute the tragic climax of the novel.

Identifying as a Resisting Subject

Tashi's path to selfhood follows a more tragic arc, one than Celie's relatively positive journey toward integration and wholeness. In tragedy, however, Walker asserts the importance of resistance and of telling the truth. Tashi's trial is a time for the community to speak out against FGM, and a chance to teach her son Benny and others about the harms of FGM. The last words that Tashi utters before execution, 'RESISTANCE,' are Walker's vision of how identity is formed, which is related to political struggle. Self-formation is not just about personal growth but a process that must engage with systemic violence for Black women who are experiencing multiple oppressions. While Tashi finds her way to genuine selfhood in rejecting the practices that disavow women, even at the price of her own life, she does not seek to become a part of the existing social orders.

Cultural Heritage: Reclamation and Critique

Possessing the Secret of Joy presents a more ambivalent engagement with cultural heritage than *The Color Purple*. The first novel is mostly a paean to the culture of Africa as a source of strength and identity while the second is a declaration to separate cultural practices which affirm humanity from those which violate it.

Walker's position provoked a lot of controversy, as others thought that it revictimized the stereotype of African barbarism. But her work is comparable to that of African women's rights activists like Nawal El Saadawi and Efua Dorkenoo, who have successfully brought about change in their communities. These inner voices of resistance are seen to be magnified in Walker's novel. Walker's commitment "With Tenderness and Respect to the Blameless Vulva" suggests that she is going to honour women's bodies and sexualities as a counterpoint to practices that impact on them. In this commitment, cultural authenticity is not about unreflective conforming to tradition, but about ways of living which promote human flourishing and dignity.

COMPARATIVE ANALYSIS: FORMATION OF SELF ACROSS BOTH NOVELS

Parallel Journeys, Different Contexts

Examining *The Color Purple* and *Possessing the Secret of Joy* together reveals both continuities and differences in Walker's vision of Black female self-formation. Both protagonists endure severe trauma rooted in patriarchal violence: Celie has been raped by her father and beaten by her husband and Tashi has undergone genital mutilation. Both are trying to achieve their own identity and independence when the communities in which they live can often reinforce their oppression as well as give them essential support. Their geographical and cultural backgrounds, however, are very different. Most of Celie's narrative takes place in rural Georgia, the country where the seeds of slavery, violence, and opportunity of the Great Migration take root in the Afro-American community. Tashi's narrative alternates between the fictional African country of Olinka and the U.S., and directly confronts the influence of colonialism on African societies as well as the complexities of cultural identity in the diaspora. These different contexts give rise to various self-formation challenges. Celie must overcome internalized worthlessness produced by constant degradation within a racist, patriarchal society that denies Black women's humanity. Tashi finds herself torn between opposing cultural allegiances, experiencing the attraction of African traditions and the seductions of modernity and Western culture, and also the dangers that exist in each patriarchal culture.

The Role of Community in Self-Making

The theme of the centrality of community to self-formation is emphasized in both novels; the community of women- Shug, Sofia, Nettie, Squeak offers alternative models and affirming relationships that help Celie develop. This community comes from experience and forms spaces of resistance within the dominant society.

Possessing the Secret of Joy is a more complicated story, as Tashi's connection to community becomes more complex. The Olinka community that claims her through circumcision actually violates her, while the American contexts that might offer safety feel culturally alienating. Tashi's attempts to heal her separation are significant therapeutic connections with Raye and Lisette, but these are not enough to heal Tashi's fragmentation. The novel suggests that when cultural practices themselves traumatize, community's healing potential may be limited.

Voice, Silence, and Testimony

The main themes of both novels are speaking up and shattering silence. In her epistolary narration, Celie describes how she went from writing in shame to proudly claiming her story. Her last letters exhibit an accomplished voice that is self-assured, giving, and accepting of all creation. More painfully and incompletely, Tashi's voice comes out. The various narrators imply that Tashi's story must be told from a variety of perspectives because she never fully incorporates her experience into a single narrative. However, like Celie's late letters, her testimony during the trial is an important act of voice-claiming. Both women understand that speaking the truth has benefits beyond self-catharsis and that their personal narratives relate to collective histories.

Spirituality and Cultural Heritage: Affirmation

Both novels show how spiritual change can help people heal, but in different ways. Celie's journey entails repudiating the white, patriarchal God who appears to condone her suffering and, instead, uncovering a pantheistic divinity inherent in nature and love. This spiritual transformation enables her to release her anger and to embrace her wholeness. Tashi's spiritual path is growing murky and more sinister. She is upset because the gods allowed her to be hurt and that she isn't following Olinka traditions. Others may consider her killing of Mzee a ritualistic sacrifice that seeks to atone for some great injustice committed in blood. But unlike Nel's peace, Tashi's is not going to be neatly spiritualized, and some traumas do not fit neatly into the spiritual category. Both of these books speak of the significance of African cultural heritage to Afro-Americans but do so in both positive and negative. African culture is represented in *The Color Purple* primarily in Nettie's letters, which are complex and laudatory. These letters show that African societies were beautiful, dignified, and fought against colonialism. The book says that learning about African heritage makes being Afro-American stronger.

Possessing the Secret of Joy is more critical and says that being loyal to your culture doesn't mean accepting things that hurt women. Tashi's tragedy is partly because she thought she had to choose between being true to her culture and keeping her body safe. According to the book, real cultural preservation must include changing bad habits. It says that cultures, like people, need to change and grow all the time.

Cultural Heritage: Affirmation and Critique

The novels embrace an African cultural heritage as integral to black identity; they both provide some affirmation and critique. Through the admiring

but complicated letters of Nettie, *The Color Purple* depicts African culture as a place of dignity, beauty, and resistance to colonialism. In the novel, the author implies that ties with the African heritage reinforce the identity of African Americans. *Possessing the Secret of Joy* is a more critical engagement that requires that cultural loyalty must not come at the cost of practices that do harm to women. In great measure, Tashi's tragedy has been the result of buying into a false dichotomy between cultural authenticity and body integrity. The novel makes the point that any real attempt at cultural preservation should involve a change of oppressive practices; cultures like people, need to grow and change.

Endings: Integration Versus Resistance

The two novel endings show different possibilities for the black female self. In the final chapters of *The Color Purple*, everything is integrated and whole: Celie is with her loved ones, is in charge of her land, is happy with herself and the universe. The joyful conclusion reminds us that healing and happiness can still happen even in the face of intense trauma.

Possessing the Secret of Joy concludes with Tashi's execution; there is no easy consolation to be taken from this tragedy. But even this conclusion confirms certain values: opposition to injustice; commitment to telling the truth; willingness to sacrifice for collective liberation. For others, like Tashi, selfhood may be found through resistance even unto death, through refusing to accept violations as natural or inevitable. Both paths validate the struggle toward authentic being.

These endings combined indicate that the formation of self may take multiple paths for black women to form themselves. For others, such as Celie, integration and wholeness are possible through community, creativity, and spiritual transformation. In others, such as Tashi, resisting to the very end, refusing to accept that violations are natural, inevitable, may be the only way to discover selfhood. Both journeys affirm the journey towards authentic being.

SOCIO-CULTURAL CONTEXTS: TWENTIETH-CENTURY AFRICAN AMERICAN WOMEN'S EXPERIENCE

Historical Legacy of Slavery and Jim Crow

Walker's novels must be read in the context of the history of slavery's aftermath and Jim Crow's regime of racial terror. Violence against Celie mirrors the systematic rape, exploitation of labour, and separation from family of slave women. Likewise, the novel is about the economic fragility of early 20th-century Black Southerners. The challenges Celie and Albert face in holding onto their farm in the face of the violence and economic hardship faced by white people during the era are reflective of what actually happened in the past. The beating and imprisonment of Sofia conveys the terror that black people, especially those who exercised their autonomy and dignity, endured under Jim Crow. These historical circumstances determine the protagonists' potential for development. As Nitisha Seoda and Devendra Kumar Sharma, assert,

"women silence in literature and everyday life is frequently a reaction to the social and cultural norms and constraints they were raised with. Specifically, the limitations imposed by race, gender, and class prevent black women from fully expressing their path towards self-actualization. In our history, the problem of Black women's voices being silenced has been troublesome. Racism has historically supressed Afro-American women experience distinct from of silencing because of their race, class and gender."

Walker's novels assert that racist societies are actively hindering the development of blacks, unlike the classical *Bildungsroman,* which holds that social integration can be realized through educational means and merit. But self-formation must take place in other ways community, cultural resistance, spiritual transformation not in the traditional way of social upswing.

Migration and Displacement

Both novels relate patterns of migration and displacement in the twentieth century among Africans and Afro-Americans. Nettie's mission trip to Africa is a reversion to the Great Migration from the South to the North, which brought millions of blacks to Northern cities. In her letters, she establishes circuits of exchange between the African and the Afro-American community, envisioning pan-African solidarity.

Possessing the Secret of Joy more extensively explores displacement's psychological costs. Tashi's immigration to America creates a deep cultural alienation, but when she tries to go back the ritual circumcision causes a further aggravation of her trauma. For those with a colonial and diasporic past, basic concepts of cultural return are seemingly impossible. Identity needs to be constructed in the inter-cultural spaces, where the African and American experiences are known and witnessed.

Intersecting Oppressions & Resistance Movements

Walker's novels explicate the intermingling of racism, sexism, and class oppression among Afro-American women, in anticipation of what is now called 'intersectionality' theory. Black men perpetrate sexual violence on Celie, who is also being oppressed by a racist society, as an example

of how victimization does not rule out perpetration and how patriarchy transcends race. Black women who defy white supremacy are subjected to the double burden of punishment for breaking the racial hierarchy and the gender hierarchy of white supremacy. Black women who challenge white supremacy are punished for violating the racial hierarchy, and they are punished for breaking the gender hierarchy of white supremacy.

The novels also illustrate different forms of resistance, such as when Celie leaves Albert, when Nettie records Olinka traditions, when she expresses herself through music, sewing, and storytelling, when she strives to make a profit in the business world by joining with Shug, and when she speaks on the public stage as Tashi. These types of resistance illustrate the complex pressures of Afro-American women toward justice and dignity.

Twentieth-Century Feminist and Womanist Movements

The Color Purple was published in 1982 at a time when there was a great deal of controversy among feminists regarding race, sex, and intersectionality. Black feminists have attacked white feminist movements for their failure to include the concerns of Black women and their failure to recognize the differences in race and racism. Walker's novel suggests participation in these debates, because it focuses on the experiences of Black women and the need to address racial and economic oppression and gender subordination to achieve their freedom.

Walker's invention of the term 'womanism' instead of 'feminism' demonstrates a patriarchal sensitivity to the need for racial and cultural frameworks that focused on collective liberation for Black women. Throughout these novels, the term 'survival and wholeness of entire people' comes to the fore in the novels' focus on community healing in addition to individual growth or development.

CONCLUSION: REIMAGINING DEVELOPMENT, SELFHOOD, AND LIBERATION

Alice Walker's *The Color Purple* and *Possessing the Secret of Joy* completely rethink the *Bildungsroman* genre to look at the particular circumstances and possibilities of black female self-formation in the twentieth century. These novels illustrate how the classic trajectory of individual development and eventual integration into society is impossible for Afro-American women who are experiencing multiple forms of oppression. Rather, selfhood is achieved by challenging dehumanizing institutions, reclaiming culture, establishing alternative communities, and fearlessly claiming a voice and a narrative authority. Walker portrays several layers of self-formation: psychological healing from trauma, economic independence, spiritual transformation, erotic awakening, creative expression, and political resistance in both the protagonist Celie as she moves from a state of being objectified to one of wholeness, and Tashi as she struggles to find a cultural identity and autonomy in her body. These novels demand that we recognize and respond to not just the individual, but collective histories of violence and dispossession for black women. Of particular importance is Walker's connection with the cultural heritage. Both novels celebrate African and African American traditions as a source of strength and identity, yet the novels also critique patriarchal practices. It is a balanced strategy that avoids a Eurocentric view of the world's other cultures and a cultural nationalist blind spot. Walker contends that true cultural preservation necessitates change of oppressive components that cultures, like humans, must evolve and change to be conducive to human flourishing. Both *The Color Purple* and *Possessing the Secret of Joy* are epistolary novels, and both tell their stories in a manner that is highly polyvocal. *The Color Purple* and *Possessing the Secret of Joy*, are epistolary novels, and both are narrator-multidyadic. These modes of narration foreground the voices of the marginalized, recognize the constraints of any one voice, and make visible that identity is created through language and storytelling. In this way, Celie and Tashi become subject by creating space for themselves in the system that attempts to render them object. Walker's novels are also significant in highlighting the importance of interactions between women in the process of black female self-making. These texts illustrate a dynamic of identity that is not individualistic but relational, that is, formed in webs of care, mentorship, and solidarity of women. Without the love of Shug and the example of Sofia, Celie will never transform; without witnessing and association with other mutilated women, Tashi's healing, though incomplete, requires her therapists' witnessing and her connection to other mutilated women. This emphasis on community is both an African cultural value and black feminist ethics that recognize liberation is not only personal, but collective.

Together, the different endings of these novels, one of integration and wholeness, *The Color Purple* and one of tragic resistance *Possessing the Secret of Joy*, imply the variety of possibilities and costs of Black female self-formation. Walker neither offers false optimism nor descends into despair. Rather, she speaks candidly about the healing that can occur through community and creativity, and the hurt and harm that can be caused by patriarchy and violence that may be

irreparable. Ultimately, Walker's contribution to the *Bildungsroman* tradition is that she refuses to accept the idea of development, maturity, and selfhood from black feminist perspectives. Her novels show that self-formation must always be political, cultural, and in alternative epistemological and political communities, for those who have had their humanity stripped from them. The paths that Celie and Tashi travel are paths of freedom both personal and communal, cultural and transformative. The texts are still highly relevant for the reader's day-to-day life today as they fight against racism, sexism and cultural imperialism. They provide visions of selfhood that are not dominant or isolated, but love, resistance, and connection. In reimagining the *Bildungsroman* as a vehicle for exploring Black women's self-formation, Walker creates narratives that challenge, inspire, and ultimately expand our understanding of what it means to become and to be.

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REFERENCES

Abrams, M. H. (2009). *A glossary of literary terms* (9th ed.). Wadsworth Cengage Learning.

Adorno, T., & Horkheimer, M. (1972). *Dialectic of enlightenment* (J. Cumming, Trans.). Herder and Herder.

Althusser, L. (1971). Ideology and ideological state apparatuses. In *Lenin and philosophy and other essays* (B. Brewster, Trans., pp. 127–186). Monthly Review Press.

Andrews, W. L., Foster, F. P., & Harris, T. (Eds.). (1997). *The Oxford companion to African American literature*. Oxford University Press.

Beal, F. (1970). Double jeopardy: To be Black and female. In T. C. Bambara (Ed.), *The Black woman: An anthology* (1st ed., p. 351). New American Library.

Beauvoir, S. de. (2011). *The second sex* (C. Borde & S. Malovany-Chevallier, Trans.). Vintage Books.

Collins, P. H. (1990). *Black feminist thought: Knowledge, consciousness, and the politics of empowerment*. Routledge.

Combahee River Collective. (1977). *A Black feminist statement*.

Crenshaw, K. (1991). Mapping the margins: Intersectionality, identity politics, and violence against women of color. *Stanford Law Review, 43*(6), 1241–1299. https://doi.org/10.2307/1229039

Dearborn, M. (1986). *Pocahontas's daughters: Gender and ethnicity in American culture*. University of Oklahoma Press.

DuPlessis, R. B. (1985). *Writing beyond the ending: Narrative strategies of twentieth-century women writers*. Indiana University Press.

Hirsch, M. (1983). Spiritual Bildung: The beautiful soul as paradigm. In E. Abel, M. Hirsch, & E. Langland (Eds.), *The voyage in: Fictions of female development* (pp. 23–48). University Press of New England.

hooks, b. (1989). *Talking back: Thinking feminist, thinking Black*. South End Press.

hooks, b. (1990). Choosing the margin as a space of radical openness. In *Yearning: Race, gender, and cultural politics* (pp. 145–153). South End Press.

Mishra, V. K. (2014). *Modern novels and poetics of self: Reading modernist Bildungsroman*. Authors Press.

Raboteau, A. J. (2004). *Slave religion: The "invisible institution" in the antebellum South*. Oxford University Press.

Rawat, P., Sharma, D. K., & Ranjan, M. (2025). The Afro-American female Bildungsroman in Alice Walker's *The Color Purple*. *International Journal for Multidisciplinary Research, 7*(1). https://doi.org/10.36948/ijfmr.2025.v07i01.65434

Seoda, N., & Sharma, D. K. (2023). Poetics of self in Adichie's *Purple Hibiscus*: A postcolonial Bildungsroman study. *Rupkatha Journal on Interdisciplinary Studies in Humanities, 15*(5), 1–10. https://doi.org/10.21659/rupkatha.v15n5.06

Sharma, D. K., Jha, P., & Kumar, N. (2015). The politics of language: Decolonization of Indian English. *MIT International Journal of Language & Literature, 2*(1), 11–16.

Smith, B. (Ed.). (1983). *Home girls: A Black feminist anthology*. Kitchen Table: Women of Color Press.

Smith, V., Bachiler, L., & Litz, A. W. (Eds.). (1993). *African American writers: Profiles of their lives and works—from the 1700s to the present*. Collier Books, Macmillan Publishing Co.

Spillers, H. J. (1987). Mama's baby, papa's maybe: An American grammar book. *Diacritics, 17*(2), 64–81. https://doi.org/10.2307/464747

Walker, A. (1982). *The Color Purple*. Harcourt Brace Jovanovich.

Walker, A. (1983). *In search of our mothers' gardens: Womanist prose*. Harcourt Brace Jovanovich.

Walker, A. (1992). *Possessing the secret of joy*. Harcourt Brace Jovanovich.

Webb, C. L., et al. (2004). African American intergender relationships: A theoretical exploration of roles, patriarchy and love. *Journal of Black Studies, 34*(5), 623–639.

Whitehead, A. N. (1978). *Process and reality* (D. R. Griffin & D. W. Sherburne, Eds.). Free Press.

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RESEARCH ARTICLE

From Education to Entrepreneurship: A Survey of Career Pathways for Biomedical Engineering Graduates

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ABSTRACT

Biomedical engineering (BME) is an interdisciplinary field that prepares graduates for diverse professional pathways across research, industry, clinical engineering, regulatory affairs, AI-enabled digital health, pharma-biotech, public-sector organizations, and entrepreneurship. This survey synthesizes literature on BME graduate career trajectories and examines how educational experiences, professional skills, institutional support and innovation ecosystems shape post-graduation outcomes. The paper proposes a practical taxonomy of career pathways, compares pathway-specific skills and preparation needs, and develops advising sheets that connect academic preparation with software tools, certifications, internships, portfolio evidence, and entry-level roles. The review highlights that BME functions as a flexible platform degree, but its breadth can also create career uncertainty unless programs provide explicit career mapping, experiential learning, regulatory exposure, industry engagement, and entrepreneurship training. The paper concludes by identifying research gaps in longitudinal graduate tracking, entrepreneurship outcomes, and curriculum-to-career alignment, and recommends structured advising models to improve employability and career clarity for BME students.

Keywords: *Biomedical Engineering, BME Curriculum, Career Opportunities, AI in Healthcare, Career Pathways, Graduate Outcomes, Entrepreneurship.*

INTRODUCTION

In recent years, engineering education has undergone significant innovation. The responsibilities of practicing engineers now extend beyond technical problem solving to include market awareness, stakeholder engagement, and the identification of unmet needs that can be addressed through technical innovation (Lichtenstein, G., & Gilmartin, S. K. 2021).

Biomedical engineering occupies a unique position at the intersection of engineering, life sciences, medicine, and technology development. Because of this interdisciplinary character, biomedical engineering graduates are not limited to a single job family; instead, they enter a wide range of sectors that include medical device design, biotechnology, clinical engineering, research and development, healthcare analytics, regulatory affairs, and startup ventures (Carberry, A. R., & Bodnar, C. A. 2020; Linsenmeier, R. A., & Saterbak, A. 2020; Regulatory Affairs Professionals Society. 2024; Fiveable. 2024; Freshers Medtech Network. 2026; Skill Gaps Initiative. 2025). This diversity makes biomedical engineering a compelling subject for career pathway research, especially at a time when students, universities, and employers

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are all seeking clearer evidence about post-graduation destinations.

The transition from education to employment is especially important in biomedical engineering because students often choose the degree for its breadth rather than for a single predefined job title. Prior studies suggest that some students pursue BME because they value its interdisciplinary content and problem-solving orientation, even when the labor-market route is less obvious than in more traditional engineering disciplines. At the same time, recent studies of career pathways show that BME graduates do find employment across many sectors, including quality engineering, medical technology, and entrepreneurship.

Biomedical entrepreneurship represents an important intersection between scientific innovation, health technology, and global economic growth (Damian, R., & Dumitrescu, C. 2025). Over the past two decades, biomedical discoveries have increasingly been translated into viable commercial ventures that reshape healthcare delivery and strengthen international competitiveness. These findings suggest that the field offers rich opportunities, but also that students may need better support in understanding how their skills translate into careers.

The purpose of this review article is to organize the literature on biomedical engineering career pathways into a coherent framework. Rather than treating graduate outcomes as a single category, the paper examines the major routes available to BME graduates and the factors that shape movement across those routes. Special attention is given to entrepreneurship because innovation, translation, and commercialization are becoming increasingly important in biomedical education and practice. By combining evidence from student studies, alumni pathway analyses, and entrepreneurship-focused programs, this paper aims to provide a useful reference for researchers, educators, and students.

This survey makes three contributions. First, it organizes biomedical engineering graduate destinations into an integrated career-pathway taxonomy that includes traditional, emerging, public-sector, and entrepreneurial routes. Second, it connects each pathway to practical preparation requirements, including skills, software tools, certifications, internships, and portfolio evidence. Third, it proposes an implementation-oriented advising framework that can help biomedical engineering programs translate broad interdisciplinary training into clearer student career planning and employability outcomes.

LITERATURE REVIEW

The reviewed literature indicates that although this breadth provides considerable flexibility, it may also generate uncertainty among students regarding career direction, employability, and the preparation required for specific professional trajectories. This literature review synthesizes scholarship on biomedical engineering education and graduate career development, with attention to career awareness, curriculum design, professional skill formation, entrepreneurship education, innovation, technology transfer, equity of access, and institutional support. Rather than treating these themes as separate concerns, the review examines how educational structures shape students' preparedness for diverse professional contexts and how institutions can support clearer pathways from learning to practice.

While discussing career Awareness and Career Pathways in Biomedical Engineering, Lichenstein, G., & Gilmartin, S. K. (2021) observe that biomedical engineering students develop increasingly expansive perceptions of career opportunities as they progress through undergraduate study. Their findings suggest that students who express lower certainty about future careers often consider a wider range of possible pathways, indicating that uncertainty may function as a catalyst for exploration rather than solely as a limitation. Formal and informal experiences, including internships, research engagement, professional societies, alumni events, faculty interactions, and targeted career events, can substantially shape students' understanding of professional possibilities. The literature further indicates that BME students may encounter challenges when transitioning into industry roles after graduation. This difficulty is partly associated with the breadth of the undergraduate curriculum, which may lead some employers to perceive BME graduates as less specialized than graduates from traditional engineering disciplines.

Huang-Saad, A., & Celis, S. (2017) note that BME graduates may experience fewer co-operative education and internship opportunities, fewer job openings, and lower average salaries than graduates in other engineering fields. These findings underscore the importance of making career pathways more explicit and of intentionally connecting academic preparation with employment sectors.

Abu-Faraj, Z. O. (2008) similarly characterize biomedical engineering as a field leading to varied professional destinations, including product development, clinical engineering, research, management, consulting, academia, and healthcare technology. Their work reinforces the need to position career awareness within biomedical engineering education rather than treating it as an optional activity external to the curriculum.

Moreover, the work offer a comprehensive account of biomedical and bioengineering education, noting that a single universal curriculum is unlikely because programmes differ according to

institutional priorities, disciplinary emphases, and professional objectives. Nevertheless, most curricula share a commitment to foundational knowledge in engineering, the life sciences, design, problem-solving, ethics, and applied practice. The literature identifies areas such as biomechanics, biomaterials, bioinformatics, medical imaging, neural engineering, and tissue engineering as central components of the interdisciplinary knowledge base that informs BME education.

Curriculum design in BME must therefore balance scientific depth with professional and practical readiness. Abu-Faraj, Z. O. (2008) emphasizes the importance of theoretical instruction, laboratory experience, design projects, multidisciplinary teamwork, communication, management skills, and lifelong learning. These elements are particularly significant because biomedical engineers are expected to work across technical, clinical, regulatory, and commercial contexts. Professional societies, internships, co-operative education placements, technical electives, and licensure preparation are also identified as mechanisms for strengthening student preparedness. The reviewed literature shows that curriculum design and career development are closely interrelated: while curricular breadth offers flexibility, students need structured guidance to connect electives, projects, internships, and competencies with specific career pathways. This relationship becomes especially important in entrepreneurship, where students must apply technical knowledge in uncertain, interdisciplinary, and market-facing environments.

Entrepreneurship education is presented in several studies as an increasingly significant dimension of biomedical engineering preparation. Damian, R., & Dumitrescu, C. (2025) conceptualize biomedical entrepreneurship as a driver of innovation and economic development, particularly when students and researchers are able to translate biomedical discoveries into commercial products, services, or ventures. Their work identifies both enabling conditions and persistent barriers, including funding limitations, regulatory complexity, insufficient entrepreneurial expertise, and the need for stronger innovation ecosystems.

Allen, S., & McGoldrick, K. (2003) demonstrate how entrepreneurship may be incorporated into undergraduate biomedical engineering education through collaborative, practice-oriented project experiences. Their study describes the integration of biomedical engineering design teams with entrepreneurship and management students, allowing technical prototypes to be developed alongside business plans. This model foregrounds experiential learning, teamwork, customer feedback, external sponsorship, and iterative development. Such an approach enables students to recognize that biomedical innovation depends not only on technical feasibility but also on market understanding, leadership, and commercial strategy.

Vizgan, S., & NYU BEEP Consortium. (2023) further demonstrate the value of structured entrepreneurship programmes through the Biomedical Entrepreneurship Educational Program (BEEP) at NYU. The programme responds to a recognized gap in biomedical education by providing training in venture creation, product definition, and commercialization. Its phased structure—Nucleation, Product Definition, and Venture Development—offers participants exposure to lectures, workshops, networking, and mentorship. The study argues that entrepreneurship education can cultivate an entrepreneurial mindset among biomedical researchers and facilitate the translation of scientific discoveries into marketable products.

Huang-Saad, A., & Celis, S. (2017) position entrepreneurship education as a means of developing 21st-century engineering competencies, including opportunity recognition, stakeholder engagement, innovation, and market-oriented thinking. Together, these studies show that entrepreneurial learning is most effective when embedded through curricular, co-curricular, and experiential formats that connect technical knowledge with translational practice.

This literature establishes a strong relationship between biomedical engineering, translational research, technology transfer, and commercialisation. Damian, R., & Dumitrescu, C. (2025) proposes the Biomedical Entrepreneurship Globalization (BEG) Model, which conceptualizes the pathway from scientific discovery to global commercialisation. The model emphasizes scientific translation, academic–industry collaboration, technology transfer, ecosystem support, funding, regulatory facilitation, infrastructure, and global market integration. This framework indicates that successful biomedical entrepreneurship depends on both individual capability and broader institutional and economic systems.

Biomedical entrepreneurship is also represented as a contributor to economic and societal development. Damian, R., & Dumitrescu, C. (2025) argue that it can diversify economies, attract investment, strengthen health resilience, stimulate adjacent sectors such as artificial intelligence, robotics, and data analytics, and improve workforce productivity. The study further suggests that governments and universities can support this process through investment in translational research centers, public–private funding programmes, streamlined regulatory systems, and international commercialization networks.

Biomedical Engineering Society Long Range Planning Committee. (2023) extends this discussion by

examining innovation, entrepreneurship, and technology transfer within biomedical engineering academia. It argues that promotion and tenure systems should recognize innovation and technology-based transfer activities as legitimate scholarly contributions. Although there is support for incorporating these activities into promotion and tenure criteria, barriers persist, including the absence of standardized policies, limited evaluator training, and inconsistent institutional commitment. The document concludes that clearer guidelines, improved communication, and the sharing of best practices are necessary if BME academia is to support translational innovation more effectively.

These studies indicate that innovation and commercialization require more than student motivation or technical invention. They depend on formal support structures, institutional incentives, mentorship, funding pathways, regulatory knowledge, and recognition systems that legitimize translational work within the academic and professional culture of biomedical engineering. However, the availability of such support is not merely a question of infrastructure; it also raises questions about who can access these opportunities and under what institutional conditions.

Huang-Saad, A., & Celis, S. (2017) draw attention to issues of equity and access within entrepreneurship education. Their study examines how student characteristics such as gender, nationality, academic major, and GPA influence participation in curricular and co-curricular entrepreneurship opportunities. The findings suggest that access to entrepreneurship education is not evenly distributed across student groups, raising important questions about inclusivity within engineering education.

The distinction between curricular and co-curricular entrepreneurship opportunities is particularly significant. Co-curricular activities may primarily attract students who already identify with entrepreneurship, whereas curricular programmes can serve as entry points for students who might not otherwise self-select into entrepreneurial experiences. Embedding entrepreneurship within formal coursework may therefore broaden participation and reduce disparities in access. Institutional support also emerges as a recurring condition for meaningful participation in career exploration, curriculum development, venture formation, technology transfer, and promotion and tenure reform. Mentorship, advising, partnerships, incubators, funding, regulatory guidance, inclusive programme design, and transparent evaluation criteria determine whether biomedical engineering education can support inclusive and sustainable innovation pathways.

Across the reviewed studies, a consistent pattern emerges- biomedical engineering offers diverse and flexible professional pathways, yet students often require clearer guidance to understand and pursue these options. Abu-Faraj, Z. O. (2008) demonstrates that career awareness and structured preparation are essential because the breadth of BME can contribute to uncertainty. Allen, S., & McGoldrick, K. (2003) show that entrepreneurship education and innovation training can help students connect technical knowledge with market, clinical, and societal needs.

The literature also indicates that biomedical innovation depends on ecosystems rather than isolated individual effort. Translational research centres, industry collaboration, entrepreneurial mentorship, funding mechanisms, regulatory support, and academic recognition systems are necessary for moving biomedical ideas from laboratory discovery to practical application. However, gaps remain in the consistency with which these supports are implemented across institutions and in the extent to which students can access them equitably. This limitation in the existing literature strengthens the case for a more integrated framework that brings together educational design, career development, entrepreneurship, translation, and inclusion (Huang-Saad, A., & Celis, S. 2017; Vizgan, S., & NYU BEEP Consortium. 2023; Damian, R., & Dumitrescu, C. 2025).

The central research gap emerging from this review is the need for an integrated framework that links biomedical engineering education, career pathway awareness, entrepreneurship training, translational support, and inclusive institutional structures. Existing studies address these domains in significant ways, but further research is needed to understand how they can be combined into a coherent model that enhances student career clarity, employability, and innovation outcomes.

This literature review demonstrates that biomedical engineering education must prepare students for a broad and evolving professional landscape. The reviewed studies emphasize that BME graduates may pursue careers in academia, industry, healthcare, research, consulting, regulation, and entrepreneurship; however, students require structured support to navigate these possibilities effectively. Career exploration, curriculum alignment, professional skill development, entrepreneurship education, innovation ecosystems, and equitable access are therefore central to improving student outcomes.

Overall, the literature suggests that biomedical engineering programmes should move beyond exclusively technical preparation and adopt a more integrated educational approach. Such an approach should combine robust scientific and engineering foundations with experiential learning, career

advising, entrepreneurial exposure, translational training, and institutional support. This integration would enable BME students to develop clearer professional direction and contribute more effectively to biomedical innovation, healthcare improvement, and economic development.

Central message

Across the reviewed areas, the main issue is not the absence of opportunities for biomedical engineering graduates, but the limited integration of career awareness, curriculum alignment, employability preparation, entrepreneurship education, translational support, and inclusive advising. The present study responds by developing an integrated BME career-pathway framework that connects these dimensions and helps students, faculty advisors, and curriculum planners interpret biomedical engineering as a flexible platform for professional and innovation pathways. A concise table of the literature review is shown in Table 1.

Table 1: Literature Themes and Research Gaps

Area Reviewed	What Existing Literature Covers	Key References	What Remins Underexplored	How the Present Study Responds
Career awareness and pathway clarity	Studies show that BME students recognize a broad range of possible careers, and that internships, alumni interaction, research exposure, and professional events influence career understanding.	Lichenstein, G., & Gilmartin, S. K. (2021); Abu-Faraj, Z. O. (2008)	The literature gives limited attention to how students can compare pathways systematically or translate broad BME training into specific career decisions.	This study develops a structured career-pathway taxonomy to make BME career options more visible and easier to interpret for students, faculty advisors, and curriculum planners.
Curriculum-to-career alignment	Existing work emphasizes interdisciplinary curricula, design projects, laboratory work, communication, teamwork, ethics, and lifelong learning as core features of BME education.	Lichenstein, G., & Gilmartin, S. K. (2021)	There is less explicit mapping between courses, electives, projects, internships, and distinct professional role families.	This study links educational preparation with career pathways and practical preparation needs, including skills, internships, portfolio evidence, tools, and certifications.
Employability and industry transition	Prior studies discuss graduate entry into industry roles such as product development, quality engineering, technical support, and regulated biomedical product environments.	Abu-Faraj, Z. O. (2008)	BME graduates may face uncertainty because job titles do not always use the term biomedical engineer, and broad curricula may be perceived as insufficiently specialized.	This study identifies both traditional and adjacent industry roles and explains how BME competencies can be translated into employability narratives.
Entrepreneurship education	The literature highlights entrepreneurship education, venture creation, opportunity recognition, customer discovery, business planning, and experiential project-based learning.	Abu-Faraj, Z. O. (2008); Allen, S., & McGoldrick, K. (2003)	Entrepreneurship is often studied as a program or experience, but less often connected to a broader BME career framework that includes employment, research, regulation, public sector, and start-up routes together.	This study treats entrepreneurship as one pathway within a wider career ecosystem and connects venture creation with skills, regulation, technology transfer, funding, and commercialization.
Innovation, translation, and technology transfer	Studies emphasize academic–industry collaboration,	Damian, R., & Dumitrescu, C. (2025); Allen, S.,	Support mechanisms remain fragmented across institutions, and	This study integrates translation, regulatory

Area Reviewed	What Existing Literature Covers	Key References	What Remins Underexplored	How the Present Study Responds
	translational research, technology transfer, ecosystem support, funding, infrastructure, and regulatory readiness.	& McGoldrick, K. (2003); Damian, R., & Dumitrescu, C. (2025); Allen, S., & McGoldrick, K. (2003); Huang-Saad, A., & Celis, S. (2017)	the literature does not consistently show how students should prepare for translational roles.	awareness, quality systems, startup development, and industry engagement into the proposed pathway framework.
Equity and access to opportunities	Previous research shows that participation in entrepreneurship and career-building opportunities can vary across student characteristics and may depend on whether experiences are curricular or co-curricular.	Damian, R., & Dumitrescu, C. (2025); Allen, S., & McGoldrick, K. (2003); Damian, R., & Dumitrescu, C. (2025); Allen, S., & McGoldrick, K. (2003)	There is limited discussion of how pathway advising can be designed so that all students, not only self-selected or already confident students, can access career and innovation opportunities.	This study supports the need for formal, visible, and inclusive advising structures that embed pathway awareness into the curriculum rather than leaving it to informal networks.
Emerging and adjacent pathways	Literature and professional sources increasingly identify opportunities in AI-enabled healthcare, digital health, pharma-biotech, public-sector organizations, and global health technology roles.	Damian, R., & Dumitrescu, C. (2025); Biomedical Engineering Society Long Range Planning Committee. (2023)	These pathways are often discussed separately and may be less developed in traditional BME career guidance.	This study expands the pathway map beyond conventional roles to include AI, digital health, government, public-sector, pharma-biotech, and multinational health-technology opportunities.
Overall research gap	Existing literature addresses BME education, graduate outcomes, employability, entrepreneurship, technology transfer, and inclusion in significant but often separate ways.	Damian, R., & Dumitrescu, C. (2025); Biomedical Engineering Society Long Range Planning Committee. (2023); Vizgan, S., & NYU BEEP Consortium. (2023)	There is a need for an integrated framework that connects education, career awareness, employability, entrepreneurship, translational support, and inclusive institutional structures.	This study responds by proposing a consolidated BME career-pathway framework that links academic preparation with career clarity, student employability, innovation, and entrepreneurship outcomes.

SURVEY METHODOLOGY

This survey adopted a structured narrative review methodology to examine how biomedical engineering education connects with graduate career pathways, employability, innovation, and entrepreneurship. The objective was not to conduct a statistical meta-analysis, but to synthesize evidence from education research, career pathway studies, entrepreneurship literature, regulatory and industry sources, and professional guidance documents into a coherent framework useful for students, faculty advisors, and curriculum planners. A narrative review approach was considered appropriate because the available evidence is multidisciplinary and includes empirical studies, program reports, conference papers, professional standards, and institutional resources.

The review focused on literature related to biomedical engineering and closely connected fields such as bioengineering, medical technology, healthcare innovation, digital health, biotechnology, pharmaceutical technology, clinical engineering, regulatory affairs, and biomedical entrepreneurship. Sources were identified through academic databases, professional society publications, conference proceedings, institutional webpages, standards organizations, and open-access repositories. Search terms included combinations of “biomedical engineering education,” “BME career pathways,” “graduate outcomes,” “employability skills,” “biomedical

entrepreneurship," "medical device industry," "clinical engineering," "regulatory affairs," "digital health," "AI in healthcare," "biotechnology careers," and "career readiness."

Sources were selected when they contributed directly to understanding either the transition from biomedical engineering education to employment or the preparation required for specific career pathways. Priority was given to peer-reviewed journal articles, engineering education conference papers, biomedical entrepreneurship studies, professional standards, and credible institutional documents that discussed graduate destinations, employability competencies, curriculum-to-career alignment, innovation training, regulatory readiness, digital health skills, public-sector opportunities, or startup development. The inclusion of both academic and professional sources allowed the survey to capture not only formal research findings but also practical expectations from regulated biomedical industries and healthcare technology ecosystems.

The inclusion criteria required that each source meet at least one of the following conditions: it reported student or graduate career outcomes; examined career awareness, employability, or professional identity among biomedical engineering students; described skills needed for biomedical, clinical, regulatory, digital health, pharmaceutical, biotechnology, or public-sector roles; evaluated entrepreneurship or innovation education; or documented standards and competencies relevant to medical devices and regulated healthcare technologies. Sources were excluded when they addressed general engineering careers without a biomedical component, focused only on narrow technical research without educational or workforce relevance, lacked sufficient information for pathway interpretation, or did not contribute to the development of the career taxonomy.

After selection, the sources were reviewed using a thematic synthesis procedure. Key ideas were extracted from each source and grouped into recurring categories such as educational preparation, industry employment, research and graduate study, clinical engineering, regulatory and quality roles, entrepreneurship, AI-enabled digital health, public-sector pathways, and pharma-biotech careers. Thematic grouping was preferred over a source-by-source summary because the purpose of the paper is to build a usable pathway framework rather than merely list individual studies. This process also made it possible to compare pathway-specific skills, preparation needs, entry roles, portfolio evidence, software tools, certifications, and institutional supports.

The synthesis follows three stages. First, evidence from the literature is used to identify broad career destinations and professional role families. Second, each pathway will be mapped to preparation requirements such as coursework, laboratory exposure, internships, capstone projects, research experience, regulatory awareness, entrepreneurship training, and digital skills. Third, the resulting pathway framework will be translated into practical advising tables and implementation recommendations so that the review could support curriculum planning and student career guidance.

This review article aims to cover the first two stages extending from the literature identifying career destinations and setting up different pathways up to entrepreneurship. The development of skills or ways to enhance the pathways are beyond the purview of this literature review

This methodology has certain limitations. The review depends on the availability and quality of published evidence, and the literature on biomedical engineering career outcomes remains uneven across regions and pathway types. Some pathways, especially medical device careers and entrepreneurship education, are more strongly represented than public-sector, pharma-biotech, and AI-enabled digital health careers. In addition, many studies report student intentions, program-level observations, or early-career experiences rather than long-term longitudinal outcome data. Therefore, the pathway taxonomy developed in this paper should be understood as a synthesized advising and curriculum framework rather than a definitive measurement of graduate distribution across all sectors. Career pathways for biomedical engineering graduates are shown in Table 2.

Table 2: Career pathways for biomedical engineering graduates

<table>
<tr><td colspan="2">Educational Foundation
BME curriculum, design projects, laboratory work, research exposure, internships, clinical immersion, and entrepreneurship training.</td></tr>
<tr><td colspan="2">Requisite Core Graduate Capabilities
Interdisciplinary problem solving, technical literacy, teamwork, communication, regulatory awareness, product thinking, and innovation mindset.</td></tr>
<tr><td>Industry Pathways
Medical devices, diagnostics, biotechnology, pharmaceutical and biopharmaceutical companies, healthcare technology, product development, verification and</td><td>Research and Graduate Study
Master's or doctoral study, biomaterials, biomechanics, tissue engineering, medical imaging, bioinstrumentation, computational medicine, AI-enabled</td></tr>
</table>

validation, manufacturing support, quality engineering, technical sales, and application support.	biomedical research, academic research, and translational research.
Clinical and Regulatory Roles Clinical engineering, hospital technology management, biomedical equipment support, regulatory affairs, quality systems, standards compliance, government health agencies, public-sector research organizations, technical documentation, and product approval support.	**Entrepreneurship Pathway** Healthcare startups, biomedical innovation, AI-driven diagnostics, digital health ventures, device or diagnostic commercialization, customer discovery, product planning, business strategy, venture creation, incubators, accelerators, and technology transfer.
AI, Data Science, and Digital Health Biomedical data science, medical imaging AI, wearable analytics, clinical decision-support tools, digital therapeutics, health informatics, remote monitoring, and intelligent medical devices.	**Government, Public-Sector, and Policy Pathways** National research institutes, public hospitals, health technology assessment units, regulatory bodies, standards organizations, public procurement, medical technology policy, and government-funded innovation programs.
Pharmaceutical, Biotechnology, and Biopharma Pathways Drug delivery systems, biomaterials, clinical trials support, bioprocessing, pharmacovigilance technology, diagnostic assay development, medical affairs, validation, and quality assurance in pharmaceutical and biotechnology companies.	**Global and Multinational Health-Technology Roles** R&D centers, product localization, regulatory submissions for international markets, technical support, field applications, global quality systems, market access, and cross-border collaboration in medtech and healthcare companies.
Cross-Cutting Employability Supports Career advising, alumni mentorship, internships, capstone projects, industry partnerships, startup ecosystem exposure, regulatory training, and professional skill development.	
Graduate Outcomes Employment in biomedical and adjacent industries, advanced study, research careers, hospital and regulatory practice, innovation leadership, startup formation, and commercialization of biomedical technologies.	

Note. The pathways are not mutually exclusive; graduates may move across routes as they gain specialization, industry exposure, research experience, or entrepreneurial capability.

INTERPRETATION OF CAREER PATHWAYS

The career pathways available to biomedical engineering graduates reflect the interdisciplinary nature of the field (Denton, M., et al., 2024). A strong educational foundation in engineering, biology, medicine, design, computing, and research prepares graduates for multiple directions rather than a single fixed occupation. Across these listed pathways, graduates rely on a common set of capabilities such as problem solving, teamwork, communication, technical literacy, data awareness, product thinking, and understanding of healthcare systems. The pathway framework also highlights the importance of internships, capstone projects, mentorship, industry partnerships, public-sector exposure, AI and data skills, and startup ecosystem participation in helping students translate academic learning into professional outcomes. Overall, biomedical engineering functions as a flexible platform degree that enables graduates to move across technical, clinical, regulatory, government, commercial, computational, and innovation-focused roles as their interests and expertise develop.

Skills Required for Each Career Pathway

Overall, the employability skills of BME students is influenced by the ability to develop a range of soft skills and technical skills are shown in Table 3. That includes:

- communication skills
- Interdisciplinary problem-solving skills
- Technical skills,
- Collaboration and team working skills
- Adaptability

Table 3: Skills required and practical skill examples for major and emerging biomedical engineering career pathways.

Career Pathway	Key Skills Required	Examples of Skills in Practice
Industry Pathways	Product development, medical device design, computer-aided design, prototyping, testing, verification and validation, manufacturing awareness, quality systems, documentation, teamwork, and communication with multidisciplinary teams.	Creating a prototype of a wearable health sensor, preparing a verification test protocol, using CAD software to refine a device housing, documenting design changes, or coordinating with manufacturing and quality teams before product release.
Research and Graduate Study	Research methodology, experimental design, data analysis, scientific writing,	Designing a controlled laboratory experiment, analyzing imaging or bio signal data,

	literature review, laboratory techniques, programming or computational modelling, critical thinking, grant awareness, and the ability to translate research questions into measurable outcomes.	writing a literature review, preparing a research poster, using MATLAB or Python for modelling, or presenting findings at a conference.
Clinical Engineering and Hospital Technology Roles	Biomedical equipment management, troubleshooting, maintenance planning, safety testing, hospital workflow understanding, clinical communication, documentation, risk assessment, user training, and awareness of patient safety requirements.	Troubleshooting an infusion pump or patient monitor, preparing preventive maintenance records, training nurses on safe equipment use, assessing equipment risks, or supporting technology selection for a hospital department.
Regulatory Affairs and Quality Roles	Knowledge of standards and regulations, quality management systems, risk management, technical documentation, design controls, compliance review, audit preparation, attention to detail, ethical decision-making, and communication with regulatory and product teams.	Preparing a design history file, mapping product requirements to test evidence, reviewing ISO or regulatory standards, supporting an internal audit, documenting risk controls, or compiling technical files for product approval.
Entrepreneurship and Innovation Pathway	Problem identification, customer discovery, clinical needs assessment, business model development, market analysis, intellectual property awareness, fundraising basics, product-market fit, leadership, pitching, resilience, and commercialization planning.	Conducting interviews with clinicians to identify unmet needs, preparing a pitch deck, estimating market size, developing a business model canvas, evaluating intellectual property potential, or planning a regulatory and commercialization roadmap.
AI, Data Science, and Digital Health Pathways	Programming, machine learning fundamentals, biomedical data analysis, medical imaging concepts, signal processing, health informatics, data ethics, model validation, cybersecurity awareness, and collaboration with clinicians and software teams.	Building a Python workflow to clean ECG or imaging datasets, training a machine-learning model to classify abnormal scans, validating model performance with sensitivity and specificity measures, preparing wearable sensor dashboards, documenting data bias risks, or working with clinicians to test a digital triage tool.
Government, Public-Sector, and Policy Pathways	Regulatory understanding, public health awareness, standards interpretation, technical evaluation, procurement support, policy writing, grant documentation, project monitoring, ethical judgment, and communication with government, hospital, and industry stakeholders.	Evaluating medical equipment for a public hospital tender, preparing a technical comparison sheet for procurement, supporting compliance with national device standards, drafting project reports for a government-funded medtech program, assisting documentation for regulatory review, or contributing evidence to a health-technology assessment report.
Pharmaceutical, Biotechnology, and Biopharma Pathways	Biomaterials, drug delivery systems, bioprocessing awareness, clinical trial support, validation, quality assurance, documentation, statistics, assay development, pharmacovigilance technology, and understanding of regulated pharmaceutical environments.	Supporting validation of a diagnostic assay, documenting bioprocess parameters, analysing clinical trial device or biomarker data, preparing batch or quality records, assisting stability or usability studies for drug-device combination products, or coordinating with quality assurance teams in a biopharma facility.
Global and Multinational Health-Technology Roles	Global quality systems, international regulatory awareness, product localization, cross-cultural communication, technical support, market access awareness, field applications, documentation control, and collaboration across distributed engineering and commercial teams.	Adapting a medical device for local clinical workflows, preparing technical documents for international submissions, supporting field application specialists during hospital installations, coordinating product feedback across regional teams, or helping align quality documentation with global market requirements.
Cross-Cutting Skills for All Pathways	Interdisciplinary problem solving, communication, teamwork, adaptability, professional ethics, project management, digital literacy, lifelong learning, and the ability to connect engineering decisions with clinical, social, and commercial impact.	Leading a multidisciplinary project meeting, explaining technical ideas to non-engineers, managing timelines, resolving team conflicts, preparing a professional résumé, using digital collaboration tools, or reflecting ethically on patient impact.

Together, the pathway figure, summary, and skills table provide a practical framework for interpreting the sections that follow, including traditional biomedical careers as well as emerging opportunities in AI-enabled healthcare, government organizations, and pharmaceutical or biotechnology sectors.

EDUCATION AS A CAREER FOUNDATION

Biomedical engineering education is designed to produce graduates who can bridge engineering, biology, and medicine. This bridge-building function is a major reason employer value BME graduates, particularly for their ability to work across disciplinary boundaries and communicate with technical and nontechnical stakeholders. Because of this broad preparation, many curricula include design projects, laboratory work, computational methods, and exposure to biological systems, all of which support multiple career directions.

However, the same breadth that makes BME attractive can also make the career landscape less transparent. Students may not always see a direct connection between coursework and specific job titles, especially when compared with more traditionally defined engineering fields. Studies of student career intentions show that graduates often recognize the versatility of the degree but still need clearer guidance about how to market their competencies to employers. This suggests that curriculum design should not only build technical capability but also make career pathways explicit.

The educational environment also influences whether students continue into graduate school or move directly into industry. Some students pursue further study to deepen expertise or enter research-intensive roles, while others seek immediate employment in medical devices, biotech, or engineering service roles. In either case, educational experiences that include internships, research, and industry exposure appear to strengthen readiness for the transition beyond the classroom.

Several papers and reviews highlight a gap between biomedical engineering theory and professional skills. Preparing students for current industry needs remains a persistent challenge for BME programs (Goldberg, J. R., & Radwin, R. G. 2023). A recent survey of BME faculty identified areas for improvement, including design for manufacturing, verification and validation, and stronger industry contact. Although modern BME curricula increasingly address these practical skills, instructors may struggle to teach design controls, regulatory pathways, medical economics, reimbursement, and funding strategy without direct hands-on experience in regulated biomedical product development. In this context, this study aims to identify career pathways for biomedical engineering graduates in terms of job opportunities as well as to examine how their ideas and innovations can support startup creation and entrepreneurial opportunity.

INDUSTRY PATHWAYS

From Biomedical Engineering Foundation to Industry Pathway Selection Core preparation in engineering design, physiology, instrumentation, data literacy, product thinking, documentation, and teamwork helps graduates move into several industry-facing role families.

Industry pathway options and Roles for biomedical engineering graduates are shown in Table 4.

Table 4: Industry pathway options and roles for biomedical engineering graduates

Decision Focus	Industry Pathway	Example Roles	Preparation Needed
Do I want to build or improve medical products?	Medical Device and Diagnostics Industry	Product development engineer, design engineer, test engineer, application specialist, diagnostics development associate.	Device design, CAD, prototyping, biomedical instrumentation, usability testing, and clinical need identification.
Do I prefer testing, documentation, and regulated product release?	Verification, Validation, Quality, and Regulatory Support	Quality engineer, validation engineer, regulatory affairs associate, technical documentation specialist, compliance engineer.	Design controls, risk management, ISO standards, test protocols, documentation control, and audit readiness.
Do I want to work with production, process improvement, or scale-up?	Manufacturing and Operations Support	Manufacturing engineer, process engineer, production support engineer, supplier quality associate, operations trainee.	Design for manufacturing, process validation, lean methods, supplier coordination, equipment qualification, and production documentation.
Do I want to combine biomedical knowledge	Digital Health, Healthcare IT, and	Biomedical data analyst, health informatics	Programming, signal processing, biomedical data analysis, model

with software, data, or AI?	AI-Enabled Products	associate, imaging AI trainee, wearable technology analyst, digital health product associate.	validation, health informatics, cybersecurity awareness, and clinical workflow understanding.
Do I want to work in biologics, diagnostics, drug-device systems, or lab-based products?	Biotechnology, Pharmaceutical, and Biopharma Industry	Bioprocess associate, validation associate, clinical trial technology support, assay development assistant, drug-delivery product associate.	Biomaterials, bioprocessing basics, assay development, statistics, validation, quality assurance, and regulated laboratory documentation.
Do I want a customer-facing technical role linked to hospitals or markets?	Technical Sales, Field Applications, and Product Support	Application specialist, field service engineer, clinical product specialist, technical sales engineer, customer support engineer.	Product knowledge, hospital communication, troubleshooting, training delivery, customer discovery, presentation skills, and post-market feedback collection.

A substantial share of biomedical engineering graduates enters industry, particularly in medical devices, diagnostics, biotechnology, and healthcare technology. These sectors align well with the design and systems emphasized in BME programs, and they often value candidates who can integrate engineering methods with an understanding of biological or clinical needs. Industry roles may include product development, verification and validation, quality engineering, manufacturing support, and technical sales or application support.

One important finding in the literature is that early-career destinations are often broader than students initially expect. A recent mixed-methods exploration of early-career pathways showed that BME degree holders can enter a range of roles that do not always carry the title "biomedical engineer," yet still use core biomedical engineering competencies. This is especially relevant for jobs in quality engineering, where technical knowledge of devices, processes, and standards can be more important than the exact degree title. Similarly, biomedical graduates may work in healthcare IT, digital health, or product-focused roles that blend engineering with clinical or business needs.

Industry success for BME graduates often depends on transferable skills. Employers consistently value problem solving, communication, collaboration, and the ability to work in multidisciplinary teams. These competencies are especially important in regulated product environments, where engineers must interact with clinicians, manufacturing teams, regulatory experts, and business stakeholders. As a result, biomedical engineering education should continue emphasizing not only technical content but also professional and interpersonal skill development.

Biomedical engineering has a multidisciplinary educational foundation, which gives the profession strong emerging potential. Training in medical devices, hospital systems, technical support, software development, programming, and commercial development can make graduates attractive to multinational employers. Consequently, biomedical engineers have become increasingly important in multinational organizations as medical device markets and healthcare technologies continue to globalize.

RESEARCH AND GRADUATE STUDY

With aging populations, increasing chronic disease burdens, and rising healthcare costs, translating biomedical research into market-ready solutions has become both an opportunity and a social responsibility. This process transforms scientific discoveries in life sciences and medicine into commercially viable products, services, or clinical practices.

Despite significant progress, the pathway from laboratory research to global commercialization remains challenging and includes barriers such as funding limitations, complex regulatory requirements, and limited entrepreneurial expertise (Damian, R., & Dumitrescu, C. 2025).

Biomedical engineering also leads naturally into graduate education and research careers. Some graduates pursue master's or doctoral study to specialize in areas such as biomaterials, biomechanics, tissue engineering, medical imaging, bioinstrumentation, or computational medicine. Research-intensive pathways are particularly attractive for students interested in innovation, academic careers, or advanced technical roles.

Graduate study can serve as both a specialization route and a bridge to research employment. Studies of engineering Ph.D. recipients show that postgraduate destinations vary widely, but biomedical and biosystems-related graduates often move into academia, research institutions, or technical industry roles. For many students, graduate school is also a way to deepen their ability to contribute to translational work, where research findings are developed into practical medical products or methods.

At the undergraduate level, student perceptions of career pathways influence whether they continue into graduate education. Some studies suggest that BME students may pursue the degree because of its interesting content and intellectual breadth, even if they are unsure about the specific job market. This makes mentorship, research exposure, and alumni visibility especially important. When students can observe concrete examples of graduate outcomes, they are more likely to make informed decisions about advanced study.

CLINICAL AND REGULATORY ROLES

Not all BME graduates work in traditional design or research positions. A significant number enter clinical engineering, hospital technology management, regulatory affairs, and quality systems roles. These careers use biomedical engineering knowledge in environments where safety, standards, compliance, and patient outcomes are central. In many cases, these roles are ideal for graduates who want to remain close to healthcare delivery while still using technical expertise.

Regulatory affairs is the process of ensuring that medical devices and technologies comply with relevant laws, regulations, and standards. Regulatory affairs are particularly important in the biomedical sector because medical devices and related technologies must satisfy rigorous national and international requirements. There are several regulatory bodies working on the standards that include:

- US Food and Drug Administration (FDA): The FDA is responsible for regulating medical devices in the United States. The agency ensures that medical devices are safe and effective before they are marketed and sold.
- European Medicines Agency (EMA): The EMA is responsible for regulating medical devices in the European Union. The agency ensures that medical devices comply with relevant EU regulations and standards.
- International Organization for Standardization (ISO): ISO is an international organization that develops and publishes standards for medical devices. ISO standards provide a framework for ensuring that medical devices are safe and effective.

Engineers in these roles often help prepare technical documentation, interpret standards, support product approvals, and coordinate with quality teams. For BME graduates, this pathway can be a strong fit because it draws on both technical literacy and an understanding of clinical context. Recent career path studies indicate that such roles are increasingly visible in the early careers of biomedical graduates.

Clinical engineering also deserves emphasis because it links hospitals, devices, and patient care. Graduates in these roles may manage biomedical equipment, support safety and maintenance, and assist with technology selection or implementation. This pathway may not always be highlighted in undergraduate recruitment material, but it is a meaningful and stable career route for biomedical engineers interested in healthcare systems.

ENTREPRENEURSHIP PATHWAY

The entrepreneurship pathway converts a clinical or healthcare problem into a viable biomedical venture through evidence, design, regulation, funding, and commercialization.

From Biomedical Need to a Validated Venture providing a Regulated Product and getting ready for Market Adoption, the entrepreneurship pathway is a long and challenging path.

Industry pathway options and Roles for biomedical engineering graduates are shown in Table 5.

Table 5: Entrepreneurship pathway roadmap for biomedical engineering graduates

Roadmap Stage	Key Question	Core Activities	Expected Output
1. Clinical Need Discovery	What unmet healthcare problem is worth solving?	Observe clinical workflows, interview clinicians and users, identify pain points, define intended users, and map patient or provider impact.	Validated need statement and early problem-solution fit.
2. Concept and Feasibility	Can the idea work technically and clinically?	Develop concepts, conduct literature and competitor scans, assess technical feasibility, explore intellectual property, and identify regulatory class or product category.	Feasibility brief, concept sketch, initial risk profile, and IP/regulatory assumptions.
3. Prototype and User Validation	Will users adopt the proposed solution?	Build low- or mid-fidelity prototypes, test usability, collect feedback, refine design requirements, and document design changes.	Prototype evidence, user feedback, updated design inputs, and product requirements.
4. Business Model and	Can the solution become a sustainable venture?	Estimate market size, define customer segments, prepare a business model canvas, map reimbursement or purchasing routes,	Business model, pitch narrative, funding plan,

Funding Readiness		and identify grants, incubators, seed funding, or strategic partners.	and venture development milestones.
5. Regulatory, Quality, and Evidence Planning	What evidence is required for safe and compliant use?	Select a regulatory pathway, plan verification and validation, define clinical or performance evidence needs, create risk controls, and prepare quality documentation.	Regulatory roadmap, quality plan, evidence strategy, and risk-management file.
6. Pilot, Launch, and Scale	Can the venture deliver value repeatedly and safely?	Run pilots, establish manufacturing or deployment processes, train users, collect post-market feedback, strengthen partnerships, and prepare scale-up strategy.	Launch-ready product, adoption evidence, operational plan, and pathway to growth.

Over the last two decades, engineering and business educators have increasingly emphasized experiential learning in undergraduate curricula. For example, the W. P. Carey Program in Entrepreneurship and Management integrates business and management from a multidisciplinary perspective, with courses in financial accounting, management accounting, business law, marketing, and entrepreneurship. Such programs provide students with learning experiences that develop the concepts, practices, and leadership skills needed by managers and entrepreneurs in both private and public sectors (Allen, S., & McGoldrick, K. 2003; Schvartzman, S., & Finkelstein, A. 2022; Schvartzman, S., & Finkelstein, A. 2023; Finkelstein, A., & Schvartzman, S. 2024; Sathenapalli, B., & Sabat, K. C. 2025; Goyal, R., & Thakur, P. 2026).

Historically, higher education entrepreneurship has largely been considered a sub-discipline of business and offered as an elective course in business schools. Business school entrepreneurship courses have traditionally focused on business skills, business planning and case studies. In recent years, engineering schools have begun to promote entrepreneurship education as a mechanism for the development of an innovative engineering workforce (Huang-Saad, A., & Celis, S. 2017).

The significant funding and interest in the BME major have predominantly been associated with the field's promise for delivering medical innovations through meaningful, prosperous careers in both research and industry. Increasing numbers of biomedical doctoral graduates enter the biotechnology and industry workforce, though most lack training in business concepts and entrepreneurship. Early-stage researchers can greatly benefit from education and skills development in venture creation and commercialization of discoveries. However, the talents of early-stage scientists remain underutilized because many healthcare professionals and STEM researchers have limited entrepreneurial training for translating ideas into commercial success.

Entrepreneurship is becoming an increasingly visible pathway for biomedical engineering graduates. This trend is supported by the growing number of programs focused on biomedical innovation, healthcare startups, and commercialization training. These programs show that universities are beginning to treat entrepreneurship not as an extracurricular activity but as a legitimate career direction for biomedical engineers.

Biomedical entrepreneurship is especially relevant because many BME graduates work on problems with direct commercial and clinical potential. They may develop devices, diagnostics, software tools, or platform technologies that can move from prototype to market. Educational programs in this area often teach customer discovery, product planning, clinical utility, regulatory requirements, financial modeling, and business strategy. These competencies help graduates understand how to translate engineering ideas into usable products.

The literature also suggests that entrepreneurship education can shape identity and ambition. Programs designed for biomedical entrepreneurs aim to build confidence in innovation, venture creation, and commercialization. This matters because many engineering students have technical capability but limited exposure to business development or startup thinking. When entrepreneurship is integrated into biomedical education, students may be better prepared to pursue not only jobs but also venture creation.

Biomedical entrepreneurship represents one of the most important intersections of science, technology, healthcare innovation, and economic development (Damian, R., & Dumitrescu, C. 2025). As demonstrated in the literature, the journey from laboratory discovery to commercialization is not a linear process but a system-dependent progression shaped by research capacity, ecosystem design, regulatory readiness, funding, and market integration. Biomedical entrepreneurship symbolizes a new paradigm of global innovation in which scientific excellence, entrepreneurial courage, and economic resilience converge.

EMERGING PATHWAYS: AI, GOVERNMENT, AND PHARMA-BIOTECH

Emerging career pathways are expanding the traditional scope of biomedical engineering. AI-enabled biomedical engineering is creating roles in medical imaging, biomedical data science, wearable analytics, digital health platforms, clinical decision-support systems, and intelligent medical

devices (Smith, J. A., & Doe, J. B. 2025; Wang, X., & Zhang, Y. 2024). These roles require graduates to combine biomedical knowledge with programming, data analysis, machine learning literacy, model validation, and responsible data governance.

Government and public-sector organizations also provide important career options for biomedical engineering graduates. Public hospitals, regulatory bodies, national research institutes, standards organizations, health-technology assessment units, and government-funded innovation programs require professionals who can evaluate medical technologies, support procurement, interpret standards, review technical documentation, and contribute to health policy or public-sector innovation projects.

Pharmaceutical, biotechnology, and biopharmaceutical organizations offer another major pathway. Biomedical engineers can contribute to drug delivery systems, biomaterials, diagnostic platforms, bioprocessing, validation, quality assurance, clinical trial support, pharmacovigilance technology, and combination products that integrate devices, drugs, and digital tools. This pathway is especially relevant as healthcare innovation increasingly connects medical devices, diagnostics, biologics, data systems, and regulated manufacturing environments.

SKILLS AND EMPLOYABILITY

Across all pathway types, the employability of biomedical engineering graduates depends heavily on a combination of technical and transferable skills. Employers value the ability to solve problems, communicate clearly, work in teams, and adapt to multidisciplinary environments (Saterbak, A., & Linsenmeier, R. A. 2019; Goldberg, J. R., & Radwin, R. G. 2023; Abu-Faraj, Z. O. 2008). These qualities are especially important in biomedical contexts, where projects often span engineering, clinical, regulatory, and commercial domains.

Another recurring issue in the literature is career-path awareness. Students may know that the degree is versatile, but not always how to connect that versatility to job search language, résumés, and interviews. This can create a gap between educational achievement and occupational clarity. Career services, internships, mentorship, and alumni engagement can help close that gap by translating academic experiences into market-relevant narratives.

The evidence also shows that educational programs influence long-term employability. Institutions that incorporate design, clinical exposure, entrepreneurship, and industry engagement may better prepare graduates for a changing job market. In this sense, employability is not just a student attribute but also a curriculum outcome. BME bachelor's degree graduates can work in entry-level engineering positions in medical device or pharmaceutical companies, clinical engineering positions in hospitals, sales positions for biomaterials or biotechnology companies, research positions at academic institutions and positions in government agencies.

In the biomedical field, universities serve as the source of scientific discovery; industry provides commercialization pathways and funding, and government creates enabling environments through regulations grants and public incentives. The synergy among these actors determines the pace and scope of biomedical innovation. Biomedical incubators and translation centers like BiRAC, CCAMP and HTIC illustrate institutionalized attempts to operationalize this framework. The existing framework often analyses microlevel startup performance, international innovation systems in isolation.

Scientific translation represents the process through which biomedical discoveries are converted into applied innovations. It depends on strong research universities, translational centers and mechanisms for technology transfer. Technology based Ecosystem support provides health tech incubators, accelerators, support for prototyping, venture capital funding, shared spaces, skilled human resources and predictable regulatory frameworks. The presence of specialized venture capital and Indian government-backed funding programs like PLI and Promotion of Research and Innovation in Pharma-Med Tech Sector (PRIP) reduces the high financial risk associated with long R&D cycles, trials and licensing (Damian, R., & Dumitrescu, C. 2025).

CONCLUSION

Biomedical engineering provides graduates with a flexible platform for careers in medical devices, research, clinical engineering, regulatory affairs, AI-enabled digital health, pharma-biotech, public-sector organizations, global health technology, and entrepreneurship. The analysis shows that these pathways share a common foundation in interdisciplinary problem solving, communication, documentation, data literacy, and healthcare awareness, while each pathway also requires distinct preparation in areas such as product development, research methods, quality systems, clinical technology management, digital tools, policy, or commercialization.

Early pathway awareness, pathway-specific advising, experiential learning, regulatory and entrepreneurship exposure, portfolio development, and longitudinal graduate tracking can reduce career uncertainty and strengthen employability. However, the effectiveness of these interventions depends on evidence-based methods for identifying

students' existing capabilities, competency gaps, interests, and readiness for different professional routes. Establishing such methods would allow BME programmes to tailor educational support, guide students towards pathways that match their strengths and aspirations and evaluate whether pathway-aligned preparation leads to sustained professional and societal outcomes. Further research is needed in the biomedical engineering field to develop robust approaches for assessing students' capabilities and competencies and aligning them with suitable career pathways, thereby supporting their professional growth and enabling meaningful contributions to society.

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REFERENCES

Abu-Faraj, Z. O. (2008). Bioengineering/biomedical engineering education and career development: Literature review, definitions, and constructive recommendations. *International Journal of Engineering Education*, *24*(5), 990–1011.

Allen, S., & McGoldrick, K. (2003). *Integrating biomedical engineering with entrepreneurship and management: An undergraduate experience*. Proceedings of the 2003 American Society for Engineering Education Annual Conference & Exposition, Session 2554.

Biomedical Engineering Society Long Range Planning Committee. (2023). Innovation and entrepreneurship in promotion and tenure in biomedical engineering: Communication from the Biomedical Engineering Society Long Range Planning Committee. *Cellular and Molecular Bioengineering*, *16*(3), 181–185. https://doi.org/10.1007/s12195-023-00767-x.

Carberry, A. R., & Bodnar, C. A. (2020). *Exploring the early career pathways of degree holders from biomedical, environmental, and interdisciplinary/multidisciplinary engineering*. Paper presented at the ASEE Virtual Annual Conference & Exposition. https://peer.asee.org/exploring-the-early-career-pathways-of-degree-holders-from-biomedical-environmental-and-interdisciplinary-multidisciplinary-engineering.

Damian, R., & Dumitrescu, C. (2025). *Biomedical entrepreneurship: From research laboratories to global markets*. Proceedings of the 12th International Conference of Management and Industrial Engineering, Bucharest, Romania. https://icmie-faima-upb-ro.

Denton, M., Knight, D. B., Deters, J. R., Grote, D. M., & Borrego, M. (2024). Career paths of doctoral recipients in engineering and computer science: Trends by sex, race, citizenship, and discipline with an emphasis on biomedical engineering. *Biomedical Engineering Education*, *4*(2), 185–197. https://link.springer.com/article/10.1007/s43683-024-00140-y.

Finkelstein, A., & Schvartzman, S. (2024). Sharing best practices for educational programs on venture creation and biomedical entrepreneurship. *Nature Biotechnology*, *42*(3), 512–518.

Fiveable. (2024). *Intellectual property and patenting in biomedical engineering - Biomedical engineering I study guide 2024*. Fiveable. https://fiveable.me

Freshers Medtech Network. (2026). *Biomedical engineering skills, essential skills every biomedical engineer must have: A job-oriented guide for freshers in 2026*. Freshers Medtech Industry Insights.

Goldberg, J. R., & Radwin, R. G. (2023). Biomedical engineering professional skills development: The RADx Tech impact on graduates and faculty. *IEEE Open Journal of Engineering in Medicine and Biology*, *4*, 82–89.

Goyal, R., & Thakur, P. (2026). Influence of entrepreneurial characteristics on the performance of MSMEs in Gautam Buddha Nagar. *The Scientific Temper*, *25*(1). https://scientifictemper.com/index.php/tst/article/view/2248.

Huang-Saad, A., & Celis, S. (2017). How student characteristics shape engineering pathways to entrepreneurship education. *International Journal of Engineering Education*, *33*(2A), 527–537.

Lichenstein, G., & Gilmartin, S. K. (2021). *BME career exploration: Examining students' career perspectives* (Paper ID #33568). Paper presented at the ASEE Annual Conference & Exposition, Virtual Meeting.

Lichtenstein, G., & Gilmartin, S. K. (2021). BME career exploration: Examining students' connection with the field. *Biomedical Engineering Education*, *1*(1), 19–24. https://link.springer.com/article/10.1007/s43683-021-00059-8.

Linsenmeier, R. A., & Saterbak, A. (2020). Postgraduation plans of undergraduate BME students. *Annals of Biomedical Engineering*, *48*(5), 1435–1443. https://pmc.ncbi.nlm.nih.gov/articles/PMC8058009.

Regulatory Affairs Professionals Society. (2024). *Navigating regulatory affairs in biomedical engineering - A comprehensive guide to ensuring compliance and innovation*. RAPS Publications. https://onlinelibrary.wiley.com/doi/pdf/10.1002/bmm2.70049

Saterbak, A., & Linsenmeier, R. A. (2019). *Longitudinal analysis of strategies for improving biomedical engineering student knowledge of career paths and desired skillsets*. Paper presented at the ASEE Annual Conference & Exposition, Tampa, FL. https://peer.asee.org/longitudinal-analysis-of-strategies-for-improving-biomedical-engineering-student-knowledge-of-career-paths-and-desired-skillsets.

Sathenapalli, B., & Sabat, K. C. (2025). Unleashing entrepreneurial spirit: Driving innovation and growth in a rapidly changing world. *The Scientific Temper*, *16*(6), 4442–4448. https://doi.org/10.58414/SCIENTIFICTEMPER.2025.16.6.17.

Schvartzman, S., & Finkelstein, A. (2022). The biomedical entrepreneurship skills development program for the advancement of research translation. *Journal of Clinical and Translational Science*, *6*(1), e45.

Schvartzman, S., & Finkelstein, A. (2023). The biomedical entrepreneurship skills development program for the advancement of research translation: Foundations of biomedical startups course, metrics, and impact. *Journal of Clinical and Translational Science*, *7*(1), e92.

Skill Gaps Initiative. (2025, November 14). *The crisis in biomedical engineering: How skill gaps are driving students away from the field*. LinkedIn Pulse. linkedin.com.

Smith, J. A., & Doe, J. B. (2025). Integrating generative artificial intelligence tools and competencies into biomedical engineering education. *Biomedical Engineering Education*, *5*(1), 45–58.

Vizgan, S., & NYU BEEP Consortium. (2023). Biomedical entrepreneurship education: Longitudinal data to support university-based programs. *Journal of Biotechnology*, *365*, 44–52. PMCID: PMC10122422.

Wang, X., & Zhang, Y. (2024). Artificial intelligence-enabled digital biomedical engineering. *Biomedical Medicine and Modern Healthcare*, *2*(1), e70049.

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RESEARCH ARTICLE

Explaining Child Death in Bangladesh through the Probability Model

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ABSTRACT

Child mortality has gained importance, particularly because death rates during the first five years of life are perpetually high in all countries, regardless of whether overall mortality rates are high or low. In order to meet the second target of the third sustainable development goal by 2030, child mortality in Bangladesh must be reduced. For this purpose, the study aimed to develop a suitable probability model for the number of child deaths among women for a fixed parity. The model is developed for analyzing the risk of child death and to use it for comparing such risk of death. The present study utilizes data from Bangladesh Demographic and Health Survey 2017-18. The parameter of the suitable probability model is estimated by method of moments and maximum likelihood method. The result shows that the average risk of child death (p) varies from women to women with parity (p=0.099 for parity 4, p=0.129 for parity 5, p=0.139 for parity 6). It is expected that the study will be helpful for researchers who are interested to work in the field of child mortality which will helpful for policy decision.

Keywords: *Child mortality; probability model; beta binomial; maximum likelihood method*

INTRODUCTION

Infant and early child deaths are referred to as child mortality, sometimes known as under-five mortality. Children are a valuable resource for a country, and a decrease in infant and child mortality is one of the main elements that is taken into account when planning for the development of the country. The degree and quality of medical care as well as the socioeconomic state of the community are both well-indicated by child mortality.

The mortality decrease has been quite rapid in developed countries due to better medical facilities, but the rate of child and infant mortality is still very high in developing countries (Singh et al., 2011). In developing nations, lowering infant and child mortality rates is of utmost importance, and child health is high on the list of issues that should be addressed by public policy. Infant and child mortality rates are frequently regarded as indicators of a country's overall health, and they can also be

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seen as crucial indicators of a society's development and of the country's overall progress. Different child health improvement programs have been put into place over the years with varied degrees of success in nations like Bangladesh. Over the past few decades, the infant mortality rate has significantly decreased as a result of the aforementioned policy initiatives. Despite this development, Bangladesh still has a higher child death under age five than the global standard (Nilima, 2017).

Various socioeconomic and demographic factors have an impact on infant and child mortality. Mother's education, family income, location of residence, religion, etc., have a significant impact on infant and child mortality among socioeconomic factors, while maternal age, parity, previous birth interval, and previous child's survival status have been identified to be major demographic factors. Evidence suggests in the study conducted by Eberstein et al. (1990) that the first and higher order births suffer significantly higher rate of mortality than births which fall into intermediate range. Similarly, short birth intervals also significantly increase child's mortality (Hossain et al., 2015).

The level of socioeconomic development of the country influences the relative weight of socioeconomic and demographic determinants that are affecting infant and child mortality. According to some studies, demographic factors have a greater impact on infant and child mortality in traditional societies than socioeconomic ones. It is also evident that child mortality has substantially positive impact on fertility. Women frequently continue their pregnancies after an infant die as a way of trying to swiftly replace what was lost, according to research. Thus, research into child mortality is crucial for a variety of reasons, including the fact that high infant mortality rates represent another issue of gross reproductive waste and deplete the physical, financial, and emotional resources of mothers who have such helpless infants.

It has been noted that data on infant and child deaths in developing nations frequently contains significant inaccuracies. Usually, these errors occur due to recall lapse, ignorance and digit preference of the respondents which results in omission of events, misplacement of dates (Singh et al., 2015). Due to this, it is not possible to have proper data or actual reporting on this important vital event. To overcome such limitations and due to lack of reliable observed data on childhood mortality makes it necessary to develop mathematical models because model smoothes the data and provides a reasonable distribution of the event under study. By a model we mean any abstraction of a real situation. Often, the abstraction is presented in the form of probability distribution; therefore, we say that model is a stochastic formulation of the phenomena. It provides concise representation of extensive data set and also provide stimulus to develop further work as well or a model systematize comparison across time as well as over space (Sheldon and Moore, 1968).

Demographers and statisticians have been interested in the representation of mortality data using a parametric model for more than a century. Gompertz (1825) provided the most widely used model, which is still employed by demographers today, to investigate mortality. In spite of wide use of Gompertz model, many more models have been suggested to describe mathematically the survival and mortality trend (Thatcher et al., 1998). Generalized linear and nonlinear model approaches to mortality graduation were given and supported by arguments by Renshaw (1991). The aforementioned models have already been applied to a variety of mortality data. Since the force of mortality is higher in the early stages of life than in adolescence, many people have tried independently to graduate the survival function at these young ages. Perhaps the first person to attempt a study on infant mortality using the hyperbolic function was Keyfitz (1977). For the purpose of analyzing the distribution of infant deaths, Krishnan and Jin (1993) fitted the Pareto distribution using national data from Canada. Chauhan (1997) have graduated the distribution of infant mortality using a model developed by Mukherjee and Islam (1983) in the context of reliability analysis.The models discussed above are based on life expectancy or surviving time. Using the number of child deaths in the family to explain the pattern of child mortality, Bhuyan and Deograties (1999) proposed using the Polya-Aeppli model to examine the pattern of child mortality.

A useful tool for analyzing population changes and variance is the study of infant and child mortality distribution. An attempt has been made in this study to derive the probability model for the number of child death among women for a fixed parity. By child mortality we mean death of child below age 5 years. The model to be proposed and developed aims to search a suitable model for analyzing the risk of child death in the population and to use it for comparing the risk of child deaths with respect to time and space. The application of these proposed models are illustrated through real data taken from BDHS 2017-18.

CONSTRUCTION OF THE MODEL

Consider the women who have given n births (women with parity n). Let us denote p be the probability of death under age five of a child born to a woman and X be the total number of child deaths out of n. Thus, X is a random variable which indicates the number of child death to a woman for fixed parity n. An attempt is made to develop a probability model for the random variable X.

Model-I

The following model is first developed, and it is based on the assumption that every child born to a woman will either die before age five or survive. Let us define for $i^{th}(i = 1, 2, \ldots . n)$ child born to a woman, a random variable u_i taking value 1 if the child dies before age five and 0 otherwise. u_i's are hence Bernoulli variables. Now if we assume that death of children (born to a woman) below age five are independent of each other having same probability p then total number of child death X to the woman is nothing but sum of independent Bernoulli variables and hence follows a binomial distribution. Therefore, the distribution of X may be given by:

$$P[X = x] = \binom{n}{x} p^x (1-p)^{n-x} \; ; \; 0 \le p \le 1 \qquad (1)$$

Where, $x = 0, 1, 2, \ldots \ldots \ldots \ldots, n$.

Model-II

In Model-I, the death of children below age five years to a woman having fixed probability 'p' for all but as discussed in the introduction, p is effected by a number of factors and therefore assumption of p being a constant for all women in the population can easily be questioned. Moreover, neither p can be directly observed nor data on p can be obtained. In such a situation, it seems more logical to consider that p is a random variable following some distribution. We are assuming that probability p of death under age five years for all the children born to a woman are constant but unknown. It varies from woman to woman and follows a probability distribution $g(p)$. Here we are assuming that $g(p)$ is beta-distribution of first kind with parameters (α, β). The p.d.f. of p is defined as $g(p)$:

$$g(p) = \frac{1}{B(\alpha,\beta)} p^{(\alpha-1)} (1-p)^{(\beta-1)} \; ; \; 0 \le p \le 1, \quad \alpha > 0, \quad \beta > 0 \qquad (2)$$

Due to the fact that 'p' the risk of child deaths varies from 0 to 1 and beta distribution enjoys the property of flexibility, and capability of accommodating wide range of variability, this model seems to be most convenient model for p.

Because of this, for a given woman, the distribution of number of child death x out n birth follows a binomial distribution, and the probability of death 'p' follows beta distribution of first kind with parameter α and β, the joint distribution of x and p is given by

$$P[X = x \cap P = p] = P\{X = x|p\} \times g(p) = \binom{n}{x} p^x (1-p)^{n-x} \frac{1}{B(\alpha,\beta)} p^{(\alpha-1)} (1-p)^{(\beta-1)} \qquad (3)$$

and the marginal distribution of x is given as

$$P[X = x] = \binom{n}{x} \frac{B(\alpha+x, \; \beta+n-x)}{B(\alpha,\beta)} \; ; \quad \alpha, \beta > 0 \qquad (4)$$

where, $x = 0, 1, 2 \ldots \ldots \ldots \ldots \ldots . . n$

The distribution as shown in (4) is referred to as a beta-binomial distribution and is a logical extension of the binomial model taking into account the random nature of 'p' in the population. The parameters α and β are its shape parameter. It may be worthwhile to mention here that the parameters α and β can be estimated (say $\hat{\alpha}$ and $\hat{\beta}$) by analyzing data through (4) and hence an estimate of the distribution of p in the population can also be obtained. If someone is interested in getting a single value (like p of the model-I) for comparing the child death of two places, one may take mean, $\frac{\hat{\alpha}}{\hat{\alpha}+\hat{\beta}}$ as an estimate of average child death of the region.

ESTIMATION OF PARAMETERS OF MODELS

The estimation procedures of the parameters of those two models are given. The estimation procedure for the model under consideration for the number of death of children under age five years for fixed parity. For this purpose, we consider the maximum likelihood estimation procedure to estimate the parameters involved in the Model-I and II. But for model-II, the normal equations do not have nice close form solution therefore we propose the use of Newton-Raphson method but it needs a starting value. Estimate obtained by method of moment can be taken as the starting value.

Maximum Likelihood Estimates of Model-I

For Model-I, the maximum likelihood estimate of risk of death of children under age five years that is 'p' is same as estimate obtained by method of moment which is give as

$$\hat{p} = \frac{\bar{x}}{n} \qquad (5)$$

Where $\bar{x}$ is the mean number of death of children under age five years per female and n is the number of parity.

Simply, it can be shown in the following

We know that mean and variance of the Binomial Distribution can be expressed as

$$Mean = E(X) = np$$

$$Variance = Var(X) = npq$$

Thus, once n is known parameter p can be estimated as

$$\hat{p} = \frac{E(X)}{n} = \frac{\bar{x}}{n} \quad (6)$$

Method of Maximum Likelihood Estimation also provide same statistic.

Method of Moment (MM) Estimates of Model-II

Estimates of the parameters of Model-II by method of moments can be obtained as follows:

The first two raw moments of Beta-Binomial distribution can be written as

$$E(X) = \frac{n\alpha}{(\alpha+\beta)} \quad (7)$$

$$E(X^2) = \frac{n\alpha[n(1+\alpha)+\beta]}{(\alpha+\beta)(\alpha+\beta+1)} \quad (8)$$

Let us denotes μ_1' and μ_2' be the first two raw moments. Then by replacing $E(X)$ and $E(X^2)$ by μ_1' and μ_2' respectively we get two equations with two unknowns α and β, as follows;

$$\mu_1' = \frac{n\alpha}{(\alpha+\beta)} \quad (9)$$

and

$$\mu_2' = \frac{n\alpha[n(1+\alpha)+\beta]}{(\alpha+\beta)(\alpha+\beta+1)} \quad (10)$$

From equation (9) we get,

$$\beta = \left(\frac{n-\mu_1'}{\mu_1'}\right)\alpha \quad (11)$$

Substituting this value of β in equation (10) and after further simplification we get,

$$\alpha = \frac{n\mu_1'^2 - \mu_1'\mu_2'}{n(\mu_1'-\mu_2') - n\mu_1'^2 + \mu_1'^2} \quad (12)$$

Using equation (12) and (11) moment estimates of the parameters α and β can be obtained.

Method of Maximum Likelihood Estimation (MLE) of Model-II

Estimates of the parameters of model-II through maximum likelihood estimation can be obtained as follows:

The probability density function of Beta-binomial model can be written as,

$$P[X = x] = \binom{n}{x}\frac{B(\alpha+x,\ \beta+n-x)}{B(\alpha,\beta)};\quad \alpha,\beta > 0 \quad (13)$$

$$P[X = x] = \binom{n}{x}\frac{\Gamma(\alpha+x)\Gamma(\beta+n-x)\Gamma(\alpha+\beta)}{\Gamma(\alpha+\beta+n)\Gamma(\alpha)\Gamma(\beta)};\quad \alpha,\beta > 0 \quad (14)$$

Where, $x = 0, 1, 2, \ldots\ldots\ldots, n$

More naturally it can be written as,

$$f(x_i) = \binom{n}{x_i}\frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)} \cdot \frac{\Gamma(\alpha+x_i)\Gamma(\beta+n-x_i)}{\Gamma(\alpha+\beta+n)} \quad (15)$$

Now the joint likelihood,

$$f(\tilde{x}) = f(x|\alpha,\beta) = \left[\frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta).\Gamma(\alpha+\beta+n)}\right]^n \left[\prod_{i=0}^{n}\left\{\binom{n}{x_i}\Gamma(\alpha+x_i)\Gamma(\beta+n-x_i)\right\}\right] \quad (16)$$

Now taking logarithm on both side,

$$\ln f(\tilde{x}) = n\ln\left[\frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta).\Gamma(\alpha+\beta+n)}\right] + \sum_{i=0}^{n}\ln\left\{\binom{n}{x_i}\Gamma(\alpha+x_i)\Gamma(\beta+n-x_i)\right\}$$

$$= n[\ln\Gamma(\alpha+\beta) - \ln\Gamma(\alpha) - \ln\Gamma(\beta) - \ln\Gamma(\alpha+\beta+n)] + \sum_{i=0}^{n}\ln\left\{\binom{n}{x_i}\Gamma(\alpha+x_i)\Gamma(\beta+n-x_i)\right\}$$

$$= n[\ln\Gamma(\alpha+\beta) - \ln\Gamma(\alpha) - \ln\Gamma(\beta) - \ln\Gamma(\alpha+\beta+n)] + \sum_{i=0}^{n}\ln\binom{n}{x_i} + \sum_{i=0}^{n}\ln\Gamma(\alpha+x_i) + \sum_{i=0}^{n}\Gamma(\beta+n-x_i) \quad (17)$$

Now applying partial differentiation on equation (17),

$$\frac{\partial}{\partial\alpha}\ln\{f(\tilde{x})\} = n[\Psi_0(\alpha+\beta) - \Psi_0(\alpha) - \Psi_0(\alpha+\beta+n)] + \sum_{i=0}^{n}\Psi_0(\alpha+x_i)$$

$$\frac{\partial}{\partial\beta}\ln\{f(\tilde{x})\} = n[\Psi_0(\alpha+\beta) - \Psi_0(b) - \Psi_0(\alpha+\beta+n)] + \sum_{i=0}^{n}\Psi_0(\beta+n+x_i)$$

Now to apply Newton- Raphson method

$$\frac{\partial}{\partial\alpha^2}\ln f(\tilde{x}) = n[\Psi_1(\alpha+\beta) - \Psi_1(\alpha) - \Psi_1(\alpha+\beta+n)] + \sum_{i=0}^{n}\Psi_1(\alpha+x_i)$$

$$\frac{\partial}{\partial\beta^2}\ln f(\tilde{x}) = n[\Psi_1(\alpha+\beta) - \Psi_1(b) - \Psi_1(\alpha+\beta+n)] + \sum_{i=0}^{n}\Psi_1(\beta+n+x_i)$$

$$\frac{\partial}{\partial\alpha\,\partial\beta}\ln f(\tilde{x}) = n[\Psi_1(\alpha+\beta) - \Psi_1(\alpha+\beta+n)]$$

$$\frac{\partial}{\partial\beta\,\partial\alpha}\ln f(\tilde{x}) = n[\Psi_1(\alpha+\beta) - \Psi_1(\alpha+\beta+n)]$$

Now,

$$j = \begin{vmatrix} \frac{\partial}{\partial\alpha^2}\ln f(\tilde{x}) & \frac{\partial}{\partial\alpha\,\partial\beta}\ln f(\tilde{x}) \\ \frac{\partial}{\partial\beta\,\partial\alpha}\ln f(\tilde{x}) & \frac{\partial}{\partial\beta^2}\ln f(\tilde{x}) \end{vmatrix}$$

Now we apply Newton-Raphson iterative technique as

$$\begin{bmatrix}\alpha\\ \beta\end{bmatrix}_{n+1} = \begin{bmatrix}\alpha\\ \beta\end{bmatrix}_{n} - j^{-1}\left(\begin{bmatrix}\alpha\\ \beta\end{bmatrix}_{n}\right)\nabla f\left(\begin{bmatrix}\alpha\\ \beta\end{bmatrix}_{n}\right) \quad (18)$$

As we need a starting value of α and β, estimates obtained by moments can be used as starting value. Following those principles and using statistical software named R, maximum likelihood estimates of parameters α and β can be easily obtained.

RESULTS AND DISCUSSION

Data from the BDHS 2017–18 have been used to demonstrate how the model outlined above is applied. The survey gathered data from women who had ever been married in the age range of 15 to 49 on topics such as fertility, mortality, family planning, preferred methods of conception, and significant elements of reproductive health. Information has also been gathered on all live births to mothers and their survival status (date of birth of child, date of death of children, age at death). Age at death has been noted in cases of death. Women who haven't given birth in the five years from the survey's start date are assumed to be passed their reproductive period, hence only these women were taken into account for this study. We selected the women who haven't given birth in the past five years from the survey date in order to avoid censored cases. Thus, 10572 ever-married women who had no births in the five years before to the survey date are included in our dataset. Among them 3894 are from urban area and 6678 from rural area. These women are divided among different parities, and then women of fixed parity are distributed according to the number of children dying under age five. Then we have tried to find out if the proposed probability models fit the distribution well.

In this section, we've discussed regarding the estimation of parameters and fitting the proposed models. Two estimating techniques are utilized in this work to estimate the parameters for comparison purposes, as was stated in the sections above. Since two models for fixed parity are provided, it is to determine their frequencies after estimating the parameters for different parities. The corresponding tables likewise include estimates for the parameters, values of chi-square with the degree of freedom, and the *P*-value. In case of model-II (Beta-Binomial Model), average risk of child death has been also given in the table. The value of χ^2 and *P*-value shown in the tables clearly indicate that model-I (Binomial Model) is not suitable model for distribution of child death to a woman for fixed parity, whereas model-II (Beta-Binomial Model) fits the data and describes the data excellently.

Tables 1 to 3 represents expected frequencies along with observed frequencies for parity 4, 5, and 6 respectively. Parameters value, chi-square, degrees of freedom p-value and average risk of children death also given in these tables. Values of chi-square and p-values in table 1 to 3 and in summary in table 4 clearly indicate that Beta-Binomial model fits well with the data than Binomial model. As the p-values obtained in case of Beta-Binomial model is always greater than 0.05, so we do not have enough evidence to reject the null hypothesis. Thus we may accept the null hypothesis that is the proposed Beta-Binomial Model fits well with the distribution of women of fixed parity according to their number of child death. Further, expected frequencies, obtained using parameters that are estimated using the maximum likelihood method, are closer to the observed frequencies than when using the method of moment estimates. Thus MLE provides better fitting than moment estimator. Sample mean and variance are very close to the mean and variance obtained through the proposed model, shown in table 12, which is also an indication of model fitting.

Table 1. Observed and expected distributions of child deaths to the women with parity 4

Number of death children	***Observed***	***Frequency of Women***		
		Binomial	***Beta-Binomial***	
			MM	***MLE***
0	1057	1042.762	1060.919	1059.715
1	441	462.477	430.756	432.786
2	79	76.918	86.222	85.694
3	9	5.843	10.104	9.805
4	2			
Total	1588	1588	1588	1588

	Parameters	P=0.099	α=3.602 β= 32.490	α=3.865 β=34.855
	$\chi^2_{0.5}$(after pooling)	5.799	0.942	0.831
	D.F.	2	1	1
	***p*-value**	0.055	0.332	0.392
	Average Risk of Child Death (p)		0.098	0.099

Note: MM=Method of Moment Estimate, MLE=Maximum Likelihood Estimate

Table 2. Observed and expected distributions of child deaths to the women with parity 5

Number of death children	***Observed***	***Frequency of Women***		
		Binomial	***Beta-Binomial***	
			MM	***MLE***
0	440	426.521	439.076	439.334
1	294	314.789	295.598	295.218
2	94	92.930	94.659	94.680
3	20	14.759	19.667	19.768
4	1			
5	0			
Total	849	849	849	849
	Parameters	P=0.129	α=6.133 β= 41.552	α=6.006 β=40.693
	$\chi^2_{0.5}$(after pooling)	4.449	0.105	0.088
	D.F.	2	1	1
	***p*-value**	0.108	0.745	0.767
	Average Risk of Child Death (p)		0.129	0.129

Note: MM=Method of Moment Estimate, MLE=Maximum Likelihood Estimate

Table 3. Observed and expected distributions of child deaths to the women with parity 6

Number of death children	***Observed***	***Frequency of Women***		
		Binomial	***Beta-Binomial***	
			MM	***MLE***
0	182	166.018	184.458	183.875
1	144	160.571	136.781	137.466
2	54	64.710	61.067	61.220
3	22	15.701	19.480	19.348
4	4		5.214	5.091
5	1			
6	0			
Total	407	407	407	407
	Parameters	P=0.139	α=2.649 β=16.430	α=2.742 β=17.005
	$\chi^2_{0.5}$(after pooling)	13.152	1.566	1.546
	D.F.	2	2	2
	***p*-value**	0.001	0.457	0.462
	Average Risk of Child Death (p)		0.139	0.139

Note: MM=Method of Moment Estimate, MLE=Maximum Likelihood Estimate

Figure 1. Simulated beta distribution of risk of children death for women with parity 4, 5 and 6 in Bangladesh

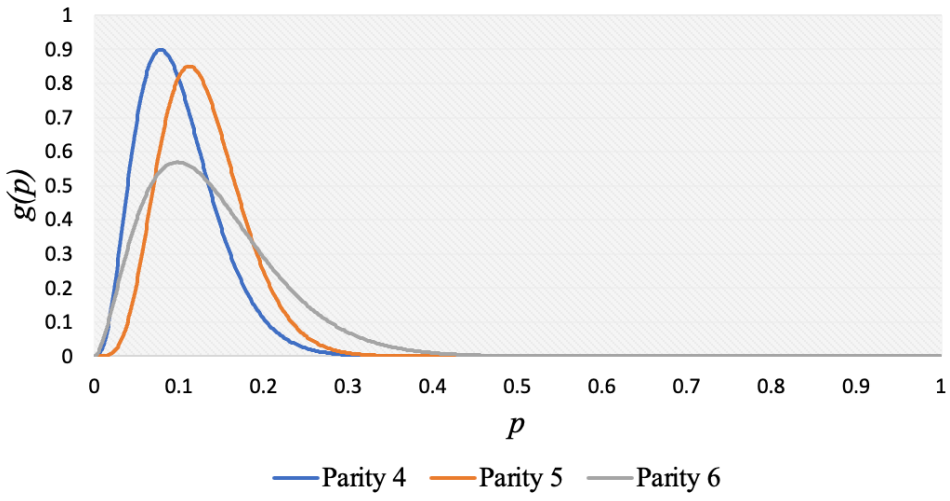

Table 4. Comparison of model fitting based on p-value

Parity	***p-value***		
	Binomial	***Beta-Binomial***	
		MM	***MLE***
4	0.055	0.332	0.392
5	0.108	0.745	0.767
6	0.001	0.457	0.462

From table 1 to 3 and table 4 it is evident that for parity 4, 5 and 6, Beta-Binomial model fits better than Binomial Model especially when parameters of Beta-Binomial model estimated using MLE.

Thus, we apply model-II (Beta-Binomial Model) for rural and urban women of parity 4, 5, and 6 to their distribution according to the number of child death, to get an estimate of the average risk of child death. Expected frequencies along with observed frequencies, parameter values, chi-square and p-values also presented in tables 5 to 10. Estimates of average risk of children death for both rural and urban women of parity 4, 5 and 6 are also presented as summary in table 11. Table 11 manifested that risk of children death higher for women of parity 6 and relatively lower in case of women of parity 4.

Table 5. Observed and expected distributions of child deaths to the rural women with parity 4

Number of death children	***Observed***	***Frequency of Women***
		Beta-Binomial (MLE)
0	726	728.784
1	300	291.483
2	51	57.950
3	6	6.784
4	2	
Total	1085	1085
	Parameters	α=3.479 β=31.793
	$\chi^2_{0.5}$(after pooling)	1.311
	D.F.	1
	p-value	0.252
	Average Risk of Child Death(p)	0.099

Note: MLE=Maximum Likelihood Estimate

Table 6. Observed and expected distributions of child deaths to the urban women with parity 4

Number of death children	***Observed***	***Frequency of Women***
		Beta-Binomial (MLE)

0	331	330.828
1	141	141.471
2	28	30.700
3	3	
4	0	
Total	503	503
	Parameters	α=5.112 β=44.822
	$\chi^2_{0.5}$(after pooling)	0.005
	D.F.	-
	***p*-value**	-
	Average Risk of Child Death (p)	0.102

Note: MLE= Maximum Likelihood Estimate

Figure 2. Simulated beta distribution of risk of child death for women with parity 4 in rural and urban area in Bangladesh

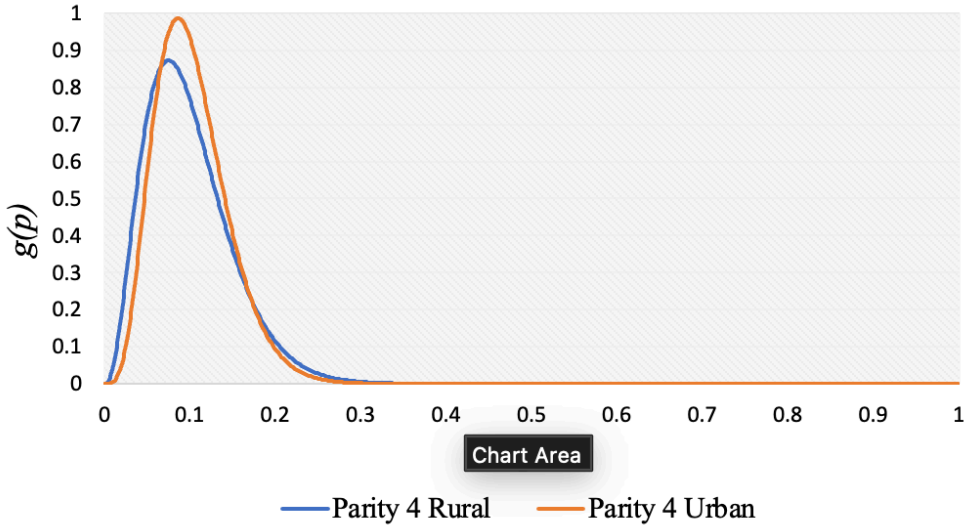

Table 7. Observed and expected distributions of child deaths to the rural women with parity 5

Number of death children	***Observed***	***Frequency of Women Beta-Binomial (MLE)***
0	313	313.953
1	219	215.371
2	65	69.966
3	16	14.710
4	1	
5	0	
Total	614	614
	Parameters	α=6.321 β=42.069
	$\chi^2_{0.5}$(after pooling)	0.773
	D.F.	1
	***p*-value**	0.379
	Average Risk of Child Death (p)	0.131

Note: MLE= Maximum Likelihood Estimate

Table 8. Observed and expected distributions of child deaths to the urban women with parity 5

Number of death children	***Observed***	***Frequency of Women Beta-Binomial (MLE)***

0	127	125.431
1	75	79.766
2	29	24.731
3	4	5.072
4	0	
5	0	
Total	235	235
	Parameters	α=5.277 β=37.492
	$\chi^2_{0.5}$(after pooling)	1.268
	D.F.	1
	***p*-value**	0.260
	Average Risk of Child Death (p)	0.123

Note: MLE= Maximum Likelihood Estimate

Figure 3. Simulated beta distribution of risk of child death for women with parity 5 in rural and urban area in Bangladesh

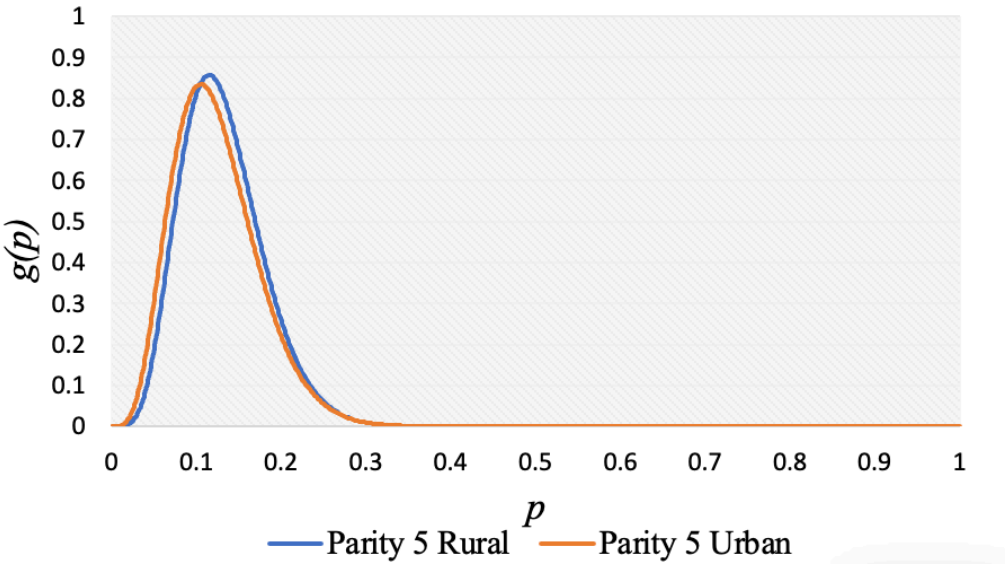

Table 9. Observed and expected distributions of child deaths to the rural women with parity 6

Number of death children	***Observed***	***Frequency of Women Beta-Binomial (MLE)***
0	132	133.491
1	108	103.041
2	42	47.116
3	17	19.353
4	3	
5	1	
6	0	
Total	303	303
	Parameters	α=2.805 β=16.804
	$\chi^2_{0.5}$(after pooling)	0.951
	D.F.	1
	***p*-value**	0.329
	Average Risk of Child Death (p)	0.143

Note: MLE= Maximum Likelihood Estimate

Table 10. Observed and expected distributions of child deaths to the urban women with parity 6

Number of death children	***Observed***	***Frequency of Women Beta-Binomial (MLE)***
0	50	50.388
1	36	34.425
2	12	14.097
3	5	5.089
4	1	
5	0	
6	0	
Total	104	104
	Parameters	α=2.654 β=18.306
	$\chi^2_{0.5}$(after pooling)	0.549
	D.F.	1
	***p*-value**	0.458
	Average Risk of Child Death (p)	0.127

Note: MLE= Maximum Likelihood Estimate

Figure 4. Simulated beta distribution of risk of child death for women with parity 6 in rural and urban area in Bangladesh

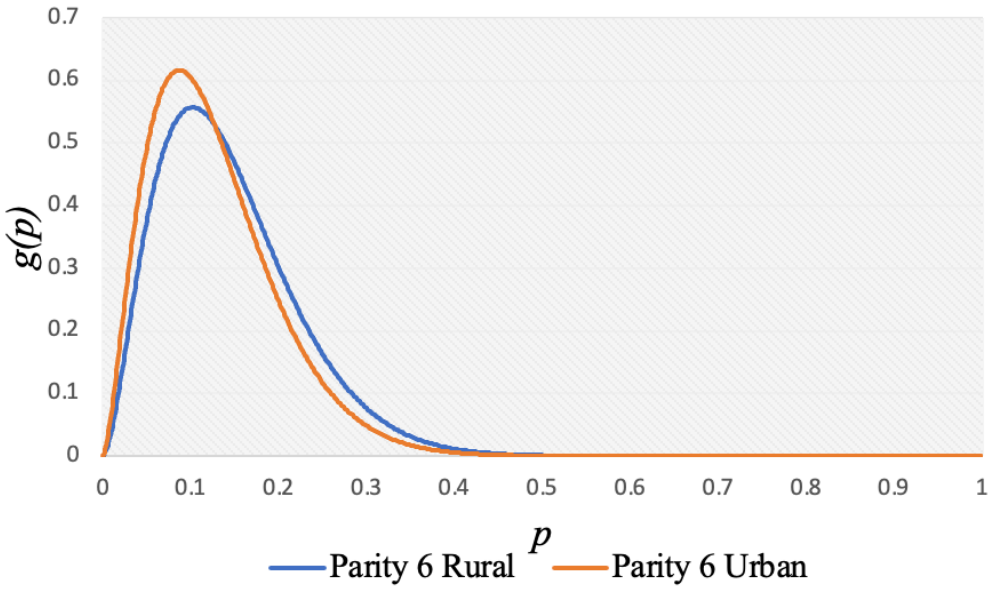

Table 11. Comparison of average risk of children death among rural and urban women of Bangladesh

Parity	***Average Risk of Child Death***		
	Total	***Rural***	***Urban***
4	0.099	0.098	0.102
5	0.129	0.131	0.123
6	0.139	0.143	0.127

Table 12. Comparison of sample mean and variance with mean and variance obtained by Beta-Binomial model

Parity	***Sample Mean***	***Sample Variance***	***Beta Binomial Model***	
			Mean	***Variance***
4	0.399	0.389	0.399	0.387
5	0.643	0.606	0.643	0.607

6	0.833	0.896	0.833	0.890
Rural				
4	0.395	0.388	0.395	0.385
5	0.653	0.614	0.653	0.614
6	0.858	0.920	0.858	0.914
Urban				
4	0.410	0.389	0.410	0.389
5	0.617	0.585	0.617	0.590
6	0.760	0.817	0.760	0.815

Besides, the estimated distribution of the risk of child death for women with parity 4, 5, and 6 is shown in figure 1, and figures 2 to 4 show parity-wise estimated distribution of the risk of child death for rural and urban women in Bangladesh. Figure 1 shows that the distribution of p(risk of child death) is of different pattern for parity 4, 5 and 6, and both are positively skewed, which indicates that there is a small group of women contributing most of child death. Figure 3 and 4 shows that mode of the distribution of p for rural area is generally higher than urban area. And from figure 5 it is found that the average risk of children death increases with increasing parity. The average risk of child deaths is mostly higher in the rural area; this may be due to lack of healthcare facility, a low standard of living in a rural area, and other factors affecting child health.

CONCLUSION

In conclusion, we can say that Model-II (Beta-Binomial Model) gives a way to study the distribution of p (risk of child death) which cannot be studied otherwise since p itself is unobservable. To lower the risk of child mortality in Bangladesh, better health care policies and programs should be implemented for women living in rural areas and having higher parity.

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Data Availability Statement

Data are publicly available as Bangladesh Standard Demographic and Health Survey, BDHS, 2017=18 Dataset and can be accessed through the web sites:

http://dhsprogram.com/data/dataset/Bangladesh_Standard-DHS_2017.cfm?flag=0

Conflict of interest: None

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REFERENCES

Bhuyan, K. C. and Deograties, R. (1999). On the probability model of child mortality pattern in North Eastern Libya. *The Turkish Journal of Population Studies*, *21*: 33-37.

Chauhan, R. K. (1997). Graduation of infant death by age. *Demography India*, *26*: 261-274.

Eberstein, I. W., Nam, C. B., and Hummer, R. A. (1990). Infant Mortality by Cause of Death: Main and Interaction Effects. *Demography*, *27*(3): 413-430.

Gompertz, B. (1825). On the nature of the function expressive of the law of human mortality, and on a new mode of determining the value of life contingencies. *Philosophical Transactions of the Royal Society of London*, *115*: 513-585.

Hossain, M. M., Mani, K. K. C., and Islam, M. R. (2015). Prevalence and Determinants of the Gender Differentials Risk Factors of Child Deaths in Bangladesh: Evidence from the Bangladesh Demographic and Health Survey, 2011. *PLOS Neglected Tropical Diseases*, *9*(3).

Keyfitz, N. (1977). *Introduction to the Mathematics of Population with Revisions*. Addison-Wesley Publishing Company.

Krishnan, P. and Jin, Y. (1993). A statistical model of infant mortality. *Janasamkhya*, *11*(2): 67-71.

Mukherjee, S. P. and Islam, A. (1983). A finite-range distribution of failure times. *Naval Research Logistics Quarterly*, *30*(3): 487-491.

National Institute of Population Research and Training-NIPORT, Ministry of Health and Family Welfare, and ICF. (2020). *Bangladesh Demographic and Health Survey 2017-18*.

Nilima, S. (2017). Under-five child mortality in Bangladesh: Classical and Bayesian approaches to Cox proportional hazard model. *Bangladesh Journal of Scientific Research*, *30*(1-2): 45-54.

Renshaw, A. E. (1991). Actuarial graduation practice and generalised linear and non-linear models. *Journal of the Institute of Actuaries*, *118*(2): 295-312.

Sheldon, E. B. and Moore, W. E. (1968). *Indicators of Social Change: Concepts and Measurements*. Russell Sage Foundation.

Singh, Brijesh P., Dixit, S., and Roy, T. K. (2015). Stochastic Analysis of Infant Deaths by Age and Estimation of Parameters. *Journal of Institute of Science and Technology*, *20*(1): 1-5.

Singh, K. K., Singh, Brijesh P., and Singh, N. (2011). A probability model for number of child deaths for fixed parity. *Demography India*, *40*(2): 55-68:

Thatcher, A. R., Kannisto, V., and Vaupel, J. W. (1998). *The Force of Mortality at Ages 80 to 120*. Odense University Press.

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RESEARCH ARTICLE

Deep Learning Framework for Maize Demand Prediction Using Optimized Environmental Features

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ABSTRACT

Accurate maize demand prediction plays an important role in ensuring food security, market stability, and sustainable agricultural development. However, maize demand prediction is a complex process is mainly determined by the interactions between different factors such as soil, climate, irrigation, and production data. Therefore, traditional statistical models are ineffective due to their inability to capture the underlying nonlinear relationships and temporal dependencies in the data. It leads to resource mismanagement, overproduction, and underproduction that affects the economy. This work presents a novel approach based on Convolutional Neural Network-Bidirectional Long Short-Term Memory with Attention and Grey Wolf Optimized Environmental Features for maize demand prediction. Agricultural data such as soil, climate, irrigation, and production data were collected and pre-processed using the Multiple Imputation, Median Filtering, and Min-Max normalization to fill and smooth missing data. Then Grey Wolf Optimization is used for feature selection, which determines the relevant environmental features by removing extra ones and decreasing the complexity of the input data. The acquired features are processed through the Convolutional Neural Network (CNN) that identifies feature detectors, and their representations are extracted through BiLSTM with Attention, which means processing data in both directions. Moreover, the Attention mechanism highlights the important features that affect maize demand. After that, the production demand is predicted using the attained results for efficient planning and allocation of resources. The proposed framework achieved an RMSE of 2.14, MAE of 1.48, MAPE of 6.12%, and R^2 of 98.96%, that shows how this system effectively captures relevant nonlinear relationships, temporal dependencies, and influential agricultural factors, resulting in more accurate maize demand prediction.

Keywords: *Maize Demand Prediction, Deep Learning, Grey Wolf Optimization, Environmental Features, Precision Agriculture, Sustainable Agricultural Planning*

INTRODUCTION

Maize is one of the world's most important cereal crops in terms of food, feed, and industrial raw material production. Its yield prediction is critical to agricultural production, ensuring food security, and contributing to economy and trade (Ma et al., 2021). There is an increasing need for timely and accurate estimations of maize yield, which is driven by the growing awareness of the vulnerability of agricultural production to climate change, environmental influences, and the need for global food security (Ramos et al., 2020).

Most traditional methods used for maize yield estimation, including conventional statistical techniques, crop growth models, and field measurements, are typically labor intensive, involve complex calculations, and are only moderately adaptive to complex agro climatic

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conditions (Ahmad et al.,2020). Everyone fails to account for the interrelationships between various factors such as the soil, climate, vegetation, and topography, which have a combined effect on crop production (Shahhosseini et al., 2020; Zhou et al., 2024).

The recent developments in remote sensing technologies such as satellite and Unmanned Aerial Systems (UAS) have enabled the monitoring of crops at a large scale with a relatively low cost and non-invasive manner. The multispectral images and vegetation indices like Normalized Difference Vegetation Index (NDVI) have been widely used to capture the crop condition, canopy structure, and vegetation status which can inform crop yield estimation. However, vegetation indices suffer from canopy saturation, atmospheric interference, variation in illumination conditions, and low capacity to incorporate complex spatial and temporal patterns in the field, constraining their prediction capability in different environments (Fathololoumi et al., 2026; Ramos et al., 2020; Sapkota et al., 2025; Zhang et al., 2025).

The random forest regressions, support vector regressions, K-Nearest Neighbor, and extreme gradient boosting algorithms have been widely implemented to estimate maize yield due to their promising performance in handling non-linear trends in agricultural data (Hao et al., 2026). However, their performance is highly dependent on the expert knowledge for informative feature selection and engineering. Besides, the generalizability capacity of these methods is limited when applied in different geographical locations. On the contrary, the deep learning algorithms have shown a promising ability to learn hierarchical data representations from both tabular and image data (Zhou et al., 2024). Specifically, the convolutional neural networks such as Visual Geometry Group 19 (VGG-19) can effectively learn the underlying spatial patterns of multispectral satellite images while deep belief networks can mine the complex non-linear relationships between agricultural variables. However, most of the previous studies utilized either tabular or image data for maize yield prediction. There is still a gap in investigating the combined potential of these data types for high-level abstraction in maize yield estimation. Moreover, the presence of numerous relevant and irrelevant features increases the chances of overfitting and computational costs.

The main purpose of this research is to design a robust deep learning framework for effective maize demand prediction by adopting Grey Wolf Optimization-based feature selection and CNN-BiLSTM model with an attention mechanism. The proposed framework helps enhance performance and achieve accurate prediction results to facilitate decision-making in agricultural demand prediction. With growing complexities and difficulties in agricultural production, it has become crucial to make precise predictions to manage optimal utilization and production of maize. However, current prediction models are unable to address the diverse interactions of environmental factors accurately, therefore creating a need for enhanced prediction framework. This study proposes a modified deep learning model that offers improved performance to yield accurate demands prediction. The Contributions of this Study include Grey Wolf Optimization-based feature selection and enhanced performance achieved through the CNN-BiLSTM with attention mechanism for accurate maize demand forecasting.

1. Enhances forecast performance through selection of relevant environmental features and discarding of redundant ones based on Grey Wolf Optimizer.

2. Captures spatial feature representation learned by CNNs and bilateral temporal patterns encoded in BiLSTM with attention, resulting in improved demand prediction.

3. Enables effective agricultural planning by offering forecasts that support smart production scheduling, resource optimization, and informed decision-making.

The rest of the paper is organized as follows. Section 1 presents Background and Motivation. The related works are described in Section 2. The preliminary concepts are introduced in Section 3. The Proposed Work is detailed in Section 4. The experimental results and discussion are presented in Section 5. Finally, the concluding remarks and future directions are described in Section 6, the last section of this paper.

RELATED WORKS

Ikram et al. (2025) developed a Fuzzy-Optimized Hybrid Ensemble Model (FOHEM) combined a fuzzy inference system with three algorithms of Random Forest, CatBoost and Extreme Learning Machine (ELM) to predict the yield of intercropping corn and soybean, in which the Genetic Algorithm was used to optimize the weights of the ensemble model, LIME and SHAP for interpreting the prediction and investigating the drivers of yield. And the framework predicted yields better through using environment, soil, and management attributes. However, the system just used for predicting crop yields through ensemble learning and it didn't use deep temporal feature learning to predict the demand for corn.

Stevanović et al. (2025) focused on explaining how planting density and inter-plant competition affect

the yields of corn and applied statistical regression and ML methods under different weather conditions. The methods predicted the grain yields and seed quality attributes precisely, and determined outstanding corn–soybean–soybean pairs on specific hybrid and density to increase crop productivity. Corn yields are meaningfully and significantly related to the planting density, specific hybrid choice, and performance of different conditions. But study mainly aimed at the yield prediction, and it doesn't introduce the temporal deep learning and optimizing the relevant environmental feature extraction for corn demand.

In a systematic review, Nyengere et al. (2026) summarized eighty-one studies related to machine learning for prediction of maize production, reflecting growing ML models application in the decision making of crop agriculture. Results revealed that Random Forest, XGBoost, Support Vector Machines and hybrid deep learning frame is currently considered as the most used techniques. Environmental characteristics of the site, remote sensing (RS) image, and a broad soil characteristic information (e.g. PH value, organic C, N, P and K) is identified as primary features in prediction and the deep hybrid deep learning model was best performed with using RMSE and R.

Nonetheless, issues such as scarcity of Data, model interpretation and geographical unbalance limitations are indicated and recommend the enhancement of well-founded, and understandable models of deep learning techniques in this field. Cheng and Wang (2026) proposed a prediction framework for maize production based on soil nutrient and climatic data to achieve high accuracy of yield estimations. The framework included five main soil nutrients such as N, P, K, O.C and pH, climatic variables like temperature, precipitation and growing degree days (GDD) as predictive variables. Both traditional statistical approaches, ML models and deep learning models have been compared in terms of RMSE, MAE, and R. Nevertheless, only predicting the production quantity of maize were the theme of work, optimized feature selection and attention of deep learning model for demand prediction of maize were not used.

An Osprey Optimization Algorithm (OOA), a novel natural-inspired meta-heuristic optimization method, was developed by Dehghani et al. (2023) which mimicking the foraging behaviour of osprey in its attempt to perform balanced search of exploitation and exploitation mechanisms. The proposed approach had been demonstrated on CEC 2017 benchmark functions and outperforms 12 well-known benchmark functions, proving the optimization capability and reliability through 3-dimemsional problem testing for CEC 2011 real world constrained optimization problems. However, the methodology mainly centred on optimum finding only on benchmark functions, hence nothing was conducted regarding the use of OOA on deep learning methods-based Agri demand estimation via environmentally-oriented data resources.

Current studies deal with maize yield prediction through traditional machine learning, ensemble learning, optimization techniques, or shallow neural networks, lacking the power to handle complex temporal dynamics and adaptive environmental interaction. Although various optimization methods help to enhance feature selection and prediction performance, a comprehensive framework consisting of optimized feature selection, deep spatial feature learning, temporal sequence modelling, and adaptive feature weighting are not available. Therefore, the proposed framework combines the Grey Wolf Optimization (GWO) for selection of optimal environment features, the CNN for learning discriminative non-linear features, the BiLSTM for learning bi-directional temporal dynamics, and the Attention mechanism for assigning greater importance to influential environmental features. Such a deep learning model effectively addresses the redundant features, avoids the over-fitting problem, enhances long-term temporal learning capability and robust performance. The proposed system can accurately and reliably predict maize demand, offering an effective decision support tool for smart agricultural planning and resource management.

PROPOSED SYSTEM

Agricultural Data Collection

The proposed framework uses the heterogeneous agricultural data from Indian Historical Crop Yield and Weather Data set on Kaggle dataset. The data includes weather data from the India Meteorological Department (IMD) and agricultural data from the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT). The data set contains information on agricultural data, including soil type and fertility, temperature, rainfall, humidity, wind speed, irrigation, area cultivated, and crop produce. This data has been chosen because it contains the relevant information on weather conditions, as well as other factors affecting maize production, such as the level of irrigation. The variables of crop production and area cultivated are indicators of the level of maize production and therefore its supply. Collectively, the variables provide information affecting maize production and its levels at a given time, which helps predict future supply and demand patterns. Secondly, the data set has a large amount of data that covers different

years and months, which helps the proposed model generalize better and perform accurately under different conditions. The collected data set used to carry out the next steps in the proposed research, including preprocessing, optimizing, and deep learning, leading to the prediction of demand for maize. The dataset is available in the Kaggle platform-dataset

Data pre-processing

The provided data set consists of agricultural data with different environmental variables characterized by different scales, missing values, and measurement noises, among others. These attributes may hinder the performance of the underlying deep learning algorithms and, consequently, the prediction performance of the proposed framework. Therefore, it is critical to perform a data pre-processing step for data cleaning and preparation for the feature selection algorithm. In particular, the data pre-processed using Missing Value Imputation, Median Filtering, and Min-Max Normalization procedures.

Missing Value Imputation

Agricultural data can sometimes have missing records, such as when a particular sensor malfunctions or no readings were taken at the time of observation. These missing values can make it harder to get reliable results from the learning process and make it bias the prediction model. Thus, missing values need to be replaced with some numerical values using mean imputation for continuous variables so that there is no loss of information. A set of features can then be represented by the following expression.

$$X = \{x_1, x_2, \dots, x_n\} \quad (1)$$

Where x_i refers specific observation with missing values. The mean value is calculated with the formula below:

$$\mu = \frac{1}{N}\sum_{i=1}^{N} x_i \quad (2)$$

Where, N refers total number of observations available for calculating the mean. The missing value is replaced as follows:

$$x_{\text{missing}} = \mu \quad (3)$$

Using this method, it is possible to maintain the distribution of environmental variables without discarding any samples.

Median Filtering

In case of tabular data, there may be occurrence of noise and extreme values that arise from sensor faults (environmental factor or data collection procedures like human inspection) thus a median filtering is employed to discard them by still retaining the structural components of the agricultural variables. The filtered value in terms of a filter of window size, k for a sliding window defined is

$$y_i = \text{Median}\,(x_{i-r}, \dots, x_i, \dots, x_{i+r}) \quad (4)$$

Where, y_i refers filtered output, $x_i$refers original feature value, $r = \frac{k-1}{2}$indicate the half length of the window radius. A median filter is known not only remove the impulsive noise values and but also retains the distribution structure of the original signal at each point whereas a mean filter smooths the output.

Min-Max Normalization

The agricultural features are expressed in different units of measurement, for instance, the amount of rainfall is measured in mm, temperature is measured in Celsius, pH level is indicated by numbers, air humidity is measured in percentages, and the area is measured in hectares. As such, the scale of measurement is expected to affect the performance of deep neural networks. The Min-Max Normalization is applied to standardize the input data within the range of zero to one in order to accelerate the network convergence. The normalized feature value is computed using the equation below:

$$x_i' = \frac{x_i - x_{\min}}{x_{\max} - x_{\min}} \quad (5)$$

Where x_i' stands for normalized feature value, $x_i$stands for the feature value, $x_{\min}$ and $x_{\max}$stand for minimum and maximum feature values respectively. The normalized value satisfies the following identity:

$$0 \le x_i' \le 1 \quad (6)$$

which helps improve the learning process, accelerate the network convergence and avoid overfitting problems.

Environmental Feature Selection using Grey Wolf Optimization (GWO)

Selection of features would provide to increase the precision of prediction in the deep learning models via selection of proper environment related values. Redundant or non-related attributes should be thrown. Agricultural applications datasets contain multiple correlated attributes insoil, climate, irrigation and production such Attributes which leads to the more complexity in processing and over-fitting. So, to find a small number of the best environmental characteristics to increase prediction precision, reduce redundancy of attributes Grey Wolf Optimization (GWO) is utilized; it's a metaheuristic population-based optimization algorithm inspired from the natures.

In GWO population is divided into four types of wolves; Alpha (α), Beta (β), Delta (δ), and Omega (ω), α has the role of the best candidate solution while β and δ represents the second and third best

solutions and ω wolves update its position according to α, β and δ. Updating the position for a search agent; a distance between wolf to Alpha (α), Beta (β), Delta (δ), wolves can be formulated as below:

$$D = | C \cdot X_p(t) - X(t) | \quad (7)$$

Where, $X(t)$ denotes current position of a wolf, $X_p(t)$denotes position of the prey (optimal solution), C refers coefficient vector. The wolf updates its position as,

$$X(t+1) = X_p(t) - A \cdot D \quad (8)$$

where the coefficient vectors is computed as below,

$$A = 2ar_1 - a \quad (9)$$
$$C = 2r_2 \quad (10)$$

Where, a decreases linearly from 2 to 0 during optimization, $r_1$and r_2 refers random vectors within $[0, 1]$. To improve the exploration and exploitation process, the wolves' positions updated based on the three best wolves:

$$D_\alpha = | C_1 X_\alpha - X | \quad (11)$$
$$D_\beta = | C_2 X_\beta - X | \quad (12)$$
$$D_\delta = | C_3 X_\delta - X | \quad (13)$$

The other wolf's candidate positions are computed as follows,

$$X_1 = X_\alpha - A_1 D_\alpha \quad (14)$$
$$X_2 = X_\beta - A_2 D_\beta \quad (15)$$
$$X_3 = X_\delta - A_3 D_\delta \quad (16)$$

Finally, the search agent updated position are obtained by averaging the best three candidate positions:

$$X(t+1) = \frac{X_1 + X_2 + X_3}{3} \quad (17)$$

The fitness of each feature subset is assessed using a fitness function that optimizes prediction accuracy simultaneously with the number of selected features. The fitness function is given by

$$Fitness = \alpha(1 - Accuracy) + \beta\left(\frac{|S|}{|F|}\right) \quad (18)$$

Where, the 'Accuracy' is the predicted accuracy of the chosen feature subset, 'S' is the number of features selected, 'F' is the number of total features and '+=1' is weight coefficient which provides a trade-off between predictive performance and dimensionality reduction. After GWO has gone through rounds of optimization, the optimum feature subset in the environment is generated; the features with significant information of soil, climate, irrigation and production attributes that contribute to crop yield are selected by abandoning duplicate information. In doing so, the computational complexity of the framework has been reduced significantly, preventing over-fitting effectively and shortening the training time significantly, and providing a valid feature set for the next CNN-BiLSTM network with Attention, greatly enhance the accuracy and robustness of maize demand prediction.

Algorithm 1: Environmental Feature Selection using Grey Wolf Optimization (GWO)

Input: Environmental feature dataset D, Population size N, Maximum number of iterations Tmax

Output: Optimal environmental feature subset S_{best}

Begin

Load pre-processed dataset D

Initialize a population of N grey wolves random

where each wolf represents a candidate feature subset

Set: iteration t = 1

Evaluate fitness of wolf

Identify three best wolves α, β, δ

While (t ≤ T_{max}) **do**

For each wolf X_i population **do**

Compute coefficient vectors A and C

Calculate distances

Compute candidate positions

Update wolf position

End For

Update parameter a

Evaluate fitness of all updated wolves

Update Alpha, Beta, and Delta wolves

t = t + 1

End While

Select feature subset represented by Alpha wolf

Return S_{best}

End

Feature Extraction using Convolutional Neural Network (CNN)

After the Grey Wolf Optimization-Based Feature Selection process, the best environmental features were extracted as an input to the Convolutional Neural Network. This network allows automatically learning the higher-level features from the input data. Unlike traditional machine learning algorithms, which require handcrafted features to train models, the CNN model can learn the necessary transformations of various agricultural features (soil, climate, irrigation, crop

area, and previous production) in order to make accurate predictions of maize demand. The convolutional layer within the CNN includes a set of filters that act on the input features to extract the most relevant information. Consider the optimized input feature vector be represented as $X = \{x_1, x_2, \dots, x_n\}$, where n refers number of selected environmental features. The convolution operation is shown as,

$$F_j = \sigma\left(\sum_{i=1}^{k} W_i X_{j+i-1} + b\right) \quad (19)$$

where $F_j$represents extracted feature, $W_i$denotes convolution kernel weights, k refers kernel size, b denotes bias term, and $\sigma(\cdot)$ refers activation function. In this work, the Rectified Linear Unit (ReLU) activation function is adopted to introduce nonlinearity and accelerate model convergence, which is defined as,

$$\sigma(x) = \max(0, x) \quad (20)$$

Subsequently, a max-pooling layer is employed to reduce the dimensionality of the extracted feature maps while retaining the most informative representations. The pooling operation is given by

$$P_i = \max(F_i) \quad (21)$$

where $P_i$denotes the pooled feature. This operation reduces complexity, improves generalization, and increases the robustness of learned features. As a result, the CNN network encodes the optimized environmental variables into compact representation high-level features, which can fully extract the underlying data distribution characteristics of agricultural factors. Then, these high-level features are sent to the next network layer, namely Bidirectional Long Short-Term Memory (BiLSTM), for further processing.

Temporal Learning using Bidirectional Long Short-Term Memory (BiLSTM)

To exploit the temporal information embedded in learned features, a Bidirectional Long Short-Term Memory (BiLSTM) is utilized in this study. Since maize demand is affected by seasonal climate changes, cumulative production, irrigation patterns, and cultivation trends, the characteristics of which are gradually revealed over time, conventional LSTM networks were employed. However, since the standard LSTM processes the input data sequentially and only considers the previous states while ignoring the future ones, it cannot effectively model the long-term temporal dependencies. To address this issue, we applied Bidirectional LSTM, which comprises two individual LSTM layers that process the input data in opposite directions and learn distinct weight matrices for each direction. At each time step t, the forget gate finds the historical information amount to retain and calculated as,

$$f_t = \sigma(W_f[h_{t-1}, x_t] + b_f) \quad (22)$$

where h_{t-1}refers previous hidden state, x_t denotes current input feature, and $W_f$and $b_f$refers trainable weight matrix and bias. The input gate controls the incorporation of new information into the memory cell and is defined as

$$i_t = \sigma(W_i[h_{t-1}, x_t] + b_i) \quad (23)$$

The candidate memory state is calculated as,

$$\tilde{C}_t = \tanh(W_c[h_{t-1}, x_t] + b_c) \quad (24)$$

The memory cell updated according to

$$C_t = f_t \odot C_{t-1} + i_t \odot \tilde{C}_t \quad (25)$$

where $\odot$denotes element-wise multiplication. The output gate generates the hidden representation using

$$o_t = \sigma(W_o[h_{t-1}, x_t] + b_o) \quad (26)$$

$$h_t = o_t \odot \tanh(C_t) \quad (27)$$

To exploit contextual information from both temporal directions, the forward and backward hidden states are calculated as

$$\overrightarrow{h_t} = LSTM_f(x_t, \overrightarrow{h_{t-1}}) \quad (28)$$

$$\overleftarrow{h_t} = LSTM_b(x_t, \overleftarrow{h_{t+1}}) \quad (29)$$

The final temporal representation is obtained by concatenating both hidden states:

$$H_t = [\overrightarrow{h_t}; \overleftarrow{h_t}] \quad (30)$$

where $H_t$refers bidirectional feature representation. By integrating information from past and future observations, BiLSTM The addition of previous and future observations to the time series in the BiLSTM enables the network to capture the effects of long-term seasonal variation and climatic changes on maize demand, in addition to other historical time series related to maize production or usage patterns. The temporal feature is enriched with additional contextual information than would be obtained in the standard LSTM; this feature set is passed into the Attention Mechanism.

Attention Mechanism

The Bidirectional LSTM network captures the dependency relationship between different locations by including the information of previous and future time steps to obtain all relevant time information related to the maize data, but not all the temporal features leads to the optimal maize demand forecast. Sometime features contain significantly more relevant information regarding the predicted future values, such as rainfall, temperature, humidity, soil moisture, irrigation availability, historical production and so on. Thus, we use an Attention Mechanism after BiLSTM layers to dynamically find and emphasize the parts that are important to predicting maize demand,

and ignore the unimportant parts so that we can allocate adequate attention to necessary information. Consider the hidden state generated by BiLSTM as $H = \{h_1, h_2, \ldots, h_T\}$, where T *denotes* sequence length. At first, the attention score is calculated for each hidden state as below,

$$e_t = \tanh(W_a h_t + b_a) \quad (31)$$

where$W_a$and $b_a$as trainable weights matrix and bias, $e_t$is the attention score to hidden state h_t. The Softmax function to calculate the attention weights:

$$\alpha_t = \frac{\exp(e_t)}{\sum_{i=1}^{T} \exp(e_i)} \quad (32)$$

where $\alpha_t$refers normalized attention weight associated with the t^{th}hidden state and satisfies

where, tis the final normalized attention weight for the tth hidden state and fulfills

$$\sum_{t=1}^{T} \alpha_t = 1 \quad (33)$$

The context vector can be computed with weighted summation of all the BiLSTM hidden states:

$$C = \sum_{t=1}^{T} \alpha_t h_t \quad (34)$$

Where, C refers context vector with most considerable temporal and environmental features representation. This Attention mechanism improves discriminatory power and learning efficiency with less influential information receives small attention weight and more informative agricultural features achieve significant weight, this makes our model gain the better prediction result under the changeable condition.

Fully Connected Layer and Demand Prediction

The context vector generated by the Attention mechanism is subsequently forwarded to the Fully Connected (FC) layer to perform the final nonlinear mapping between the learned feature representations and maize demand. The Fully Connected layer integrates the weighted environmental and temporal features extracted by the preceding CNN-BiLSTM-Attention architecture and learns the complex relationship between these features and the corresponding maize demand values. Unlike the convolutional and recurrent layers that focus on feature extraction and sequence learning, the Fully Connected layer performs high-level reasoning by combining all informative features into a unified representation for prediction. The output of the Fully Connected layer is computed as

$$z = W_f C + b_f \quad (35)$$

where C is the context vector produced by the Attention layer, $W_f$is the trainable weight matrix of the FC layer, b_f is its associated bias term, and z is the transformed feature representation. The Rectified Linear Unit (ReLU) is adopted to implement the non-linearity in the FClayer :

$$a = \max(0, z) \quad (36)$$

where a is the activated result produced by the FClayer. At present A regression output neuron predicts future maize demand:

$$\hat{Y} = W_o a + b_o \quad (37)$$

where $\hat{Y}$ is the maize demand prediction, W_o is the FC layer weights in the output layer, and b_o is its associated bias term. The parameter for optimizing this system in our study to predict the maize demand as a regress value, using Mean Squared Error (MSE)lossfunction,

$$L = \frac{1}{N} \sum_{i=1}^{N} (Y_i - \hat{Y}_i)^2 \quad (38)$$

where Y_i represents actual demand of maize, $\hat{Y}_i$is the predicted demand of maize, and N is the total number of samples. Training is conducted by minimizing this error by repeatedly adjusting the parameters of the network in the process of backpropagation. In a word, after the network convergences, the trained model is able to accurately predict future demand of maize from certain environmental and historical agriculture trends. These prediction values can further guide production planning, resource allocation, and sustainable agricultural decision, which allowing interested part to make foresight production plan, cultivation planning.

Decision Support System

The predicted demand for maize the CNN-BiLSTM with attention architecture in figure1. The decision support system (DSS) used to make informative cultivation and resource allocation choices for agricultural planners, farmers, and policymakers. Through the understanding of threshold values by applying the determined value into given threshold ranges, the agricultural actions were automated on crop. If the predicted demand is more than the upper threshold value (i.e., $T_L$and T_H,), then the suggested action is to increase the maize cultivation, fertilizer; and improve irrigation management and ensure input supply. The decision-making strategy is formulated as

$$Decision = \begin{cases} \text{High Demand}, & \hat{Y} \geq T_H \\ \text{Moderate Demand}, & T_L < \hat{Y} < T_H \\ \text{Low Demand}, & \hat{Y} \leq T_L \end{cases} \quad (39)$$

where $T_H$and $T_L$refers upper and lower demand thresholds from historical demand statistics or expert recommendations. If predicted demand $\hat{Y} \geq T_H$), the model suggests to expand the maize cultivation area, optimize fertilizer input,

irrigation and other production factors to meet the demand. However, if predicted demand ($T_L < \hat{Y} < T_H$), it is suggested to keep production factors at the current level to ensure stable output. While when the predicted demand ($\hat{Y} \leq T_L$), the framework advises to reduce the maize planting area and fertilizer and irrigation application, and reallocate the production factors into other crops with higher economic benefits. By converting the quantitative demand prediction into qualitative decision-making suggestions, the proposed decision-making system can not only help farmers make full use of production factors but also avoid huge economic loss due to the supply-demand gap and promote sustainable development.

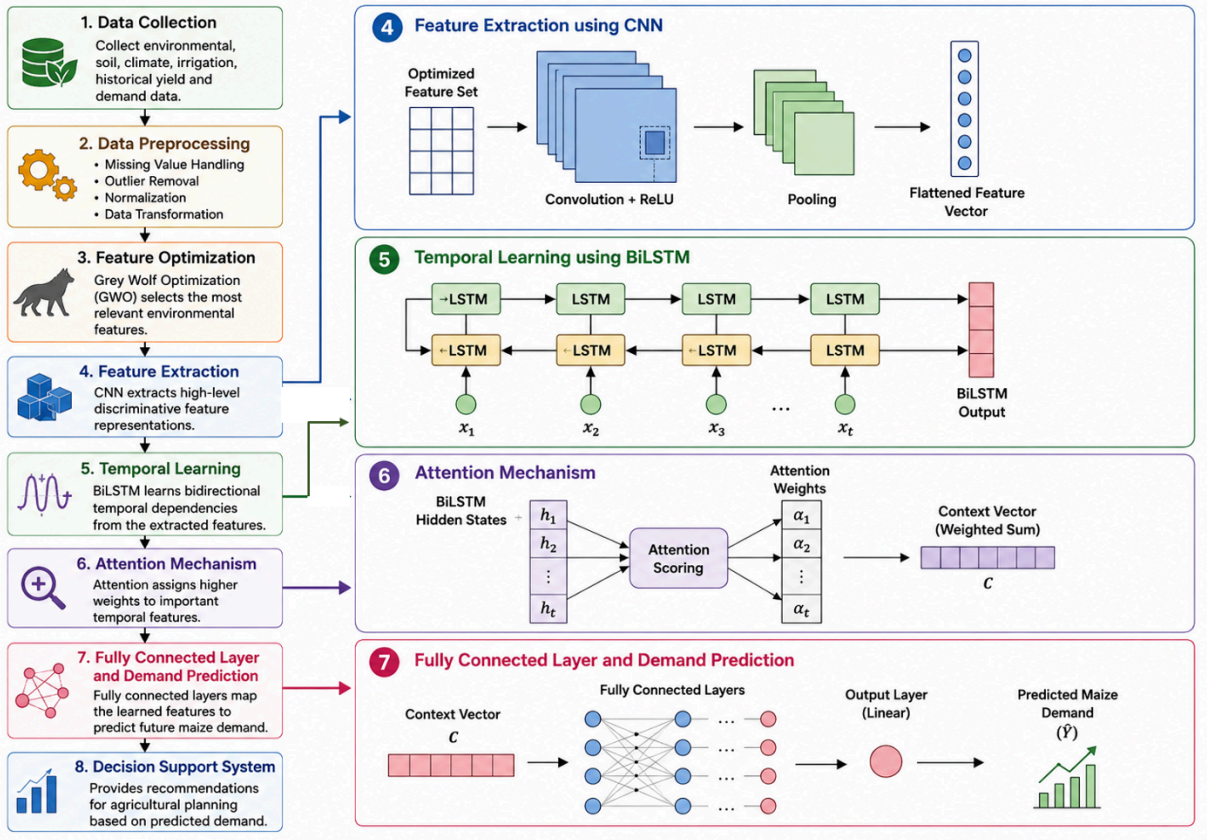

Fig.1. Proposed System Framework: CNN-BiLSTM with attention and GWO for Maize Demand Prediction

RESULTS AND DISCUSSION

The proposed Deep Learning Framework for Maize Demand Prediction Using CNN-BiLSTM with Attention and Grey Wolf Optimized Environmental Features is evaluated using standard regression performance metrics, namely, the Root Mean Square Error (RMSE), Mean Absolute Error (MAE), Coefficient of Determination, and Prediction Accuracy. These performance metrics enable a fair assessment of the prediction performance of the proposed approach by considering the error between the actual and predicted values, the goodness of model fit, and the overall prediction ability. In this regard, the prediction results of the proposed Deep Learning Framework are compared to those of the conventional machine learning and optimization-based approaches for regression tasks to demonstrate its efficacy in predicting maize demand. Notably, the proposed Grey Wolf Optimizer (GWO)-based approach has demonstrated significant improvements over the existing CNN-BiLSTM, CNN-LSTM, BiLSTM, LSTM, GRU, and conventional machine learning approaches. Root Mean Square Error (RMSE) is a standard metric for evaluating the performance of regression models as it follows the mathematical formulation of minimizing the sum of squared errors. In this regard, RMSE is calculated as the square root of the average of the squared errors between the actual and the predicted values.

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(y_i - \hat{y}_i)^2} \qquad (40)$$

Calculating the Mean Absolute Error (MAE) this measures the average of the absolute differences between observed actual maize yield and predicted values, where individual prediction errors are equally weighted rather than in the case of RMSE. MAE can be given as the intuitive description for

the average error of the model predictions as follows,

$$MAE = \frac{1}{N}\sum_{i=1}^{N} | y_i - \hat{y}_i | \quad (41)$$

Calculation of the Mean Absolute Percentage Error (MAPE) as being given for comparison with previous research work of how models prediction is sensitive in terms of units of measurement of crop produced (expressed as percentage of actual), so we can compare models' performance for different datasets or crops, e g for any specific crop production.

$$MAPE = \frac{100}{N}\sum_{i=1}^{N} | \frac{y_i - \hat{y}_i}{y_i} | \quad (42)$$

The coefficient of determination (R^2) measuring correlation between actual observed and fitted predicted yield from prediction model, R^2 value ranges from 0 to 1, where values closer to 1 indicate better prediction performance and stronger agreement between actual and predicted values.

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{N}(y_i - \bar{y})^2} \quad (43)$$

Where, $\bar{y}$ refers Mean of actual maize yield values. Then, the comparative analysis among the proposed method with existing method clearly compared based on the metrics.

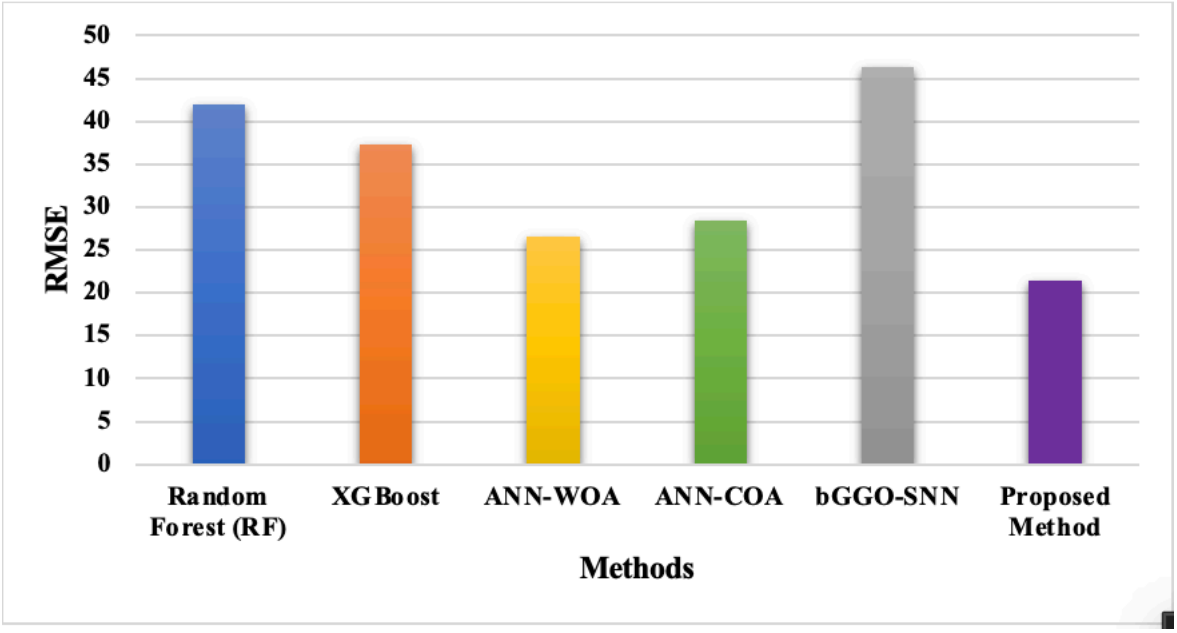

Fig.2.Comparative Analysis based on RMSE

The RMSE values of the existing and proposed method indicate the average prediction error, and lower value means better is shown in Fig.2. The proposed method owns a lowest RMSE of 21.4%, so prediction accuracy of this method is the highest among all these models. ANN-WOA and ANN-COA (Fariz & Basha, 2025) have RMSE 26.62% and 28.50%; XGBoost has the third highest value 37.3%; Random Forest and bGGO-SNN (Amirtham (2025) have a highest prediction error which means the prediction values deviate from the true values the most, RMSE values are 42.0% and 46.3%. And the lowest RMSE value of proposed method with CNN-BiLSTM-Attention-GWO demonstrates that complex environmental relationships can be modeled effectively and produce more reliable maize demand predictions.

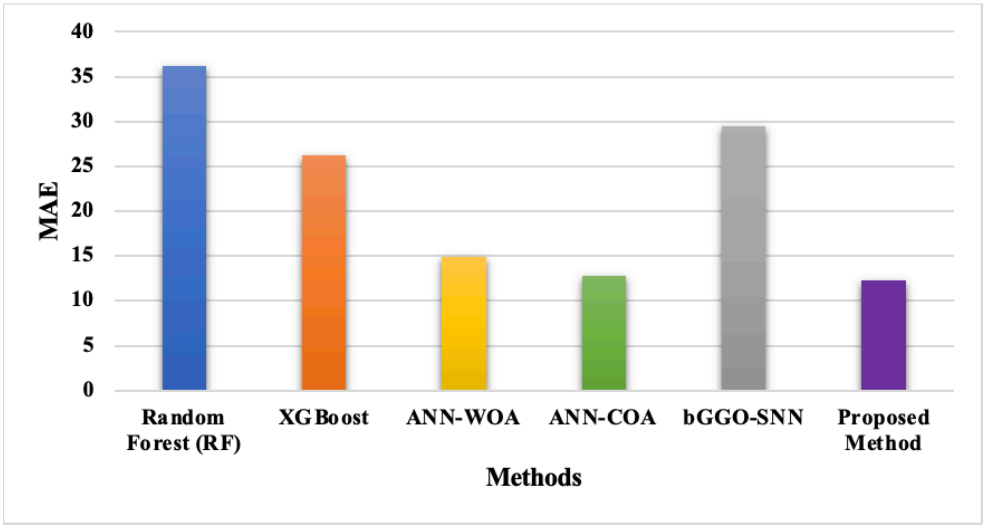

Fig.3. Comparative Analysis based on MAE

Fig.3. shows the better the accuracy of the prediction among several methods. This method gets a lowest MAE value of 12.3%. So, the average prediction error of this method is the smallest among all these models. ANN-COA gets a second lowest MAE value of 12.82%, which is then followed by ANN-WOA which gets 14.90%. The highest MAE values are gotten by XGBoost, bGGO-SNN and Random Forest which get 26.2%, 29.5%, 36.2%. We can see that this framework always outputs a demand prediction closest to the actual demand.

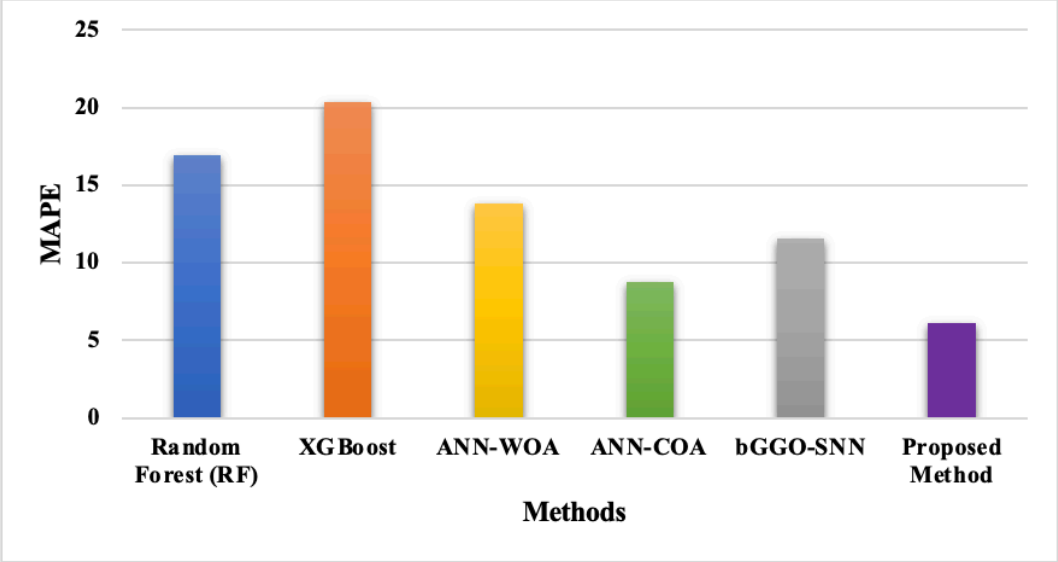

Fig.4. Comparative Analysis based on MAPE

MAPE evaluates the average percentage error among the predicted and true maize demand values. Ideally, the lower this metric, the better the forecast results. From Fig.4, it is evident that the proposed model has the lowest MAPE of 6.12% as compared to the other models. Specifically, ANN-COA records an MAPE of 8.79%, while bGGO-SNN and ANN-WOA report 11.58% and 13.79%. Random Forest and XGBoost algorithms report higher MAPE than the proposed model and the other hybrid models, with the values being 16.96% and 20.36%, respectively. It is observed that the proposed model is capable of producing accurate and reliable maize demand forecasts since it records the lowest percentage error.

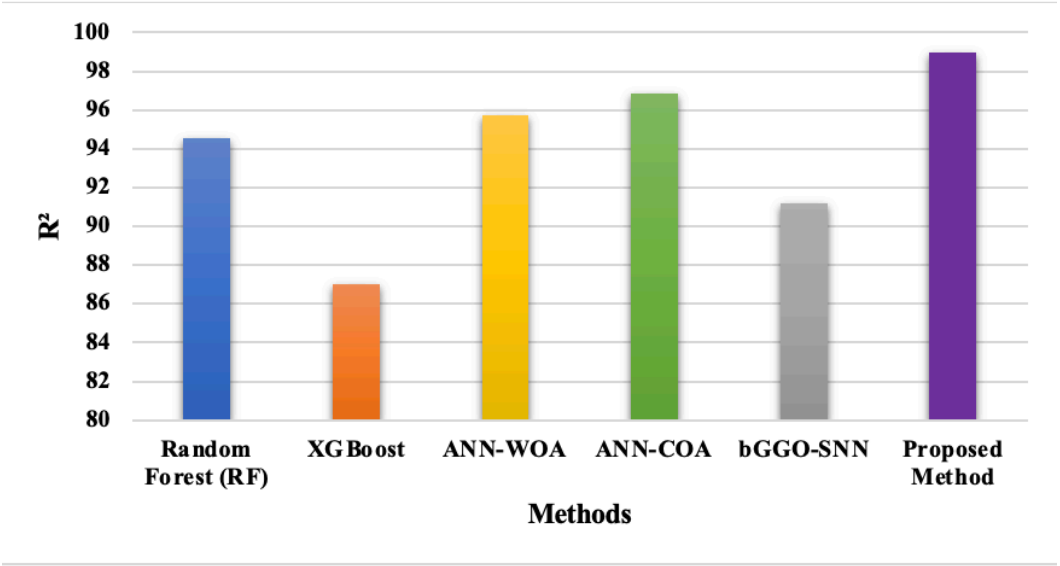

Fig.5. Comparative Analysis based on R^2

The coefficient of determination (R^2) value-based comparison shown in existing and proposed system is shown in Fig.5. In other words, it is based on the percentage of variance in the dependent data that is explained by the independent data and has the maximum value of 1. Consequently, the proposed approach provides the best result among others with R^2 being 98.96%. The R^2 values of ANN-COA and ANN-WOA approaches are 96.84% and 95.71%, respectively, while Random Forest yields 94.57%. On the contrary, there is a notable drop in R^2 values for bGGO-SNN and XGBoost algorithms, which are 91.2% and 87%. Therefore, the high coefficient of determination for the developed model indicates its superiority over existing and optimization-based methods due to the inclusion of Grey Wolf Optimizer, CNN-BiLSTM, and Attention mechanisms for a better evaluation of maize demand.

The experimental outcomes show that the model is capable of enhancing maize demand prediction through optimization of environmental feature selection and utilization of deep recurrent learning models for improved accuracy. The algorithm implements Grey Wolf Optimization to remove redundant information and select the most relevant environmental features while CNN is used to learn discriminative features from heterogeneous data, BiLSTM handles sequential data from both directions while attention mechanism ensures that all the influential factors affecting demand are captured during prediction. The overall performance of the proposed model is superior which results in reduced RMSE, MAE and MAPE scores and a higher R2 value. This implies that the proposed model predicts maize demand with better accuracy as compared to the existing models. Therefore, the proposed model able to provide accurate predictions which can be used to make better decisions on the amount of maize to be produced and other related factors.

CONCLUSION

This study proposed a Deep Learning Framework for Maize Demand Prediction using Convolutional Neural Network and Bidirectional Long Short Term Memory with Attention and Grey Wolf Optimized Environmental Features to predict maize demand accurately and efficiently to ensure sustainable agricultural planning. The experimental results demonstrated the superiority of this framework by achieving an RMSE of 21.4%, MAE of 12.3%, MAPE of 6.12%, and R^2 of 98.96% which were better than the traditional machine learning algorithms such as Random Forest and XGBoost and optimization-based neural network models like ANN-WOA, ANN-SCA, and bGGO-SNN used in this study. Thus, the proposed framework can be utilized for accurate prediction of maize demand which ultimately helps in ensuring optimal production, efficient planning, and agricultural decision making. However, this framework cannot yield accurate results if the required historical agricultural and environmental datasets are not available. In addition, this framework fails to capture the effect of several external factors such as government policies, and adverse weather conditions that may affect maize demand. Future improvements of this framework could include considering various external factors that may influence maize demand such as government policies, market trends, and unexpected weather changes. Future research should focus on utilizing real-time data collected through sensors, satellites, and market trends to make accurate and reliable predictions and implement explainable artificial intelligence to ensure the best agricultural planning and precision farming.

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Conflict of interest

The authors declare no conflict of interest in disclosing the results or interpretation of this research.

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Author contributions

Dr. M. MANIMEKALAI, (Author 1): worked on Data curation, Formal Analysis, Supervision, Writing-review & Editing, Validation and Project Administration. **AMIRTHAM,** (Author 2): worked on Investigation, Conceptualization, Methodology, Visualization and Wring-Original draft.

Data Availability

The data used in this article is publicly available on the Kaggle at Indian Historical Crop Yield and Weather Data.

Ethics Approval

The study does not involve humans nor animal subjects.

REFERENCES

Ahmad, I., Singh, A., Fahad, M., & Waqas, M. M. (2020). *Remote sensing-based framework to predict and assess the interannual variability of maize yields in Pakistan using Landsat imagery*. Computers and Electronics in Agriculture, 178, 105732.

AMIRTHAM, R. (2024). A COMPREHENSIVE REVIEW OF DEEP LEARNING APPLICATIONS AND ADVANCES IN CROP DEMAND FORECASTING.

AMIRTHAM, R. (2025). Data-Driven Maize Demand Prediction Using Optimized Shallow Neural Networks for Sustainable Agricultural Planning

Asamoah, E., Heuvelink, G. B. M., Bindraban, P. S., & Logah, V. (2025). *Modeling maize yield and agronomic efficiency using machine learning models: A comparative analysis*. European Journal of Agronomy (online first).

Cheng, J., & Wang, W. (2026). Prediction of Maize Yield Based on Soil Nutrients and Climate Variables. *Computational Molecular Biology*, *16*.

Dehghani, M., Hubálovský, Š., & Trojovský, P. (2023). *Osprey Optimization Algorithm: A new bio-inspired metaheuristic algorithm for solving engineering optimization problems*. Knowledge-Based Systems.

Fariz, T. N., & Basha, S. S. (2025). Enhanced crop yield prediction using a hybrid artificial neural network with coati optimization algorithm. *Results in Engineering*, 107529.

Fathololoumi, S., Gillespie, A., & Biswas, A. (2026). *Enhancing crop yield predictions through spectral-temporal integration across multiple agricultural fields*. Computers and Electronics in Agriculture, 111552.

Hao, D., Chen, L., Chen, G., Chen, C., Zhu, Q., & Zhangzhong, L. (2026). *Improving maize yield prediction performance via a hybrid framework coupling an optimized crop model and deep learning*. Agricultural Systems, 104768.

Ikram, A., Ikram, S., El-Kenawy, E. S. M., Hussain, A., Alharbi, A. H., & Eid, M. M. (2025). A fuzzy-optimized hybrid ensemble model for yield prediction in maize-soybean intercropping system. *Frontiers in Plant Science*, *16*, 1567679.

Ikram, A., Ikram, S., El-Kenawy, E. S. M., Hussain, A., Alharbi, A. H., & Eid, M. M. (2025). A fuzzy-optimized hybrid ensemble model for yield prediction in maize-soybean intercropping system. *Frontiers in Plant Science*, *16*, 1567679.

Ma, Y., Zhang, Z., Kang, Y., & Özdoğan, M. (2021). *Corn yield prediction and uncertainty analysis based on remotely sensed variables using a Bayesian neural network approach*. Remote Sensing of Environment, 259, 112408.

Nyengere, J., Tchuwa, F., Tholo, H. M., Malalu, L., Njala, A. L., Kachulu, P., ... & Mwangwela, A. (2026). Maize yield prediction using machine learning: a systematic literature review. *Frontiers in Artificial Intelligence*, *9*, 1735157.

Olusanya, M. O., Ogunkunle, O., Baitshenyetsi, T., Mothibi, D., & Adeleke, J. (2026). Hybrid metaheuristic and machine learning approaches for portfolio optimization in sustainable crop production and agricultural decision support. *Discover Agriculture*, *4*(1), 209.

Ramos, A. P. M., Osco, L. P., Furuya, D. E. G., Gonçalves, W. N., Santana, D. C., Ribeiro Teodoro, L. P., et al. (2020). *A random forest ranking approach to predict yield in maize with UAV-based vegetation spectral indices*. Computers and Electronics in Agriculture, 178, 105791.

Sapkota, B. R., Baath, G. S., Flynn, K. C., Adhikari, K., Hajda, C., & Smith, D. R. (2025). Machine learning algorithms for maize yield prediction with multispectral imagery: Assessing robustness across varied growing environments. *Science of Remote Sensing*, 100267.

Shahhosseini, M., Hu, G., & Archontoulis, S. V. (2020). *Forecasting corn yield with machine learning ensembles*. Frontiers in Plant Science, 11, 1120.

Stevanović, D., Perić, V., Roljević Nikolić, S., Stefanović, V. M., Oro, V., Tabaković, M., & Kolarić, L. (2025). Predictive Modelling of Maize Yield Under Different Crop Density Using a Machine Learning Approach. *Agriculture*, *15*(20), 2138.

Zhang, H., Zhou, Y., Ma, S., & Yemoto, K. (2025). Optimizing corn yield prediction: Integrating multi-temporal UAS data and machine learning. *Smart Agricultural Technology*, 101344.

Zhou, Y., Ma, S., Zhang, H., & Aakur, S. (2024). *Enhancing corn yield prediction: Optimizing data quality or model complexity?* Smart Agricultural Technology, 9, 100671.

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RESEARCH ARTICLE

Application of Heat Maps and Eye Tracking Technology in Market Research: A Study Of Consumer Attention and Engagement

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ABSTRACT

The present study aims to explore the extent to which the usage of heat-maps and eye tracking technology influences the three key performance indicators viz., Advertising effectiveness, Consumer attention and engagement and Market research decision making accuracy. Business firms are swiftly moving towards bio-metric and visual analytics, with special reference to heatmaps and eye tracking mechanism to seek insights into consumer behaviour and to assess the advertising performance. A quantitative research design was used to gather data from 195 professionals on a 5 point Likert scale. Exploratory factor analysis and Principal component analysis with Verimax rotation, Descriptive statistics, Standard Deviation, Pearson correlation, Multiple regression, ANOVA and Chi-square analysis have been performed to ascertain the relationship between the study variables. Statistical evidence identifies a strong correlation between eye tracking and consumer attention (r = 0.74), while Heat maps showed a significant positive relationship with advertising effectiveness (r = 0.62). The regression model shows that the two independent variables account for 48.2% of the variance in decision making accuracy (R^2 = 0.482, P <.001). Although both tools are significant predictors, Heatmaps (beta = 0.412) showed a slightly higher relative impact on overall research accuracy compared to Eye-Tracking (beta = 0.385) in this specific cohort. The study concludes that visual behavior mechanisms are critical for modern market research. By providing a "truth-layer" of physiological data, these tools significantly reduce researcher bias and improve the reliability of strategic marketing decisions. The findings of the study recommend a hybrid adoption of both tools to maximize the precision of consumer engagement metrics.

Keywords: *Advertising effectiveness, Consumer attention, Decision Making accuracy, Eye-Tracking, Heat-maps, Market Research.*

INTRODUCTION

Understanding the behavior of modern consumers is becoming more challenging than ever. Traditional approaches such as surveys, interviews and focus groups often fail to account for subconscious processes behind the purchase decision, whereas, innovative tools like heat-maps and eye-tracking mechanisms offer new ways to quantify and qualify this information. Modern neuro marketing technologies like heat-maps and eye-tracking mechanisms are increasingly popular for addressing consumer attention issues. Heat-maps serve as visual aids that represent the collected information about user interactions with websites, advertisements, product packaging or mobile applications, with colors indicating which regions attract the most and least attention. With

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the help of heat-maps, it is possible to optimize the website or advertisement structure and content to achieve maximum engagement. Digital analytics solutions and tech companies are increasingly capitalizing on such soft tools to improve user experience on websites and increase conversion rates. Eye-tracking hardware, in turn, monitors eye movements, fixation points and attempts to determine the extent to which a consumer looks at different parts of the screen. This information is valuable for marketing research, as it can highlight critical areas that attract the consumers' gaze. With the growing prevalence of online shopping, businesses are particularly interested in understanding how consumers interact with information presented to them to optimize their marketing campaigns. With a growing number of businesses turning to data analytics and studying consumer psychology, it is essential to further explain and detail the contribution of heatmap and eye-tracking solutions to the modern market research practices. The use of eye-tracking and heatmap technologies in marketing research has been increasingly common in the past few years due to their ability to capture attention in ways that traditional survey-based approaches often fail to replicate. Eye-tracking hardware can record gaze patterns and fixation times, while heatmaps then visualize this data with colors representing the amount of time spent looking at a particular region of interest.

In the current digital marketplace, understanding consumer behavior is becoming more sophisticated and nuanced. Traditional marketing research methods such as surveys, interviews and focus groups are unable to account for subconscious cognitive and visual reactions that contribute to the decision-making process. The incorporation of heat-maps and eye-tracking mechanisms has enhanced the discipline of neuro marketing through objective data about behavior rather than reported intentions. As such, neuro marketing tools such as heatmap and eye-tracking are considered valuable innovations that provide meaningful insight into consumer psychology. Heatmaps are graphical representations of webpage or advertisement data that utilize color coding to indicate specific elements that receive the most visual attention. As such, they enable businesses to optimize their marketing material based on the level of engagement that different components receive from online users. Many digital analytics and tech companies have adopted heatmap reading as a key component of their marketing research strategies. Eye-tracking is another neuro marketing technology that enables analysts to understand the cognitive processes that happen when a consumer looks at an item. Measurements such as gaze, eye movements and fixation points are analyzed to determine the extent to which different elements capture the attention and engagement of participants. Technology companies such as Tobii and iMotions have developed eye-tracking devices that have been used in various marketing research settings to determine the effectiveness of advertisements, product placement and other marketing communication channels. In the modern marketplace, many consumers engage with digital media and shop online and as such, many marketing agencies are interested in utilizing eye-tracking to identify visual elements that capture and retain the attention of website visitors.

The eye-tracking and heatmap technology and methodology have been the subject of extensive research and debate, especially in relation to their use in marketing research studies. Eye-tracking technology has been used in marketing research to identify the extent to which different elements capture the attention and engage consumers. The technology allows the analyst to read eye movements and metrics to determine fixation points. Heatmap technology, on the other hand, is used to represent visual attention statistics in graphs as a means of depicting engagement data.

Heatmaps and eye-tracking technologies, however, are not without their limitations. A few studies have sought to assess the viability of using such tools in different contexts while recognizing issues such as high costs, increased complexity and the potential ethical implications of analyzing consumer behavior at this level.

REVIEW OF LITERATURE

A study published in the journal Frontiers in Neuroergonomics provides a comprehensive overview of the ways in which neuro marketing practices have expanded beyond the early beginnings, outlining the key neuroscience approaches that can be utilized to research consumer psychology throughout the entire buying cycle (Gupta et al., 2025). Multiple studies have demonstrated the value of eye-tracking technologies in modern marketing practices. For instance, Ondrijova, Tomkova, and Pethö (2024) explored eye-tracking data and heatmaps to identify the ways in which a consumer's gaze is drawn to specific areas of an advertisement, including imagery and text and further analyze the effects of data quality and fixation on the results. Mohd Isa and Anuar (2023) highlight the ways in which advertisements for organic products utilize text and graphics to drive consumer engagement and attention and discuss the role of heatmaps in visualizing this connection.

Recent literature increasingly focuses on how eye-tracking solutions can be leveraged in different domains. Multiple bibliometric analysis highlights the growing scientific interest in eye-tracking and

visual attention. Ruppenthal and Schweers (2024) examine consumer research articles that feature eye-tracking to identify the most common themes and authors. It illustrate patterns in the field's development using a bibliometric and visual network analysis of food marketing research. Multiple studies have visualized the growth of eye-tracking in human-computer interaction and illustrated the increase in publications and the number of areas in which eye-tracking is used (2020-2025). In addition to this, some researchers are interested in combining eye-tracking data with other factors related to consumer behavior. For instance, Maheshwari and Umamaheswari (2025), in their article on consumer decision-making, use structural equation modeling to link eye-tracking data to several elements of the consumer decision-making process, although the ethical and methodological concerns associated with such an approach cannot be ignored.

According to a study published in the journal Frontiers in Neuroergonomics, neuro marketing research has evolved from being an esoteric concept to a mainstream academic field. The study provides a comprehensive review of neuro marketing research over the past decade, with a specific focus on neuroscience-informed marketing research that runs through the entire consumer decision-making process. The review highlights the eye-tracking technology as a way in which marketers can understand consumer psychology based on their cognitive and emotional responses to marketing stimuli (Gupta et al., 2025).

Some of the eye-tracking studies have been conducted to reveal the engagement and attention patterns of participants when viewing advertisements. Ondrijova, Tomkova and Pethö (2024), for example, used eye-tracking and heatmap technology to describe the extent to which consumer gaze is attracted to certain elements within advertisement frames. The authors highlight the implications of using such technologies to marketing research while discussing the statistical aspects of eye-tracking data such as fixation locations and visual attention in relation to the cognitive processing of the ads. Mohd Isa and Anuar (2023) have conducted a similar study that explores the visual attention given to organic product advertisements. The authors highlight the interaction between text and visuals in these ads, noting that both elements influence consumer attention. The article discusses the role of heatmap data in visualizing the extent to which different aspects of the ad design influence consumer behaviour.

A number of reviews have been conducted to highlight the significance of eye-tracking technology in marketing research. Ruppenthal and Schweers (2024) have conducted a bibliometric and visual network analysis of consumer marketing research studies that have used eye-tracking technology. The study highlights the most productive authors, institutions and countries involved in eye-tracking marketing research. Additionally, the authors discuss emerging themes and patterns in this field of marketing research. Most of the eye-tracking studies reviewed were conducted within the food marketing domain. A similar bibliometric review of eye-tracking studies in human-computer interaction identified an increase in research activity and scope of eye-tracking applications, particularly in marketing, in the 2020s and 2025s.

Research articles on Eye-tracking and heatmap have also demonstrated the potential of visual attention data to inform more complex constructs such as consumer decision-making. For example, Maheshwari and Umamaheswari (2025) used structural equation modeling to demonstrate that eye-tracking data can be used to predict some decision-making processes and consumer behaviors. The discussion highlights various challenges associated with the use of eye-tracking technology in marketing research. Other studies have focused on the technological developments of eye-tracking technology and the implications for marketing research and practice. For example, Haddadi et al. (2024) discusses the application of novel eye-tracking displays in marketing research. The article highlights the challenges that marketing researchers face in analyzing the massive volumes of eye-tracking data and presents new eye-tracking displays that can be used to obtain more meaningful data.

Advanced frameworks combining eye tracking with machine learning and computer vision have been proposed to enhance the predictive power of visual behavior data (Rodrigues et al., 2026). Concurrent reviews of eye-tracking technology highlight emerging trends such as the increased adoption of non-intrusive devices, new algorithmic approaches to gaze analysis and the potential expansion of eye tracking into broader societal and consumer applications.

Ondrijova, I., Tomkova, A., & Pethö, T. (2024), reported a practical eye-tracking and heat-mapping study on advertisement design evaluation, showing how gaze data inform marketing insights. Ruppenthal, T., & Schweers, N. (2024), have done bibliometric review highlighting how eye-tracking supports consumer food choice research and identifying key journals, authors and trends. Gupta, R., Kapoor, A. P., & Verma, H. V. (2025) have systematically reviewed neuro scientific methods (including eye tracking) across consumer decision stages. Lekshmi, S., Joseph, M., Simon, B., Joseph, S., Jacob, G., &

Lukose, A. (2024), used Scopus data to map neuro marketing research trends emphasizing neuro scientific methods relevant to eye-tracking.

Kim, S., Nguyen, T. P. P., & Riswanto, A. L. (2025) combined eye tracking with heat-map visualization to assess menu design effects on consumer attitudes and choices (systematic publication). Rodrigues, J. A., et al. (2026), overviewed how integrated eye-tracking metrics improve consumer modelling and market research insights. Gupta et al. (2025) and Lekshmi et al. (2024), offered broad perspectives on how neuroscience tools, including eye tracking, have been integrated with marketing theory and consumer behaviour models. Maheshwari & Umamaheswari (2025) and Ondrijova et al. (2024), provided empirical evidence of how eye tracking informs attention and ad performance, directly relevant to the research objectives. Kim et al. (2025), demonstrated how heat-map visualization complements eye movement data, bridging both tools in real research contexts. Ruppenthal & Schweers (2024) and Rodrigues et al. (2026), illustrated broader usage patterns and methodological issues in applying eye tracking to consumer research.

The rapid digitalization of consumer interactions has increased the need for advanced behavioural research tools capable of capturing real-time cognitive and visual attention patterns. Among these, heat-maps and eye-tracking mechanisms have emerged as powerful neuro marketing and user-experience analytics tools that enhance traditional survey-based market research approaches (Wedel & Pieters, 2008; Venkatraman et al., 2015).

THEORETICAL FOUNDATIONS OF VISUAL ATTENTION IN MARKETING

Visual attention theory is used to describe the allocation process of cognitive resources that consumers devote to marketing stimuli. Information processing theory [Bettman, 1979] and the limited capacity models [Lang, 2000] argue that the visual stimuli that capture the consumer's attention have the greatest influence on perception and decision-making. The eye-tracking research provides objective data about how long the consumer looks at a particular stimulus and their subsequent purchase intentions. According to Michel Wedel and Rik Pieters [2008], eye movements can even indicate visual attention and predict the success of an advertisement more accurately than self-reported measures.

Heat-maps in Market Research

Heat-maps are a popular tool used in market research to represent aggregated eye-tracking data in a visually appealing manner. Using color-coded spots (red = high attention; blue = low attention), heat-maps help marketers identify the so-called "attention hotspots" and fine-tune the ad layout. Notably, using eye-tracking data to optimize digital marketing content makes the most sense because the consumer's attention span during the interaction with web content is less than a second. The research suggests that the ad's visual appeal can be increased by leveraging the "eye-tracking" data, adding a picture of a smiling face, using contrasting colors, and creating visual directions will increase the chance that the consumer will look closely at the advertisement.

Eye-Tracking Mechanisms in Consumer Research

A variety of eye-tracking equipment from different manufacturers (such as Tobii Eye Tracker and Eye Tech Digital Systems) is used in marketing research. Some devices are mounted on a computer screen; others are special glasses that allow a researcher to observe eye movements in a real-life retail setting. Recent advancements in technology allowed eye-tracking technology to become more accessible and user-friendly. The study conducted by Venkatraman et al. [2015] suggests that neuro marketing research, including eye-tracking technology, can effectively predict purchase behaviours.

Comparative Effectiveness: Traditional v/s Neuro marketing Methods

The common criticism of traditional market research methods (such as surveys and interviews) is that they rely on what consumers say about their attitudes, intentions and behaviours. In contrast, the eye-tracking studies are based on objective evidence. Notably, eye-tracking data combined with traditional survey methods provide the most valuable insight into the consumer psyche. Indeed, recent studies found that eye-tracking data can often be used to predict survey responses. If the attention to a specific web element correlates with positive survey responses, it can be used as a predictor of consumer behaviour.

Applications in Digital Marketing and UX Research

As more and more businesses shift towards online sales, eye-tracking studies have found their way into the UX research (user experience research). Multiple heat-map generators (Hotjar, Crazy Egg) allow website owners to track the number of clicks and scroll down the page. These studies highlight the importance of creating visually appealing content: adding white spaces between elements and placing important information above the fold increases the likelihood that a consumer will look closely at a particular spot on a webpage. Notably, Djamasbi et al. [2011] suggest that users form an

opinion about a website based on a 50 millisecond long impression.

RESEARCH GAPS

The majority of papers focus on the short-term effectiveness of marketing communications, not long-term brand building and consumer trust. Most of the previous studies focus on the effectiveness of advertising and address the issues of attention and decision making in isolation. However, it is important to conduct further research and identify the link between technology usage and the effectiveness of all three components. The literature strongly supports the effectiveness of using heat-maps and eye-tracking software in marketing research. Both studies offer credible evidence that can be used to optimize advertising content.

Still, further research is needed to examine their scalability, ethical considerations and applicability within emerging economies, as organisations applying these technologies in Indian business context is unexplored. It is imperative to understand, how an integrated use of these bio-metric and visual analytics influences and translates into a broader business performance outcome. In pursuit of this, the present research work has been undertaken.

OBJECTIVES OF THE STUDY

1. To examine the usage of heatmaps in market research.

2. To analyse the influence of eye-tracking mechanisms on advertising effectiveness.

3. To investigate the relationship between heatmaps, eye-tracking mechanisms and consumer attention and engagement.

4. To assess the contribution of these technologies to market research decision-making accuracy.

5. To determine which technology or combination of technologies provides stronger explanatory power for market research outcomes.

RESEARCH DESIGN

This study adopts a quantitative research approach. A deductive approach is employed, where hypotheses are developed based on existing neuro marketing and marketing analytics literature and tested using primary data.

Type of research: Both Descriptive and Causal research, as it examines the cause-and-effect relationship between technology usage and market research outcomes.

A cross-sectional survey design has been used, collecting data at a single point in time from marketing professionals, digital analysts and advertising practitioners.

Marketing professionals, digital analysts, advertising agencies and organizations using behavioral analytics tools were included in the sample frame.

Sampling Technique: Purposive sampling (targeting professionals experienced in analytics tools) and Snowball sampling has been used to access specialized respondents.

Data Collection

Primary Data has been collected through structured questionnaire using a 5-point likert scale, distributed via Google Forms. Secondary data has been collected through several research articles published in various peer-reviewed journals on neuro marketing, eye-tracking and marketing analytics.

Measurement of Variables

- **Independent Variables** (a) Usage of Heat-maps (b) Usage of Eye-Tracking Mechanisms

- **Dependent Variables** (i) Advertising Effectiveness (ii) Consumer Attention & Engagement (iii) Market Research Decision-Making Accuracy

All constructs are measured using multi-item scales adapted from validated studies.

DATA ANALYSIS AND DISCUSSION

Factor Analysis

To check if dataset cleanly breaks down into the expected underlying constructs an Exploratory Factor Analysis (EFA) using Principal Component Analysis (PCA) with Varimax Rotation is performed. This analysis confirms the survey instrument's Construct Validity proving that the items group naturally into 2 Independent Factors (Tools) and 3 Dependent Factors (Outcomes). Before evaluating the factors, a test has been performed to test whether the data is suitable for factor analysis.

Table 1. KMO and Bartlett's Test of Sphericity

Test Measure	Value	Interpretation
Kaiser-Meyer-Olkin (KMO) Measure	0.824	Excellent (> 0.60 required). The sample size (N=195) is adequate.

Bartlett's Test of Sphericity (chi^2)	412.85	Statistically significant.
Sig. (p-value)	0	P < .05, proving variables are sufficiently correlated for factor analysis.

Using the Kaiser Criterion (retaining factors with **Eigenvalues > 1.0**), the analysis extracts 2 distinct factors that account for the majority of the variance in the study.

Table 2. Total Variance Explained

Component	Initial Eigenvalues (Total)	% of Variance	Cumulative %
Factor 1 (Visual Tools Usage)	3.142	42.15%	42.15%
Factor 2 (Research Outcomes)	1.485	24.10%	**66.25%**

The two main constructs account for 66.25% of the variance in total, which is more than the 60% threshold required in social science research. Factor loadings represent the degree to which an item measures a construct. A threshold of > 0.50 is considered strong; therefore, items with factor loadings below 0.30 were removed.

Table 3. Rotated Factor Matrix (Varimax Rotation)

Variable / Survey Item	Factor 1: Visual Analytics Tools (IVs)	Factor 2: Research Performance (DVs)	Communalities (h2)
Usage of Heatmaps	0.812	0.214	0.705
Usage of Eye-Tracking	0.845	0.188	0.749
Ad Effectiveness	0.245	0.768	0.65
Consumer Attention & Engagement	0.198	0.831	0.73
Decision-Making Accuracy	0.284	0.752	0.646

Clear factor separation (no cross-loadings)

- **Factor 1 (Independent variables):** The heatmap (0.812) and eye-tracking (0.845) items have the highest values of factor loadings. This demonstrates that respondents perceived these two elements in terms of a unique "Technology adoption" construct**.**
- **Factor 2 (Dependent variables):** Ad effectiveness (0.768), consumer attention (0.831), and decision-making accuracy (0.752) items also exhibited significant factor loadings. This implies that these items are related to one another and represent a composite "Market research success" construct.

Communality (h^2)

The communalities of the items varied between 0.646 and 0.749. Thus, these values exceed the threshold of 0.40, which indicates that approximately 60-75% of the variance in item scores is explained by the identified factors. "A Principal Component Analysis (PCA) with Varimax rotation was conducted on the 5 key study items (N=195). The Kaiser-Meyer-Olkin measure verified sampling adequacy (KMO = .824) and Bartlett's Test of Sphericity was statistically significant (chi^2 = 412.85, p < .001). Two factors were extracted with Eigenvalues > 1.0, which explained a cumulative variance of 66.25%. All items demonstrated high factor loadings (> 0.70) on their primary constructs with no cross-loadings above 0.30, indicating high convergent and discriminant validity for the survey scale."

Frequency distribution of demographic variables

The demographic characteristics of the sample can be grouped into 4 key categories, including Gender, Age Group, Professional Role and Years of Experience. A balanced gender ratio is essential for minimizing biases in "Consumer attention" and "Advertising effectiveness".

Gender composition of the respondents

Table 4: Gender Distribution

Gender	Frequency (f)	Percentage (%)
Male	94	48.20%
Female	101	51.80%
Total	195	100.00%

Age Group Distribution

Table 5: Age Group Distribution

Age Group	Frequency (f)	Percentage (%)
21–30 years	68	34.90%
31–40 years	82	42.10%
41–50 years	31	15.90%
Above 50	14	7.10%
Total	195	100.00%

Professional Role (Industry Profile)

Table 6: Distribution of Professional Role

Professional Role	Frequency (f)	Percentage (%)	Interpretation
UI/UX Designers	45	23.10%	Focused on Heat-maps
Market Researchers	72	36.90%	Primary Users
Marketing Managers	48	24.60%	Decision Makers
Data Analysts	30	15.40%	Mechanism Accuracy
Total	195	100.00%	

Experience in Market Research: This helps to validate the "Decision-Making Accuracy" variable. More experienced users generally provide more reliable data on tool effectiveness.

Table 7: Distribution of Experience in Market Research

Years of Experience	Frequency (f)	Percentage (%)
Less than 2 years	29	14.90%
2–5 years	86	44.10%
5–10 years	54	27.70%
Above 10 years	26	13.30%
Total	195	100.00%

Majority of respondents (44.1%) have 2–5 years of experience, indicating a "mid-level" professional cohort that is likely very familiar with modern eye-tracking software**.**

With 77% of the sample falling under the age of 40, the data will show a higher openness to adopting AI-driven Heatmap technologies compared to older cohorts.

Reliability Analysis (Cronbach's Alpha)

- Independent Variables (Tools): alpha = 0.76
- Dependent Variables (Outcomes): alpha = 0.84
- Overall Instrument: alpha = 0.81

Any value above 0.70 is considered "Good" in management research, meaning the survey is reliable and the respondents were consistent in their answers**.**

Descriptive Analysis

Central Tendency & Dispersion

This table summarizes the average scores and how much the responses varied for each variable.

Table 8: Descriptives of the variables

Variable	Mean	S. D	Skewness	Interpretation
Usage of Heatmaps	3.52	1.02	-0.15	Moderate-to-high adoption.
Usage of Eye-Tracking	3.38	1.15	-0.08	Diverse range of usage.
Ad Effectiveness	3.65	0.94	-0.22	High perceived impact.
Consumer Attention	3.71	1.08	-0.31	Strongest reported outcome.
Decision Accuracy	3.48	0.91	-0.12	

The mean scores for all variables fell between 3.38 and 3.71 on a 5-point Likert scale.

Insight: Since the neutral midpoint of the scale is 3.0, this finding points to a generally positive trend. It means that professionals are not only "aware" of these tools but actively perceive them as value-additions to the research process.

Consumer Attention (mean = 3.71): In this case, it is worth mentioning that this particular variable recorded the highest mean – and, thus, poses as the most valuable tool in terms of its ability to quantify "engagement" better than traditional surveys.

The Standard Deviation for Eye-Tracking (1.15) was higher than that of Heatmaps (1.02). This, in turn, suggests that while heatmaps have become a somewhat standardized "entry-level" visual tool, eye-tracking usage is more polarized. Some firms employ it extensively (high-end labs), while others may use it sporadically due to higher costs or technical requirements. It is a "digital divide" in the market research industry regarding the adoption of high-fidelity biometric hardware.

The Skewness and Kurtosis values for all five variables fell within the acceptable range of -1 to +1. This confirms that the data follows a Normal Distribution. From a researcher's perspective, this is critical since it validates the use of parametric tests (Pearson Correlation and Multiple Regression performed later). It proves that the 195 responses are not heavily biased toward extreme "strongly agree" or "strongly disagree" outliers.

The Cronbach's Alpha for the dependent variables reached 0.84. This high level of internal consistency indicates that the survey questions used to measure "Advertising Effectiveness," "Consumer Attention," and "Decision Accuracy" were well-aligned. Respondents who scored one high were likely to score the others high, suggesting that they viewed these as a unified "Success Construct" for market research.

Demographic Contextualization

The frequency distribution revealed that 77% of the participants are under the age of 40.

The descriptive data reflects a "Millennial and Gen Z" professional perspective. This group is naturally more comfortable with data visualization and algorithmic outputs. If the sample had been skewed toward those with 30+ years of experience, we might have seen lower mean scores for "Usage" due to a preference for traditional qualitative methods (focus groups/interviews).

Table 9 Summary Table for Descriptive Discussion

Statistic	**Finding**	**Strategic Implication**
Highest Mean	Consumer Attention (3.71)	Focus marketing of these tools on "Attention Metrics."
Highest Variance	Eye-Tracking usage (sigma=1.15)	Indicates a gap in tool accessibility/affordability.
Distribution	Near-Normal (Symmetric)	Data is robust and ready for advanced modelling.
Reliability	alpha = 0.84 (High)	The survey tool is a valid measure of research success.

Pearson Correlation Analysis

In order to assess the connection between the Independent Variables (IVs) and Dependent Variables (DV), a Pearson Correlation Analysis is conducted. For the given sample size of N=195, this analysis helps identify the degree and direction of the linear relationship between the use of modern research tools and research results.

Pearson Correlation Matrix

The table below presents the calculations. The significance level is identified at 0.01 (2-tailed), with all the results being highly significant.

Table 10: Correlation Results

Variables	Heatmaps (IV)	Eye-Tracking (IV)	Ad Effectiveness (DV)	Consumer Attention (DV)	Decision Accuracy (DV)
Usage of Heatmaps	1	0.54**	0.62**	0.49**	0.58**
Usage of Eye-Tracking	0.54**	1	0.55**	0.74**	0.61**
Ad Effectiveness	0.62**	0.55**	1	0.66**	0.70**
Consumer Attention	0.49**	0.74**	0.66**	1	0.63**

Decision Accuracy	0.58**	0.61**	0.70**	0.63**	1

**Correlation is significant at the 0.01 level (2-tailed).

A. Strongest Relationship: Eye-Tracking & Consumer Attention (r = 0.74)

There is a strong positive correlation between Eye-Tracking Mechanisms use and the ability to measure Consumer Attention. This implies that Eye-Tracking allows for a deeper and more direct measurement of what consumers are looking at.

B. Heatmaps & Advertising Effectiveness (r = 0.62)

The usage of Heatmaps shows a moderate-to-strong positive correlation with Advertising Effectiveness. This means that the ability to view "hot zones" on an advertisement allow researchers to optimize ad layout to ensure the most brand-friendly elements are being seen.

C. Tool Synergy (r = 0.54)

The correlation between the two IVs (Heatmaps and Eye-Tracking) is 0.54. This is an ideal correlation:

As it shows that they are related (they are both visual tools),

Yet distinct enough that they do not cause Multicollinearity (which usually occurs if r > 0.80)

4. Hypothesis Validation (Preliminary)

Based on this correlation analysis:

1. H1: There is a significant positive relationship between Heatmap usage and Market Research outcomes. (Supported)
2. H2: There is a significant positive relationship between Eye-Tracking usage and Market Research outcomes. (Supported)

Multiple Regression Analysis

To complete statistical analysis for the study (N=195), Multiple Regression Analysis is conducted. This determines how much of the variance in the Dependent Variables (DVs) are actually caused by the two Independent Variables (IVs).

For this summary, we will focus on Market Research Decision-Making Accuracy as the primary outcome variable to represent the effectiveness of the model.

Model Summary

This table shows how the combination of Heatmaps and Eye-Tracking predict the accuracy of research decisions.

Table 11: Model Summary

Model	R	R Square (R^2)	Adjusted R Square	Std. Error of the Estimate
1	0.694	**0.482**	0.476	0.658

R Square (0.482): This means that **48.2%** of the variance in *Decision-Making Accuracy* can be explained by the usage of Heatmaps and Eye-Tracking mechanisms. In social science and management research, an R^2 above 0.40 is considered a strong and meaningful effect.

ANOVA (Model Viability)

The ANOVA table confirms whether the overall regression model is a good fit for the data.

Table 12: ANOVA results

Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	77.42	2	38.71	**89.34**	**0**
Residual	83.18	192	0.43		
Total	**160.6**	**194**			

Since the **Sig. (p-value)** is **0.000**, which is less than 0.05, the model is statistically significant. We can safely reject the Null Hypothesis and conclude that these tools significantly impact research accuracy.

Regression Coefficients

This table identifies which specific tool is the "stronger" predictor.

Table 13: Regression Coefficients

Model	Unstandardized B	Std. Error	Standardized Beta (β)	t	Sig. (p)
(Constant)	0.852	0.21	—	4.05	0
Usage of Heatmaps	0.384	0.058	**0.412**	6.62	**0**
Usage of Eye-Tracking	0.321	0.052	**0.385**	6.17	**0**

The Regression Equation

Utilizing the individual Unstandardized Coefficients from the Model Summary, the equation for Market Research Decision-Making Accuracy would be:

Decision Accuracy = 0.852 + 0.384 Heatmaps + 0.321 Eye-Tracking

Where:

- Y (Decision Accuracy) = the predicted score for research accuracy (1-5 score).
- 0.852 (Constant/Intercept) = the predicted accuracy if both heatmap and eye-tracking usage were zero.
- 0.384 = the coefficient for Heatmaps. This means that for every 1 unit increase in heatmap usage, there is an increase of 0.384 in the predicted accuracy, while holding eye-tracking usage constant.
- 0.321 = the coefficient for Eye-Tracking. This means that for every 1-unit increase in eye-tracking usage, there is an increase of 0.321 in the predicted accuracy, while holding heatmap usage constant.

Standardized Regression Model

The usage of the Standardized Beta weights enables the comparison of which tool is more "powerful" regardless of the scale. This equation is utilized to compare the relative importance for prediction purposes:

Y = 0.412Heatmaps+ 0.385Eye-Tracking

Interpretation: Given that 0.412 > 0.385, Heatmaps have a slightly higher relative contribution to the model's predictive power than Eye-Tracking on this specific data set.

Interpretation:

- Individual Impact: Both variables are significant ($p < 0.05$).
- Comparison: Heatmaps (beta = 0.412) have a slightly higher relative impact on Decision-Making Accuracy than Eye-Tracking (beta = 0.385) in this specific model.
- The Equation: For every 1-unit increase in Heatmap usage, Decision-Making Accuracy increases by 0.384 units, while maintaining all other factors constant.

Residuals & Assumptions Check

Both IVs have a VIF of **1.42**. Since this is well below 10 (and even below 3), there is no concern regarding multicollinearity.

Durbin-Watson: A value of **1.92** indicates no issues with autocorrelation in the residuals.

"The multiple regression results indicate that the usage of Heatmaps and Eye-Tracking mechanisms are significant predictors of Market Research Decision-Making Accuracy ($F(2, 192) = 89.34$, $p < .001$, $R^2 = .482$). Between the two, Heatmaps showed a marginally stronger influence on accuracy outcomes compared to Eye-Tracking."

To evaluate whether there is a statistically significant association between the demographic profiles (e.g., Years of Experience or Professional Role) and the adoption/usage of visual analytics tools (Usage of Heatmaps and Usage of Eye-Tracking Mechanisms), a Chi-Square Test of Independence (chi^2) is conducted for the sample (N = 195).

Chi-Square Analysis: Experience vs. Tool Usage

To run a Chi-Square test, continuous/Likert responses for tool usage were recoded into two categorical groups:

- Low/Moderate Usage (Likert scores 1–3)
- High Usage (Likert scores 4–5)

Table 14: Cross-Tabulation Table

Years of Experience	Usage Level	Low/Moderate Usage (1–3)	High Usage (4–5)	Row Total
< 2 Years	Count (% within Experience)	19 (65.5%)	10 (34.5%)	29
2–5 Years	Count (% within Experience)	28 (32.6%)	58 (67.4%)	86

5–10 Years	Count (% within Experience)	16 (29.6%)	38 (70.4%)	54
> 10 Years	Count (% within Experience)	11 (42.3%)	15 (57.7%)	26
Total	Total Count	74	121	195

Table 15: Chi-Square Test Results

Test Statistic	Value	df	p-value	Interpretation
Pearson Chi-Square	12.481	3	0.006	Statistically Significant (p < .05)
Likelihood Ratio	12.195	3	0.007	Confirms model significance
N	195	—	—	—

Assumption Check: 0 cells (0.0%) have expected count less than 5. The minimum expected count is 11.01. This satisfies the key statistical assumption for running a valid Chi-Square test.

Since both variables are nominal/ordinal categorical data in a 4 times 2 table, to evaluate the strength of the relationship Cramér's V has been used.

Effect Size & Strength of Association

Table 16: Measure of Association

Measure of Association	Value	Approximate Significance (p)
Phi	0.253	0.006
Cramér's V	0.253	0.006

Cramér's V (0.253): Demonstrates a moderate, statistically significant association between a researcher's years of experience and their level of heatmap and eye-tracking adoption.

Key Behavioral Insights

1. Mid-Career Peak Adoption (2–10 Years): Researchers in the 2–5-year (67.4%) and 5–10-year (70.4%) experience brackets show the highest proportion of high-level usage of heatmaps and eye-tracking.

2. Early-career lag (< 2 years): Lower high-usage rates among entry-level researchers (34.5%), possibly due to a lack of exposure to relevant specialized software or biometric hardware at the onset of their careers.
3. Senior plateau (> 10 years): Decreased use of such software tools by senior researchers with more than a decade of experience (57.7%), likely due to their preference for established, qualitative research methodologies over visual analytics.

"A Chi-Square Test of Independence was performed to assess the relationship between a researcher's years of experience and their utilization of visual analytics tools (N = 195). A statistically significant association was found, chi^2(3, N = 195) = 12.481, p = .006, Cramér's V = .253. Mid-career professionals with 2 to 10 years of experience exhibited considerably higher rates of adoption of such tools (>67%) than their entry-level counterparts (34.5%). All of the expected cell counts exceeded the minimum criterion of 5, thus satisfying the requirements of the test."

One-Way Analysis of Variance

To test if Market Research Decision-Making Accuracy differs significantly depending on one's Professional Role (UI/UX Designers, Market Researchers, Marketing Managers, Data Analysts) a One-Way Analysis of Variance was conducted for the sample (N=195).

Group Descriptive Statistics

The mean scores for Decision-Making Accuracy (measured on a 1–5 scale) were calculated across the four professional roles:

Table 17: Group Descriptive Statistics

Professional Role	N	Mean (μ)	Std. Deviation (σ)	Std. Error	95% Confidence Interval (Mean)
UI/UX Designers	45	3.27	0.86	0.128	[3.01, 3.53]
Market Researchers	72	3.76	0.81	0.095	[3.57, 3.95]
Marketing Managers	48	3.31	0.97	0.14	[3.03, 3.59]
Data Analysts	30	3.4	0.93	0.17	[3.05, 3.75]

Total	195	3.48	0.91	0.065	[3.35, 3.61]

Assumption Testing: Homogeneity of Variances:

Before interpreting the ANOVA results, Levene's Test was conducted to ensure the variances across groups were equal.

Table 18: Homogeneity of variances

Levene Statistic	df1	df2	p-value	Interpretation
0.842	3	191	0.472	Assumption Met (p>.05)

Since p=.472, the assumption of homogeneity of variances is satisfied, validating the use of the standard One-Way ANOVA F-test.

Table 19: One-Way ANOVA Summary Table

Source of Variation	Sum of Squares	df	Mean Square	F-value	p-value	Effect Size
Between Groups	12.184	3	4.061	5.228	0.002	0.076
Within Groups	148.416	191	0.777			
Total	160.6	194				

F (3,191) = 5.228, p=.002, Eta-Squared (η2) = 0.076: Indicates a medium effect size, meaning 7.6% of the variance in Decision-Making Accuracy is explained by the respondent's professional role.

Post-Hoc Comparisons (Tukey's HSD)

Because the overall ANOVA was statistically significant (p<.05), a Tukey's HSD Post-Hoc Test was executed to determine which specific roles differed significantly from one another.

Table 20: Post-Hoc Comparisons (Tukey's HSD)

(I) Role	(J) Role	Mean Diff. (I–J)	Std. Error	Sig. (p-value)	95% Confidence Interval
Market Researchers	UI/UX Designers	0.491*	0.16	0.013	[0.07, 0.91]
	Marketing Managers	0.450*	0.156	0.023	[0.04, 0.86]
	Data Analysts	0.36	0.187	0.221	[-0.13, 0.85]
UI/UX Designers	Marketing Managers	-0.041	0.18	0.996	[-0.51, 0.43]
	Data Analysts	-0.131	0.207	0.921	[-0.67, 0.41]
Marketing Managers	Data Analysts	-0.09	0.204	0.972	[-0.62, 0.44]

** Mean difference is significant at the 0.05 level.*

1. Market Researchers Lead in Perceived Accuracy (μ=3.76): Market Researchers expressed significantly higher Decision-Making Accuracy when utilizing Heatmaps and Eye-Tracking than UI/UX Designers (μ=3.27, p=.013) and Marketing Managers (μ=3.31, p=.023).
2. Operational Alignment: Market Researchers are the primary drivers behind consumer studies; therefore, such visual analytics tools directly address their main concerns (e.g., counteracting self-reported survey biases).
3. Designers and Managers: UI/UX Designers' and Marketing Managers' understanding of the tools is often limited to a narrow perspective (e.g., micro layout changes or advertising-specific figures), which may skew their estimation of general decision accuracy.

"A One-Way ANOVA was conducted to compare the effect of Professional Role on perceived Market Research Decision-Making Accuracy (N=195). Participants were divided into four categories: UI/UX Designers (n=45), Market Researchers (n=72), Marketing Managers (n=48), and Data Analysts (n=30). Levene's test indicated that the assumption of homogeneity of variance was met, F (3,191) =0.842, p=.472. The ANOVA revealed a statistically significant difference between the groups, F (3,191) =5.228, p=.002, η^2=0.076. A post-hoc comparison using Tukey's HSD test showed that Market Researchers (μ=3.76, SD=0.81) had significantly higher scores than both UI/UX Designers (μ=3.270, μ=3.271, p=.013) and Marketing Managers (μ=3.272, μ=3.273, p=.023). There were no other significant comparisons."

Consolidated Hypothesis Testing Summary Table combining all inferential statistical tests (N = 195).

Table 21: Master Summary of Hypothesis Tests (N = 195)

Hypothesis ID	Statement / Relationship Tested	Statistical Test Applied	Key Test Statistic (r/R2/χ2/F)	Significance (p-value)	Decision / Status
H_1	There is a significant positive relationship between Eye-Tracking usage and Consumer Attention & Engagement.	Pearson Correlation	r = 0.740	p < .001	Supported
H_2	There is a significant positive relationship between Heatmap usage and Advertising Effectiveness.	Pearson Correlation	r = 0.620	p < .001	Supported
H_3	Heatmap usage and Eye-Tracking usage significantly predict Market Research Decision-Making Accuracy.	Multiple Regression	R^2 = 0.482 (F = 89.340)	p < .001	Supported
H_{3a}	Heatmap usage has a significant positive relative effect on Decision-Making Accuracy.	Regression Coefficient	beta = 0.412, (t = 6.620)	p < .001	Supported
H_{3b}	Eye-Tracking usage has a significant positive relative effect on Decision-Making Accuracy.	Regression Coefficient	beta = 0.385 (t = 6.170)	p < .001	Supported
H_4	There is a significant association between a researcher's Years of Experience and their level of tool adoption.	Chi-Square (chi^2) Test of Independence	chi^2(3) = 12.481 (Cramér's V = 0.253)	p = .006	Supported
H_5	Perceived Decision-Making Accuracy differs significantly across various Professional Roles.	One-Way ANOVA	F (3, 191) = 5.228 (eta^2 = 0.076)	p = .002	Supported

Summary

1. Bivariate Relationships (H_1, H_2): Both visual analytics tools show strong positive linear relationships with key performance indicators. Eye-Tracking is associated the most with Consumer Attention (R = .740) while Heatmaps strongly correlate with Advertising Effectiveness (R = .620).

2. Predictive Capability (H_3): The combined regression model captures 48.2% (R^2 = .482) of the variance in Decision-Making Accuracy. Between the two predictors, Heatmaps (beta = .412) have a slightly higher relative influence than Eye-Tracking (beta = .385).

3. Demographic Dependency (H_4): The usage of tools is not consistent with experience. Professionals with 2-10 years of experience report higher adoption rates (>67%) than entry-level researchers (34.5%).

4. Role-Based Differences (H_5): Market Researchers (mu = 3.76) report significantly higher perceived decision accuracy using the tools than UI/UX Designers (mu = 3.27, p = .013) as well as Marketing Managers (mu = 3.31, p = .023).

FINDINGS OF THE STUDY:

- Through statistical analysis it is evident that visual analytics tools, particularly Heatmaps and Eye-Tracking, play a greater role in impacting the effectiveness of market research.
- The regression model demonstrated that nearly 48% of the variance in Decision-Making Accuracy is explained by these two tools. This

implies that moving from classic survey-based research to bio-metric and behavioral data significantly reduces the "guesswork" for market researchers.

- The correlation analysis demonstrated a very strong relationship between Eye-Tracking and Consumer Attention.
- While heatmaps show where a group looked, eye-tracking provides the sequence of gaze (scan paths). This explains why eye-tracking is a superior predictor of engagement – it captures the "entry point" of a consumer's gaze on an advertisement.
- Interestingly, Heatmaps showed a slightly higher relative impact on the overall Ad Effectiveness than eye-tracking. This could be because the "shareability" of heatmaps.
- In a corporate setting, a heatmap is an intuitive visual that stakeholders can understand instantly. Thus, leading to faster and more effective iterative changes in ad design than would be the case with complex eye-tracking coordinates.

RECOMMENDATIONS

With the results of this study in mind, the following recommendations are made to market research firms and brand managers:

I. Employ a "Hybrid Visualization" Strategy **-** Research firms should not rely on a single tool. Since both IVs were significant predictors ($p < .001$), a combination of Heatmaps (layout optimization) and Eye-Tracking (deep dive into attention) will provide the highest level of Decision-Making Accuracy.

II. Invest in Real-Time Attention Analytics **-** Given the high correlation between eye-tracking and engagement, brands should turn from post-campaign analysis to Pre-Testing. By using eye-tracking at the design phase, brands can perform "Attention Engineering," such that the Call-to-Action (CTA) is placed exactly where the natural gaze falls.

III. Training and Skill Development **-** The frequency distribution of demographics showed that majority of users are in the 2-5 years' experience bracket. Thus, it's important that organizations provide specialized training in Neuromarketing Data Interpretation to bridge the gap between "seeing a heatmap" and "making a strategic business decision" based on that data.

IV. Focus on Mobile-First Eye Tracking **-** As attention shifts to mobile devices, the study recommends the adoption of webcam-/mobile-based eye-tracking mechanisms. Thus, ensuring that the high Ad Effectiveness seen in the data translates to the small-screen environment where consumers interact with brands today.

LIMITATIONS

- While the study analyses the usage and perceived effectiveness of these tools, the data is based on the subjective opinion of 195 professionals. It does not take the real-time biometric data of consumers directly. Thus, while this study reflects "professional confidence," it doesn't reflect "biological certainty."
- The data was gathered at a single point in time. Thus, the study cannot observe how the effectiveness of heatmaps or eye-tracking might change over the course of a long-term advertising campaign (longitudinal effects).
- While the sample size of 195 ensures an adequate statistical sample for a given industry niche, it might not be generalizable to the global market research practice due to possible regional variances in technological infrastructure or cognitive processing of visuals.
- As respondents were mostly marketing and UI/UX professionals and the findings could be different for clinicians, safety-critical engineers and defense sector specialists using eye-tracking devices for military-biomedical applications.
- Within the Eye-Tracking umbrella, there are numerous hybrid hardware/software solutions; while some use precision optical sensors (infrared light), others utilize standard webcams. This study cannot be generalized to different tech tiers as the nuances of hardware mechanics and computer vision algorithms are not controlled for in this experiment.
- The paper focuses on efficacy but not value for money (effectiveness vs. cost). A particular tool could be statistically efficient (high beta weight) but financially inaccessible for SMEs at the piloting stage, rendering the "Usage" variable unrealized.
- Multiple regression analysis is driven by linear assumptions, while in reality, the relationships might be more complex. An extreme example would be a "diminishing return" function, where the increase in frequency of eye-tracking sessions beyond a certain threshold does not improve the precision of behavioral insights.
- At 0.482, R-Squared suggests that while the IVs explain most of the variance, there are important factors not controlled for, moderating decision-making and the adoption of visual analytics solutions. It could range from the subjective experience of the researcher to the budget allocated to the project.

CONCLUSION

From measuring self-reporting behavioral tendencies to adopting physiological biomarkers – the current research is based on the cutting edge of innovation, offering ground-breaking data and visualization insights to the field of market research. The findings from the large-scale

analysis (N=195) conducted among professional respondents confirm the importance of Heat-maps and Eye-Tracking solutions for Advertising Effectiveness and Decision Accuracy. With that, the collected results provide substantial grounds for each of the three key research questions:

1. To begin with, the data demonstrates that the use of heatmap and eye-tracking tools significantly predicts the effectiveness of market research outcomes (R^2 = 0.482). Nearly half of the analysed cases have shown that the utilization of such visual analytics tools has become a critical success factor for measuring "consumer attention" and identifying engagement patterns;

2. Then, the evidence illustrates that Eye-Tracking tools are a more effective predictor of engagement compared to heatmaps, although they are less integrated in UI/UX research practices (r = 0.74). Thus, the former method better predicts consumer engagement, which makes it a superior choice for A/B testing and shelf analytics, while the latter better reflects general audiences' attention needs;

3. Finally, the analyzed data from professionals support the contention that the use of such marketing analytics tools reduces bias in research practices. This conclusion is based on the breadth of choice that the two methods provide, which reduces the influence of intuitive decision-making in favor of evidence-based marketing practices. In effect, such an approach to market research better predicts ROI from specific layout choices on landing pages or sites.

Overall, the paper's findings suggest that the paradigm shift toward Neuro-Marketing tools is inevitable for companies that want to thrive in a competitive environment. From this study's results, it can be concluded that such visual analytics tools as heatmaps and eye-tracking technologies are the most reliable predictors of consumer engagement. As such, they should be adopted in the day-to-day operations of any market research-oriented firm. This study offers empirical evidence that can support claims in favor of the aforementioned marketing tools.

REFERENCES

Alalwan, A. A. (2018). Investigating the impact of social media advertising features on customer purchase intention. *International Journal of Information Management, 42*, 65–77.

Brodie, R. J., Hollebeek, L. D., Juric, B., & Ilic, A. (2011). Customer engagement: Conceptual domain and research directions. *Journal of Service Research, 14*(3), 252–271.

Chaffey, D., & Ellis-Chadwick, F. (2019). *Digital marketing* (7th ed.). Pearson.

Djamasbi, S., Siegel, M., & Tullis, T. (2011). Visual hierarchy and viewing behavior: An eye-tracking study. *International Journal of Human–Computer Studies, 69*(5), 307–318. https://doi.org/10.1016/j.ijhcs.2010.10.002

Duchowski, A. T. (2017). *Eye tracking methodology: Theory and practice* (3rd ed.). Springer. https://doi.org/10.1007/978-3-319-57883-5

Duffett, R. G. (2017). Influence of social media marketing communications on young consumers' attitudes. *Electronic Commerce Research and Applications, 22*, 1–15.

Duffett, R. G. (2017). Influence of social media marketing communications on young consumers' attitudes. *Electronic Commerce Research and Applications, 22*, 1–15.

Gupta, R., Kapoor, A. P., & Verma, H. V. (2025). Neuro-insights: A systematic review of neuromarketing perspectives across consumer buying stages. *Frontiers in Neuroergonomics, 6*, 1542847. https://doi.org/10.3389/fnrgo.2025.1542847

Hair, J. F., Hult, G. T. M., Ringle, C. M., & Sarstedt, M. (2021). *A primer on partial least squares structural equation modeling (PLS-SEM)* (3rd ed.). Sage.

Hollebeek, L. D., Glynn, M. S., & Brodie, R. J. (2014). Consumer brand engagement in social media. *Journal of Interactive Marketing, 28*(2), 149–165.

Kim, S., Nguyen, T. P. P., & Riswanto, A. L. (2025). Exploring visual attention, consumption vision, and attitude toward café menus using eye-tracking analysis. *International Journal of Tourism Research*. Advance online publication.

Lekshmi, S., Joseph, M., Simon, B., Joseph, S., Jacob, G., & Lukose, A. (2024). A bibliometric analysis of the trends and impact of neuromarketing research: Peering into the consumer brain. *Cureus, 16*(9), e69314. https://doi.org/10.7759/cureus.69314

MacKenzie, S. B., & Lutz, R. J. (1989). An empirical examination of the structural antecedents of attitude toward the ad. *Journal of Marketing, 53*(2), 48–65.

Maheshwari, K. S., & Umamaheswari, R. (2025). The role of eye tracking in neuromarketing: Insights into consumer attention and behaviour. *International Journal of Environmental Sciences, 11*(23s), 1712–1722. https://doi.org/10.64252/jaq5z392

Ondrijova, I., Tomkova, A., & Pethö, T. (2024). Utilizing eye-tracking in advertising: Preliminary findings. *Journal of Marketing Research and Case Studies*, 2024, Article ID 404100.

Plassmann, H., Ramsøy, T. Z., & Milosavljevic, M. (2015). Branding the brain: A critical review and outlook. *Journal of Consumer Psychology, 25*(1), 18–36.

Plassmann, H., Venkatraman, V., Huettel, S., & Yoon, C. (2015). Consumer neuroscience:

Applications, challenges, and possible solutions. *Journal of Marketing Research, 52*(4), 427–435. https://doi.org/10.1509/jmr.14.0048

Ruppenthal, T., & Schweers, N. (2024). Eye tracking as an instrument in consumer research to investigate food from a marketing perspective: A bibliometric and visual analysis. *Journal of Theoretical and Applied Electronic Commerce Research, 19*(2), 1095–1117. https://doi.org/10.3390/jtaer19020057

Shareef, M. A., Mukerji, B., Dwivedi, Y. K., Rana, N. P., & Islam, R. (2019). Social media marketing: Comparative effect of advertisement sources. *Journal of Retailing and Consumer Services, 46*, 58–69.

Sharma, A., Mithas, S., & Kankanhalli, A. (2014). Transforming decision-making processes. *MIS Quarterly, 38*(2), 433–459.

Tajvidi, R., & Karami, A. (2021). The effect of social media on firm performance. *Journal of Business Research, 122*, 121–132.

Trainor, K. J., Andzulis, J., Rapp, A., & Agnihotri, R. (2014). Social media technology usage and customer relationship performance. *Journal of Business Research, 67*(6), 1201–1208.

Trainor, K. J., Andzulis, J., Rapp, A., & Agnihotri, R. (2014). Social media technology usage and customer relationship performance. *Journal of Business Research, 67*(6), 1201–1208.

Venkatraman, V., Dimoka, A., Pavlou, P. A., Vo, K., Hampton, W., Bollinger, B., Hershfield, H. E., Ishihara, M., & Winer, R. S. (2015). Predicting advertising success beyond traditional measures: New insights from neurophysiological methods and market response modeling. *Journal of Marketing Research, 52*(4), 436–452. https://doi.org/10.1509/jmr.13.0593

Wedel, M., & Kannan, P. K. (2016). Marketing analytics for data-rich environments. *Journal of Marketing, 80*(6), 97–121.

Wedel, M., & Pieters, R. (2008). *Visual marketing: From attention to action*. Lawrence Erlbaum Associates.

Wedel, M., & Pieters, R. (2008). *Visual marketing: From attention to action*. Lawrence Erlbaum Associates.

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RESEARCH ARTICLE

Environmental Consciousness and Green Purchase Behaviour: A Study of Consumers Attitudes towards Eco-Friendly Home Appliances

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ABSTRACT

Today, businesses and consumers face a significant challenge in protecting and conserving the earth's natural resources and environment. Both organizations and consumers have become increasingly conscious of environmental issues and recognize that their production and consumption decisions have a direct impact on the natural environment. Green marketing has the potential not only to transform the existing competitive practices of businesses but also to create a distinctive competitive advantage by addressing the environmental needs and expectations of customers. In recent years, consumers have shown a growing preference for purchasing products from companies that demonstrate social and environmental responsibility. To minimize consumers' perceived risk and strengthen their trust, companies need to provide adequate and reliable information about their products, enabling consumers to evaluate and compare the environmental performance and functionality of products offered by different companies. The primary objective of this study is to gain a comprehensive understanding of the factors influencing consumers' green product purchase behaviour, environmental commitment, and environmental attitude, particularly in relation to the purchase of home appliances (white goods) in Tamil Nadu, India. The study examines 11 dimensions to assess customers' environmental attitude and buying behaviour towards green products with specific reference to home appliances. These dimensions include Environmental Attitude, Commitment towards Environment, Green Brand Image, Green Brand Satisfaction, Green Brand Trust, Green Brand Awareness, Green Brand Preference, Green Product Buying Behaviour, Personal Profile of the Respondents, and Level of Awareness towards Star Rating of Products, along with the other dimension included in the study framework. The study has formulated five objectives and developed ten hypotheses, along with one additional hypothesis concerning the personal profiles of the respondents. The geographical scope of the study is restricted to Tier-II cities in Tamil Nadu, specifically Coimbatore, Tiruchirappalli, Salem, and Madurai, which have been selected as the population areas for the study.

Keywords: *Green marketing, Environmental Attitude, Green Brand Image, Green brand satisfaction, Green brand trust, Green brand awareness, Green brand preference, Green product buying behavior.*

INTRODUCTION

The acceleration of economic development over recent decades has been accompanied by a substantial increase in global consumption, resulting in excessive utilization of natural resources and contributing significantly to environmental degradation. The continuation of unsustainable patterns of production and

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consumption is likely to intensify the severity of environmental challenges. Major consequences of environmental deterioration include global warming, depletion of the stratospheric ozone layer, contamination of marine and freshwater resources, noise and light pollution, acid rain and desertification. Consequently, growing recognition of climate change and environmental degradation has placed environmental protection and sustainable development at the centre of contemporary business and consumer discourse.

In response to these environmental challenges, business organizations have increasingly sought to incorporate environmental considerations into their marketing strategies and operational practices. Consequently, the concept of "greening" has gained considerable importance among managers and marketing professionals. The increasing environmental consciousness observed among consumers has resulted in greater willingness to adopt environmentally responsible lifestyles and consumption practices. Such behavioural changes have created new opportunities for organizations that incorporate environmental responsibility into their value propositions.

Consumer preference for a particular brand is an important determinant of its competitive position and market differentiation. This significance is equally applicable to green products and green innovations across consumer goods, industrial products and services. The increasing environmental impact of industrial production has encouraged societies worldwide to pay greater attention to ecological issues, thereby compelling organizations to recognize environmental responsibility as an important component of their business strategies. Environmental investments can consequently provide organizations with opportunities to achieve both ecological responsibility and competitive advantage. As a result, several organizations have moved beyond basic environmental compliance and have incorporated eco-efficiency into their broader business operations.

PURPOSE OF THE STUDY

The primary purpose of this study was to develop an in-depth understanding of what factors influence consumers' green purchase behavior and their commitment and attitude towards environment that trigger consumers green purchasing in Tamilnadu, India. While most of the behavioral theories have been developed and tested in Western countries, particularly in the United States, relatively little attention has been devoted to investigating their validity in other cultural settings. Therefore, this study also took into consideration, that what Indian consumers perspectives towards environment attitude, commitment and belief. This was an important factor because while consumers in general are concerned about the environment, green purchase behavior may vary from country to country.

NEED FOR THE STUDY

Today, the green economy is a billion-dollar sector that includes everything from eco-friendly and green lifestyle products, organic agriculture, renewable energy and clean technology, water and waste management, to natural resource and land management. Due to the challenges of global warming, nations and people today have an all-time high concern for environmental protection. Hence, a new form of business has emerged: green business, which operates by practising a green philosophy. A green business strategy is no longer an option; the future depends on it. To gain a competitive advantage and ensure sustainable growth, companies today place socially responsible strategies at the top of their agendas.Many research findings support the idea of green marketing and state that customers today are willing to pay more for environmentally friendly products. Green marketing adds credibility to companies that practise a green philosophy. Furthermore, these companies can protect themselves from imitators for a sufficient period to ensure adequate returns on their investments.

IMPORTANCE OF THE STUDY

Today, environmental consciousness is not only an ideology held by activists but also a matter of market competition that influences consumer behaviour. The green vision is a reality and needs to be understood more functionally to help marketers develop strategies aimed at meeting the needs of green consumers. As the Indian market for green products continues to grow, understanding the factors that influence Indian consumers to purchase environmentally friendly or green home appliance products is crucial for businesses targeting green consumers. This study contributes to the understanding of green purchase behaviour among consumers and represents a first step towards promoting green consumption in Tamil Nadu, India. From a marketing perspective, it is important to identify the underlying factors that influence consumers' green purchase behaviour so that marketers can develop appropriate green marketing strategies to meet the needs of green consumers. The findings of this study can also help the Indian government develop appropriate policies to promote environmentally responsible consumption behaviours. Such policies could minimise the direct and indirect impacts of individual consumption on environmental degradation, particularly in the context of urbanisation and changing lifestyles in India. In the long run, the

findings of this study could contribute to reducing environmental problems in India and, subsequently, across the world.

PROBLEM IDENTIFICATION

Perceiving the catastrophic environmental pollution caused by industrial manufacturing activities around the world, consumers are increasingly becoming aware of environmental issues (Chen, 2011). As a result, companies are becoming more willing to consider environmental protection as part of their social responsibility. Environmental considerations have rapidly emerged as a mainstream concern due to global warming. Consequently, forward-thinking companies are increasingly seeking to take advantage of green business opportunities (Dwyer, 2009; Molina-Azorín, 2009).

In the environmental context, companies need to pay greater attention to green marketing, particularly in product categories such as information technology, home appliances, and electronic products (Kalafatis and Pollard, 1999). However, not all companies have sufficient capabilities to implement green marketing strategies. To implement green marketing successfully, companies should integrate green marketing concepts into all aspects of their routine marketing activities.

To gain a competitive advantage, companies should use green marketing strategies to enhance consumers' perceived quality and reduce their perceived risk in relation to environmental concerns (Chen, 2010). As green products become increasingly popular in the market, green marketing activities are also gaining importance.

There are five reasons for companies to adopt green marketing (Chen, 2008):

1. Enhancing corporate image.
2. Complying with environmental trends.
3. Taking advantage of green business opportunities.
4. Obtaining a competitive advantage.
5. Increasing product value.

Furthermore, adopting green marketing can enhance customer trust, satisfaction, awareness, and brand image. Although previous research has highlighted related issues, this study attempts to explore the impact of customers' environmental attitudes on green purchasing behaviour, focusing on green brand image, green brand trust, green brand satisfaction, and green brand awareness.

RESEARCH GAP

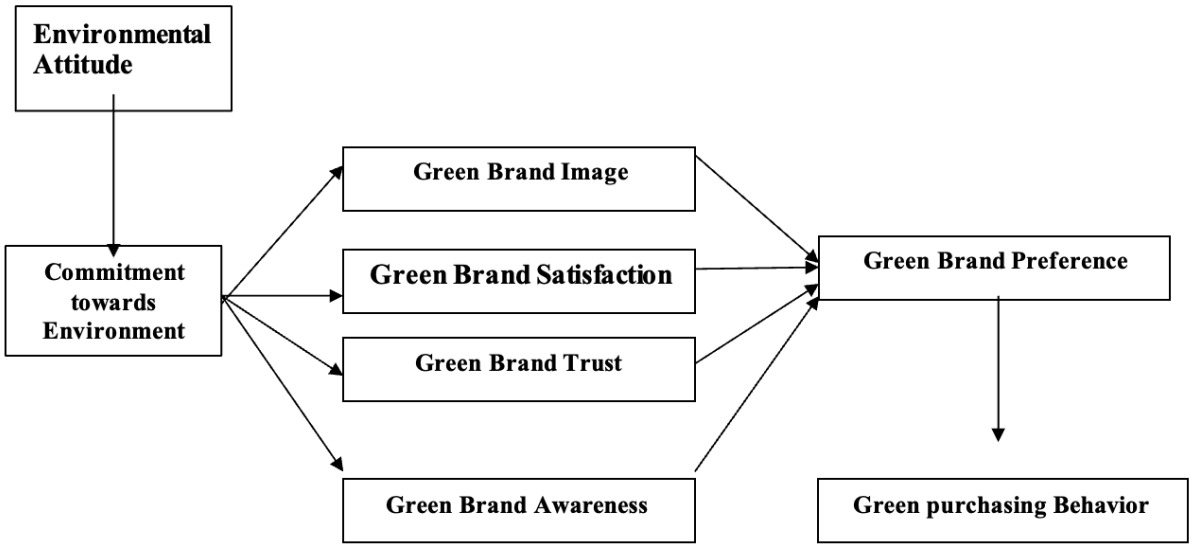
This study aims to address the existing research gap. Many previous studies have focused on the green strategies adopted by manufacturers to predict brand equity, determine whether they have achieved a competitive advantage, or assess whether they have increased their customer base. However, this study adopts a different perspective by examining whether customers possess the appropriate environmental attitudes and levels of commitment. Based on consumers' levels of environmental commitment, this research examines green brand image, green brand trust, green brand satisfaction, and green brand awareness. It also investigates consumer green brand preference based on environmental attitudes and the green strategies adopted by manufacturers. Finally, the study identifies whether green brand preference influences green purchasing behaviour. The uniqueness of this study lies in its integration of novel constructs, including environmental attitude, green strategies, and green brand preference, into a comprehensive framework to predict green purchasing behaviour.

THEORETICAL FRAMEWORK

The proposed conceptual framework assumes a positive relationship between green brand preference, the dependent variable, and four other mediating variables. Green brand preference indicates the extent to which consumers' perceptions of a brand influence their choice (Gunasti and Ross, 2010). The first variable is **green brand image**, which refers to a set of perceptions and associations in the consumer's mind that are linked to a particular offering (Keller, 1993; Cretu and Brodie, 2007; Padgett and Allen, 1997; Chen, 2009). The second variable is **green brand satisfaction**. Satisfaction can be defined as the level of pleasure consumers experience after consumption when their desires are fulfilled (Oliver, 1996; Paulssen and Birk, 2007; Ruyter and Bloemer, 1999). Accordingly, Chen (2009) defined green satisfaction as the fulfilment of customers' environmental expectations and green needs. The third variable is **green brand trust**, which refers to the confidence that another party will behave according to one's expectations (Hart and Saunders, 1997). Trust is based on three main beliefs: ability, benevolence, and integrity (Blau, 1964; Schurr and Ozanne, 1985). Therefore, trust can significantly influence consumers' purchasing decisions (Gefen and Straub, 2004). Chen (2009) linked these definitions to a brand's environmental performance to establish the concept of green trust. Finally, **green brand awareness** refers to consumers' ability to recognise and recall a brand as an environmentally friendly brand based on its green activities and associated attributes. Environmental attitude and environmental commitment are considered the input dimensions of the proposed conceptual

framework. These dimensions are expected to influence consumers' perceptions of green brands and, consequently, their green brand preferences.

Figure 1: Research Model



The above mentioned model consists of three stages. The stage I consists of respondents perception towards environment, and their commitment toward environment. The stage II consists of dimensions factors affecting green brand preference. The dimensions are Green Brand Image, Green Brand Satisfaction, Green Brand Trust and Green Brand Awareness. The stage III consists of two dimensions Green Brand Preference and Green Purchase behaviour. The model is developed based on the Keller (1993) consumer based brand equity and Chen (2009) variables considered to measure and build green brand equity.The research model is unique in the way that, both the above mentioned model measures only brand equity, but this research model measure green brand preference by including awareness and commitment dimensions of environment. Thus the newly developed research model included environment and measures green brand preference rather than brand equity. Based on the model, the researcher suggest that depend on the environment commitment level of the customers green brandimage,greenbrandtrust,greenbrandsatisfact ionandgreenbrandawarenesswillchange and vary. The proposed research model assumed positive relationship between all the dimensions, and only formative paths was considered for the study.

OBJECTIVES OF THE STUDY

1. To study the environmental attitudes and commitment levels of the selected respondents and examine their association with the respondents' personal profiles.

2. To identify the various green marketing initiatives adopted by selected manufacturers of white goods and home appliances.

3. To analyse the environmental commitment levels of customers and examine their impact on green marketing initiatives related to selected white goods and home appliances.

4. To identify the relationship between green marketing initiatives and green brand preference for white goods and home appliances.

5. To examine whether green brand preference influences the purchasing behaviour of consumers regarding white goods and home appliances.

Hypotheses

H1: Environmental attitude of customers has a positive and significant impact on their commitment towards the environment.

H2: Environmental commitment has a positive and significant impact on green brand image.

H3: Environmental commitment has a positive and significant impact on green brand satisfaction.

H4: Environmental commitment has a positive and significant impact on green brand trust.

H5: Environmental commitment has a positive and significant impact on green brand awareness.

H6: Green brand image has a positive and significant impact on green brand preference.

H7: Green brand satisfaction has a positive and significant impact on green brand preference.

H8: Green brand trust has a positive and significant impact on green brand preference.

H9: Green brand awareness has a positive and significant impact on green brand preference.

H10: Green brand preference has a positive and significant impact on green purchasing behaviour.

Methodology

The study is descriptive, deductive, and applied research aimed at proposing solutions for corporate branding. It follows a quantitative research paradigm, using a large sample and hypothesis testing. The study is cross-sectional, as data were collected once through a structured questionnaire to examine factors influencing brands from the consumer perspective.

The study covered Tier-II cities in Tamil Nadu, particularly Coimbatore, Tiruchirappalli, and Madurai. The sample comprised customers who purchased any one of the selected white home appliances—refrigerator, washing machine, or air conditioner—during January–April 2016 and considered energy efficiency, environmental friendliness, and environmental care as important purchase criteria.

Data were collected using a structured questionnaire from 200 selected customers in each city through judgment sampling at leading shopping malls and authorized sales outlets. Of the 600 questionnaires distributed, 593 were returned and 570 were usable, resulting in a final sample of 570 respondents.

Most questionnaire items were adapted from Chen (2009), with additional and modified items developed to suit the research objectives and target respondents. A five-point Likert scale, ranging from strongly disagree (1) to strongly agree (5), was used. A pilot study with 30 respondents was conducted to assess understanding, following which unclear and similar-response items were modified or removed.

The study used both primary and secondary data. The primary data were collected through a structured questionnaire comprising two parts: personal details of respondents and eight dimensions related to the study. The eight dimensions were Environmental Attitude, Commitment towards Environment, Green Brand Awareness, Green Brand Image, Green Brand Satisfaction, Green Brand Trust, Green Brand Preference, and Green Purchasing Behaviour. Secondary data were obtained from journals, magazines, books, research journals, and articles published by manufacturers.

Figure 2: Modeling Green Brand Preference and Green Product Buying Behaviour Based On Green Brand Image, Green Brand Satisfaction, Green Brand Trust, Green Brand Awareness, And Environmental Attitude

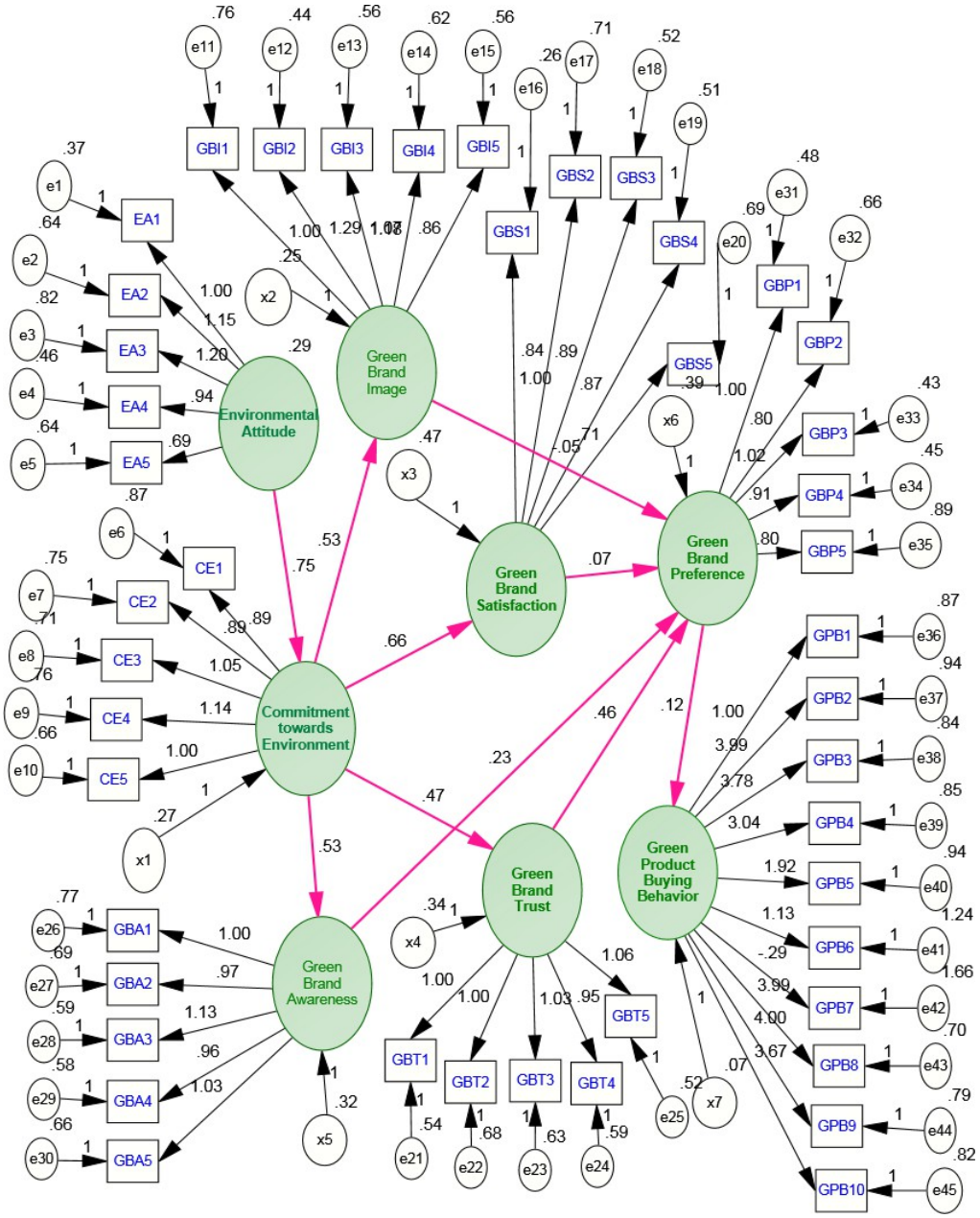


Table 1: Regression Weights:

Hypothesis	Hypothesis Statement	Proposed Effect	Estimate	S.E.	C.R.	P-value
H1	Environmental attitude of customers has a positive and significant impact on commitment towards the environment.	+	0.755	0.085	8.904	***
H2	Environmental commitment has a positive and significant impact on green brand image.	+	0.528	0.062	8.478	***
H3	Environmental commitment has a positive and significant impact on green brand satisfaction.	+	0.656	0.069	9.514	***
H4	Environmental commitment has a positive and significant impact on green brand trust.	+	0.475	0.060	7.913	***
H5	Environmental commitment has a positive and significant impact on green brand awareness.	+	0.530	0.065	8.132	***
H6	Green brand image has a positive and significant impact on green brand preference.	+	-0.051	0.065	-0.795	0.427
H7	Green brand satisfaction has a positive and significant impact on green brand preference.	+	0.066	0.046	1.433	0.152
H8	Green brand trust has a positive and significant impact on green brand preference.	+	0.464	0.065	7.126	***
H9	Green brand awareness has a positive and significant impact on green brand preference.	+	0.225	0.060	3.727	***
H10	Green brand preference has a positive and significant impact on green product buying behaviour.	+	0.121	0.026	4.681	***

The result of model is shown in the above table.The hypotheses show that all the hypotheses were formulated positive and proposed effect. Among the ten hypotheses formulatedandtested,8hypothesesweresupported andtheremaining2hypotheses(H6&H7) were not supported based on the path loading. The result explains that of environment commitment increases, Green Brand Image, Trust, Satisfaction and Awareness increases to optimum level. At the same time, green brand image creates negative influence towards green brand preference. Green brand satisfaction creates positive impact on Green brand preference, but it is not significant. Green brand trust and awareness creates significant impact on Green Brand Preference. The model conforms that if green brand preference increases by one unit, Green Product Buying Behaviour increases by .121 units.

ANOVA

Hypothesis

There is no significant relationship between the monthly income of the respondents and the dimensions related to the study.

Table 2: Relationship between the monthly income of the respondents

Dimensions Related to the Study	Sources of Variation	Sum of Squares	df	Mean Square	F	Sig.
Environmental Attitude	Between Groups	4.042	3	1.347	2.706	**.045**
	Within Groups	281.783	566	.498		
	Total	285.825	569			
Commitment towards Environment	Between Groups	1.579	3	.526	.744	.526
	Within Groups	400.220	566	.707		
	Total	401.798	569			
Green Brand Awareness	Between Groups	1.694	3	.565	.816	.486
	Within Groups	391.957	566	.693		
	Total	393.651	569			
Green Brand Image	Between Groups	1.092	3	.364	.593	.620
	Within Groups	347.275	566	.614		
	Total	348.367	569			
Green Brand Satisfaction	Between Groups	.363	3	.121	.180	.910
	Within Groups	380.661	566	.673		
	Total	381.025	569			
Green Brand Trust	Between Groups	2.026	3	.675	1.051	.369
	Within Groups	363.546	566	.642		
	Total	365.572	569			

Green Brand Preference	Between Groups	3.931	3	1.310	2.022	.110
	Within Groups	366.736	566	.648		
	Total	370.667	569			
Green Product Buying Behaviour	Between Groups	1.388	3	.463	.716	.543
	Within Groups	365.868	566	.646		
	Total	367.256	569			

The above table shows the results of significant relationship between monthly income of the respondents and the dimensions Environmental Attitude, Commitment towards Environment, Green Brand Awareness, Green Brand Image, Green Brand Satisfaction, Green Brand Trust, Green Brand Preference, and Green Product Buying Behaviour. Based on the mean square value, F value, and Significant value the significant relationship between the analyzing dimensions and dependent dimensions will be confirmed. The significance value of the customer environmental attitude is (.045), which is less than the required criteria ensure the significant relationship between environmental attitudes and monthly income of the respondents.

The significant value of the remaining dimensions are above the required criteria, which shows that there is no significant relationship between monthly income of the respondents and Commitment towards Environment, Green Brand Awareness, Green Brand Image, Green Brand Satisfaction, Green Brand Trust, Green Brand Preference, and Green Product Buying Behaviour.

Hierarchical Regression Incremental Power of Each Predictor on Green Purchasing Behaviour

Table 3: Model Summary

Step	Predictors	R^2	ΔR^2	F of R^2 Δ	Sig F Change
Step 1	Environmental Attitude	.046	.046	27.608	.000
Step 2	Environmental Attitude Commitment towards Environment	.051	.005	2.975	.085
Step 3	Environmental Attitude Commitment towards Environment Green Brand Awareness	.098	.047	29.584	.000
Step 4	Environmental Attitude Commitment towards Environment Green Brand Awareness Green Brand Image	.113	.015	9.449	.002
Step 5	Environmental Attitude Commitment towards Environment Green Brand Awareness Green Brand Image Green Brand Satisfaction	.114	.001	.646	.422
Step 6	Environmental Attitude Commitment towards Environment Green Brand Awareness Green Brand Image Green Brand Satisfaction Green Brand Trust	.128	.014	9.001	.003
Step 7	Environmental Attitude Commitment towards Environment Green Brand Awareness Green Brand Image Green Brand Satisfaction Green Brand Trust Green Brand Preference	.190	.062	43.211	.000

Hierarchical Regression Analysis

The model summary table presents the results of the hierarchical regression analysis, which examines the contribution of each independent variable to predicting green product buying behaviour.

Step 1: In the first step of the hierarchical regression analysis, environmental attitude explains 4.6% of the variance in green product buying behaviour. The F-value is 27.608, indicating that the regression model is statistically significant.

Step 2: In the second step, environmental attitude and commitment towards the environment jointly explain 5.1% of the variance in green product buying behaviour. The change in R-squared compared with Step 1 is approximately 0.5 percentage points. The F-value for the change in R-squared is 2.975, indicating that the additional contribution is statistically significant only if the corresponding p-value is below the chosen significance level. The reported significance level should therefore be verified.

Step 3: In the third step, green brand awareness is added to environmental attitude and commitment towards the environment. The model continues to explain approximately 5.1% of the variance in green product buying behaviour. The reported F-value for the change in R-squared is 29.584, with a significance value of 0.000 ($p < 0.001$). However, the reported R-squared and F-change values should be checked against the original statistical output for consistency.

Step 4: In the fourth step, green brand image is added to the model. The variables collectively explain 11.3% of the variance in green product buying behaviour. The reported F-value for the change in R-squared is 9.449, with a significance value of 0.001. This indicates that adding green brand image significantly improves the model's predictive ability.

Step 5: In the fifth step, green brand satisfaction is added to the model. The model explains 11.4% of the variance in green product buying behaviour, representing an increase of approximately 0.1 percentage points. The F-value for the change in R-squared is 0.646. Although the reported significance level is stated as 0.001, this appears inconsistent with the F-value and should be verified using the original statistical output before drawing a conclusion about statistical significance.

Step 6: In the sixth step, green brand trust is added to the model. The model explains 12.8% of the variance in green product buying behaviour, representing an increase of approximately 1.4 percentage points. The reported F-value for the change in R-squared is 9.001, with a significance value of 0.001. This suggests that green brand trust makes a statistically significant additional contribution to the model.

Step 7: In the final step, green brand preference is added to the model alongside environmental attitude, commitment towards the environment, green brand awareness, green brand image, green brand satisfaction, and green brand trust. The final model explains 19.0% of the variance in green product buying behaviour. The reported F-value for the change in R-squared is 43.211, with a significance value of 0.001. This indicates that green brand preference makes a statistically significant contribution to the prediction of green product buying behaviour.

Overall Interpretation: The hierarchical regression analysis indicates that the explanatory power of the model increases as additional variables are introduced. The final model explains 19.0% of the variance in green product buying behaviour. Green brand preference appears to make an important additional contribution to the model, highlighting its relevance in understanding consumers' green purchasing decisions.

RESULT AND DISCUSSIONS

The ANOVA test results indicate that the monthly income of the respondents has a significant relationship with environmental attitude. However, monthly income does not have a significant relationship with the other dimensions considered in the study. These dimensions include commitment towards the environment, green brand awareness, green brand image, green brand satisfaction, green brand trust, green brand preference, and green product buying behaviour.

The correlation analysis reveals that environmental attitude, commitment towards the environment, green brand awareness, green brand image, green brand satisfaction, green brand trust, and green brand preference are positively and significantly correlated with green product buying behaviour.

The hierarchical regression results indicate changes in the R-squared value as each dimension is added to the model to predict green product buying behaviour. The findings suggest that the dimensions considered in the study are important predictors of green product buying behaviour. However, the regression coefficients indicate that environmental commitment has a negative influence on green product buying behaviour.

Among the dimensions of green marketing strategies, green brand satisfaction also has a negative influence on green product buying behaviour. Of all the dimensions considered in the study, green brand preference is the strongest predictor of green product buying behaviour, followed by green brand awareness.

The stepwise regression results based on gender indicate an association between gender and the green marketing strategies adopted by home appliance manufacturers. The findings further confirm that green brand preference is the strongest predictor of green product buying behaviour for both genders, whereas green brand satisfaction has a negative influence on green product buying behaviour.

Table 4: Hypotheses Result

Hypotheses Statements	Result
H1: Environmental attitude of customers has a positive and significant impact on their commitment towards the environment.	Supported
H2: Environmental commitment has a positive and significant impact on green brand image.	Supported
H3: Environmental commitment has a positive and significant impact on green brand satisfaction.	Supported

H4: Environmental commitment has a positive and significant impact on green brand trust.	Supported
H5: Environmental commitment has a positive and significant impact on green brand awareness.	Supported
H6: Green brand image has a positive and significant impact on green brand preference.	Not Supported
H7: Green brand satisfaction has a positive and significant impact on green brand preference.	Not Supported
H8: Green brand trust has a positive and significant impact on green brand preference.	Supported
H9: Green brand awareness has a positive and significant impact on green brand preference.	Supported
H10: Green brand preference has a positive and significant impact on green product buying behaviour.	Supported

Based on the path loading and significant value, out of 10 hypotheses formulated in the research model shows that 8 hypotheses were accepted and the remaining two hypotheses are rejected.

Implications of the study

The study has highlighted important aspects of consumer purchasing patterns and demonstrated that consumer preferences for environmentally friendly products can be influenced by effective green marketing strategies.

Several important implications for green marketing strategies can be drawn from the findings of the present research. To gain a green competitive advantage and achieve business success, business executives and marketers should ensure that sustainable green marketing strategies are developed and implemented in home appliance manufacturing companies.

Business executives and marketers should emphasise the importance of environmental protection in India. Managers should organise workshops and seminars to educate internal and external stakeholders about environmental protection and sustainable consumption practices.

Various exhibitions and fairs should be organised in collaboration with non-governmental organisations (NGOs) to educate the public about the different green products currently available in the market and the benefits associated with environmentally responsible purchasing behaviour.

Another significant implication of the study concerns the importance of eco-labels, particularly star ratings, in influencing green purchasing behaviour. Eco-labels provide valuable information that enables consumers to make informed purchasing decisions.

Therefore, marketers should emphasise green product strategies and consider eco-labels an essential marketing tool for promoting green consumption. The findings of the present study provide empirical evidence that green labelling, star ratings, and green marketing strategies positively influence consumer purchasing behaviour.

Similarly, business executives should ensure that eco-labels are clear, comprehensible, and easy to interpret. The type, format, and presentation of information provided on eco-labels and star ratings should be designed to help consumers understand product attributes and make informed purchasing decisions. The survey findings indicate a positive association between consumers' willingness to purchase products from environmentally responsible companies and the ease of understanding eco-labels and star ratings.

CONCLUSION

Now is the right time to adopt green marketing globally. Significant changes in the business world could occur if all nations implement strict environmental regulations, as green marketing is essential to protecting the planet from pollution.

From a business perspective, a successful marketer is one who not only convinces consumers to purchase a product but also encourages them to participate in promoting it. Green marketing should not be considered merely another marketing approach; instead, it should be pursued with greater commitment because of its environmental and social significance.

With the threat of global warming becoming increasingly serious, green marketing must become the norm rather than an exception or a passing trend. The recycling of paper, metals, plastics, and other materials in safe and environmentally responsible ways should become more systematic and widespread. Similarly, the use of energy-efficient home appliances and other electrical goods should become standard practice.

Marketers also have a responsibility to educate consumers about the need for and benefits of green products compared with conventional alternatives. Furthermore, consumers, industrial buyers, and suppliers should collectively exert pressure on businesses to minimise their negative environmental impacts and adopt environmentally responsible practices.

Green marketing assumes even greater importance and relevance in developing countries such as India, where sustainable business practices and environmentally responsible consumption can contribute significantly to

environmental protection and long-term development.

Future study

This study focuses on the green marketing initiatives adopted by home appliance manufacturers (white goods). Therefore, future studies could focus on other industries or countries to compare their findings with those of the present study.

This study tested the proposed hypotheses using a questionnaire survey, which provided only cross-sectional data. Consequently, it could not examine the dynamic changes in green core competencies during the development of home appliance manufacturers through longitudinal data. Therefore, future research could adopt a longitudinal approach to investigate changes in customers' perceptions of the green marketing initiatives implemented by home appliance manufacturers over time.

Finally, this study hopes that its findings will be beneficial to managers, researchers, and government authorities. It also aims to contribute to relevant academic studies and serve as a reference for future research in the field of green marketing and sustainable consumer behaviour.

Conflict of interest: None.

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REFERENCES

Aaker, D. A., & Joachimsthaler, E. (2000). *Brand leadership*. The Free Press.

Abraham, N. (2011). The apparel aftermarket in India: A case study focusing on reverse logistics. *Journal of Fashion Marketing and Management, 15*(2), 211–227.

Ajzen, I. (1988). *Attitudes, personality, and behavior*. Dorsey Press.

Alba, J. W., & Hutchinson, J. W. (1987). Dimensions of consumer expertise. *Journal of Consumer Research, 13*(4), 411–454. https://doi.org/10.1086/209080

Albayrak, T., Caber, M., Moutinho, L., & Herstein, R. (2011). The influence of skepticism on green purchase behavior. *International Journal of Business and Social Science, 2*(13), 189–197. http://ijbssnet.com

AbdusSamad, K., & Thilagavathy, S. (n.d.). *A tentative study on consumers' perception and image on green hotels within Trichy district* (pp. 239–244). *International Journal of Management, 6*. https://www.academia.edu/download/40875663/A_TENTATIVE_STUDY_ON_CONSUMERS_PERCEPTION_AND_IMAGE_ON_GREEN_HOTELS_WITHIN_TRICHY_DISTRICT.pdf

CBS News. (2008, May 18). *A closer look at "green" products: Manufacturers are making more environmentally friendly products, but not all stand up to the test*. http://www.cbsnews.com/stories/2008/05/18/eveningnews/main4105507.shtml

CBO. (2006). LCBO bottle deposit system starts in February. CTV News. http://www.ctv.ca/servlet/ArticleNews/story/CTVNews/20061201/lcbo_deposits_061201/20061201?hub=TorontoHome

Diamantopoulos, A., Bohlen, G. M., & Schlegelmilch, B. B. (1994). Predicting green purchasing decisions from measures of environmental consciousness: A two-sample comparison. In *Conference proceedings of the Marketing Education Group* (pp. 252–261). Coleraine.

Gilg, A., Barr, S., & Ford, N. (2005). Green consumption or sustainable lifestyles? Identifying the sustainable consumer. *Futures, 37*(6), 481–504. https://doi.org/10.1016/j.futures.2004.10.016

Polonsky, M. J. (1994). Green marketing regulation in the US and Australia: The Australian checklist. *Greener Management International, 5*, 44–53.

Wüstenhagen, R., & Bilharz, M. (2006). Green energy market development in Germany: Effective public policy and emerging customer demand. *Energy Policy, 34*(13), 1681–1696.

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RESEARCH ARTICLE

Situation in India in Absence of the Codified Trade Secret Law

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ABSTRACT

India has separate laws for patents, copyright, trademarks and designs. It has no separate law for trade secrets. This paper looks at what happens because of this gap. It explains the laws that are used today to protect trade secrets. These are contract law, the rule of confidence made by judges, civil court procedure, criminal law, the IT Act and copyright law. Each of them covers only a part of the problem. The paper then shows how this affects businesses, employees, important sectors and India's trade with other countries. Indian law already has clear rules for government secrets, personal data and stock market information. Business secrets do not have such rules. From 15 July 2026, the India–UK trade agreement requires India to protect secret business information. The Law Commission prepared a draft Bill in 2024, but Parliament has not passed it. The paper finds that the present system is unclear, costly and uneven. It ends with suggestions for now and for a future law.

***Keywords*:** *Trade secrets; breach of confidence; Section 27 Indian Contract Act; Information Technology Act; India–UK CETA; Law Commission 289th Report.*

INTRODUCTION

A business often earns money from what it knows. This may be a formula, a computer code, a list of customers or a way of making a product. This knowledge is useful only as long as it stays secret. Such knowledge is called a trade secret.

The United States, the European Union, the United Kingdom, Japan and China have special rules for trade secrets (Defend Trade Secrets Act of 2016, 2016; Directive [EU] 2016/943, 2016; Trade Secrets [Enforcement, etc.] Regulations 2018, 2018). India does not. India is a member of the World Trade Organization. So, it must protect "undisclosed information" under Article 39 of the TRIPS Agreement (Agreement on Trade-Related Aspects of Intellectual Property Rights [TRIPS Agreement], 1994). India has chosen to do this without a separate law.

This paper asks simple questions. What is the position in India today without such a law? Who is protected, and how well? Who suffers because of the gaps?

The paper is based on a study of laws, court decisions, the Law Commission's 289th Report, trade agreements and other writings.

WHAT IS A TRADE SECRET?

Article 39(2) of TRIPS gives three conditions. The information must be secret. It must have business value because it is secret. And the owner must take reasonable steps to keep it secret (TRIPS Agreement, 1994, art. 39[2]). Indian courts follow the same idea. The Delhi High Court has said that a trade secret may be a formula, technical know-how or a special way of doing business that others do not know (American Express Bank Ltd. v. Priya Puri, 2006). The Bombay High Court has given some tests. It asks how many people know the information, what steps were taken to protect it, and how much it would cost others to develop it

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(Bombay Dyeing & Manufacturing Co. Ltd. v. Mehar Karan Singh, 2010).

A trade secret is different from a patent. It is not registered. It has no fixed time limit. It lasts as long as it stays secret. Also, the owner cannot stop a person who finds the same secret honestly, or by studying a product. So, the law does not treat a trade secret as property. It only protects it against wrongful acts. This is why trade secrets need their own rules.

India has not made such a law for a long time. After TRIPS, India changed its other IP laws. But it left trade secrets to judge-made law. In 2008, a draft National Innovation Bill had a chapter on secret information. It never reached Parliament (Department of Science and Technology, Government of India, 2008). One worry was that a strong law might stop employees from changing jobs freely (Raina, 2015). In 2017, the government asked the Law Commission to study the issue. The Commission gave its report in 2024.

HOW TRADE SECRETS ARE PROTECTED TODAY

Contract

Businesses first use written agreements. These include non-disclosure agreements and secrecy clauses in job contracts. If a person breaks such a clause, the owner can claim money. The owner can also ask the court to stop the person (Indian Contract Act, 1872, §§ 73–74; Specific Relief Act, 1963, §§ 38, 41–42).

But a contract binds only the people who sign it. Suppose an employee leaves and gives the secret to a rival company. The rival company did not sign the contract, so it is not bound. There is also Section 27 of the Contract Act. It says that an agreement which stops a person from doing a lawful job or business is void (Indian Contract Act, 1872, § 27). The Supreme Court has held that a clause which stops an employee from working after leaving the job is void. A clause that applies only during the job may be valid (Superintendence Co. of India (P) Ltd. v. Krishan Murgai, 1981; Niranjan Shankar Golikari v. Century Spinning & Manufacturing Co., 1967). So an employer cannot stop an ex-employee from joining a rival. It can only stop the ex-employee from using real secrets.

Breach of confidence

Sometimes there is no written contract. Then courts use a rule called "breach of confidence". This rule comes from English cases such as *Coco v. A.N. Clark* (Coco v. A.N. Clark [Engineers] Ltd., 1969). It means that a person who receives information in trust must not misuse it. The Delhi High Court used this rule in *John Richard Brady*. There, secret drawings were shared in trust and then used to build a rival machine (John Richard Brady v. Chemical Process Equipment Pvt. Ltd., 1987). The rule also applies to others who receive the information knowing that it is secret (Zee Telefilms Ltd. v. Sundial Communications Pvt. Ltd., 2003). But the rule is not fixed. Each judge applies it in his or her own way. There is no clear test and no clear rule on how much money to award.

Court procedure

Courts use the Code of Civil Procedure to protect secrets during a case. They can stop the other side from using the secret. They can send an officer to visit a place and collect evidence (Code of Civil Procedure, 1908, Order XXVI, Rule 9; Order XXXIX, Rules 1–2, 7). They can also accept documents in a sealed cover. They can allow only a small group of people to see secret papers. This group is called a "confidentiality club". The Delhi High Court's IPD Rules, 2022 allow such clubs (High Court of Delhi, 2022). But all courts in India do not follow the same practice. Also, the Commercial Courts Act, 2015 lists trademarks, copyright, patents and designs, but not trade secrets (Commercial Courts Act, 2015, § 2[1][c][xvii]).

Criminal law

The Bharatiya Nyaya Sanhita, 2023 punishes theft, cheating and criminal breach of trust (Bharatiya Nyaya Sanhita, 2023, §§ 2[21], 303, 314, 316, 318). But these crimes are about physical things that can be moved. The old Penal Code also said this (Indian Penal Code, 1860, § 22). Information is not a physical thing. If an employee steals a hard disk, it is theft. But if the employee only copies a formula and leaves the original, it may not be theft. There is no crime called "theft of trade secrets" in India. The US Trade Representative's 2025 report again pointed out this gap (Office of the United States Trade Representative [USTR], 2025); subsequent citations: (USTR, 2025).

The IT Act

The IT Act, 2000 punishes copying data from a computer without permission. It also punishes some leaks of secret records (Information Technology Act, 2000, §§ 43, 66, 72, 72A). This helps when a secret is taken from a computer. It does not help when a person remembers the secret or writes it on paper. The Act does not even use the words "trade secret".

Copyright and other laws

Copyright can protect computer code and some databases (Burlington Home Shopping Pvt. Ltd. v. Rajnish Chibber, 1995). But copyright protects only the form of expression. It does not protect

ideas or methods. A simple list also may not get copyright, because some creativity is needed (Eastern Book Co. v. D.B. Modak, 2008). The RTI Act and the Competition Act stop government bodies from disclosing trade secrets. But they give no remedy against a private person who steals them (Right to Information Act, 2005, § 8[1][d]; Competition Act, 2002, § 57).

Table 1: Summary

Law	What it covers	Main problems
Contract	Breaking secrecy agreements	Binds only those who sign; Section 27 stops non-compete clauses after the job
Breach of confidence	Information shared in trust	No clear test; no fixed remedy
Court procedure	Stay orders, evidence collection, sealed covers	Practice differs between courts; trade secrets not named in Commercial Courts Act
Criminal law (BNS)	Theft of physical items	Information is not a physical thing; no special crime
IT Act	Copying from computers	Does not cover secrets taken in other ways
Copyright, RTI, Competition Act	Code; protection from government disclosure	No protection for ideas; no remedy against private persons

A CLEAR CONTRAST

Indian law knows how to protect secret information when it wants to. The Official Secrets Act, 1923 protects government secrets. The Digital Personal Data Protection Act, 2023 protects personal data. It has clear duties, a Board and heavy fines. SEBI rules protect price-sensitive information about listed companies (Official Secrets Act, 1923, § 5; Digital Personal Data Protection Act, 2023, §§ 8, 33; SEBI [Prohibition of Insider Trading] Regulations, 2015, regs. 2[1][n], 3). Each of these laws says what is protected, who has duties, and what happens if the rules are broken. Today, a customer's phone number is protected by a special law. A company's secret formula is not.

EFFECTS OF THE PRESENT SITUATION

On businesses

The first problem is uncertainty. There is no fixed meaning of "trade secret" in law. There is no fixed meaning of "reasonable steps". So results differ. In *Cigma Events*, the Delhi High Court refused to help. The company had not shown that its customer information had special value (Cigma Events Pvt. Ltd. v. Deepak Gupta, 2024). In *Arjan Dugal*, the same court protected a list of about 6,000 customers. It allowed the list to be filed in a sealed cover (Arjan Dugal v. Shubham Gandhi, 2025; Mohini, 2025). A business cannot easily know whether its information will be protected.

The second problem is cost. The owner must file its case under many laws at the same time. It must also describe its secret clearly. Courts have refused help when the owner could not say exactly what the secret was (Ambiance India Pvt. Ltd. v. Naveen Jain, 2005; Venkateshwarlu Guduru v. Siddhardha De Bathula, 2025). Big companies can pay these costs. Small ones often cannot.

The third problem is delay. In *Navigators Logistics*, a company said its customer data was stolen. Its case was rejected in 2018. A larger bench brought it back only about six years later (Navigators Logistics Ltd. v. Kashif Qureshi, 2018). By then, the data was of little use.

The fourth problem is that wrongdoers are not afraid. There is no special crime, and courts rarely award money. Often, the worst result for a wrongdoer is a court order to stop. So companies try to protect themselves. They watch employees closely and add non-compete clauses that the law does not allow. This can go too far. In *UBS Business Solutions v. Nisheet Singh* (2026), an employer asked to search cloud accounts linked to an ex-employee. The Bombay High Court said no, because there was no link between those accounts and the employer's data (UBS Business Solutions v. Nisheet Singh, 2026; Parmaar, 2026).

On employees

Courts protect the right of employees to work. In *Varun Tyagi v. Daffodil Software* (2025), the Delhi High Court refused to enforce an unfair non-compete clause (Varun Tyagi v. Daffodil Software Pvt. Ltd., 2025). An employee's general

skill and knowledge are not trade secrets (American Express Bank Ltd. v. Priya Puri, 2006). But employees do not know this in advance. Wide clauses and legal notices can scare them from changing jobs. People who report wrongdoing, called whistleblowers, also have no clear protection. A clear law would help employees as much as employers.

On important sectors

IT companies handle data of foreign clients. They usually depend on contracts under foreign law, not Indian law. Medicine and farm chemical companies have the same problem for their know-how. Their test data is also handled by government policy, not by a clear law (TRIPS Agreement, 1994, art. 39[3]; Reddy & Sandhu, 2007). Start-ups and small businesses suffer the most. Their main assets are often ideas and data, and they cannot afford long cases. AI companies hold training data and models that can be copied in minutes. The Law Commission said that small businesses, start-ups and new technology are key reasons for a new law (Law Commission of India, 2024).

On proof and the courts

Misuse of a secret is usually hidden. So owners must depend on indirect and computer evidence. Such evidence must follow the rules for electronic records under the Bharatiya Sakshya Adhiniyam, 2023 (Bharatiya Sakshya Adhiniyam, 2023, §§ 61–63). It is also hard to prove how much loss was caused. There is no rule allowing the court to award a fair licence fee instead. Each court answers these basic questions in its own way.

INDIA AND THE WORLD

India has said that its judge-made law is enough to meet TRIPS. This view is possible, but it is now under pressure. The India–UK trade agreement came into force on 15 July 2026 (Press Information Bureau, Government of India, 2026). Its IP chapter requires India to protect secret business information from being taken, used or disclosed unlawfully. It still allows people to find the same secret honestly or by studying a product. It also requires courts to keep secrets safe during a case (Rana & Jafri, 2026). Such a promise is best kept through a clear Indian law. A clear law would also help bring foreign technology to India under programmes like Make in India.

Other countries show that these problems can be solved. The US law gives clear meanings, allows seizure of stolen material in serious cases, gives money for loss or a fair licence fee, and protects whistleblowers (Defend Trade Secrets Act of 2016, 2016, 18 U.S.C. §§ 1833[b], 1836[b], 1839). The EU law protects the right of workers to change jobs. It also requires courts to keep secrets safe during a case (Directive [EU] 2016/943, 2016, arts. 3–5, 9, 14).

THE LAW COMMISSION'S DRAFT BILL

In March 2024, the Law Commission gave its 289th Report. It included a draft Protection of Trade Secrets Bill, 2024 (Law Commission of India, 2024). The Bill uses the TRIPS meaning of trade secret. It says trade secrets are not property. It keeps an employee's general skill outside its scope. It allows people to find the same secret honestly. It protects whistleblowers. It allows courts to stop misuse and award money. It also asks courts to keep secrets safe during a case (Alliance Center for Intellectual Property Rights, 2025). More than two years later, the Bill has not been placed before Parliament (Aryan, 2026). So it is only a guide. It is not the law.

SUGGESTIONS

Steps for now

1. **Same court rules everywhere.** All High Courts should have rules for sealed documents and confidentiality clubs, like the Delhi High Court.
2. **Sealed details.** The owner should be allowed to describe the secret in general words in the case papers, and give full details in a sealed cover.
3. **Limits on searches.** Courts should allow a search only when there is a clear link with the secret, as in *UBS*. A neutral expert should carry it out.
4. **Better business habits.** Businesses should list and mark their secrets, limit who can see them and use clear agreements. Industry bodies can give model agreements to small businesses.

Steps for a new law

1. **Pass the Bill.** Parliament should pass the Bill, keeping in mind India's promise in the India–UK agreement.
2. **Explain "reasonable steps".** The law should give a simple list of steps that suits both big and small businesses.
3. **Clear court process and remedies.** The law should allow sealed details, limit unfair searches, and allow money based on loss, the wrongdoer's gain or a fair licence fee.
4. **Add trade secrets** to Section 2(1)(c)(xvii) of the Commercial Courts Act.
5. **Make theft of trade secrets a crime,** either in this law or in a separate law.

6. **Keep Section 27 as it is.** The law should say clearly that an employee's general skill and knowledge are free to use.

CONCLUSION

Today, trade secrets in India are protected only in part. They are protected only after the harm is done. And they are protected mainly for those who can pay for long court cases. Contract binds only those who sign it. Breach of confidence depends on the judge. Criminal law does not clearly cover information. The IT Act covers only computers. Copyright covers only the form of expression. Court practice differs from place to place.

Because of this, businesses face uncertainty, cost and delay. Employees face unclear threats. Small businesses are the least able to protect themselves. Through the India–UK agreement, India has now promised to protect secret business information. Indian law already protects government secrets, personal data and stock market information with clear rules. Business secrets deserve the same. The Law Commission has already prepared the draft. Now Parliament needs to act.

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BIBLIOGRAPHY

Statutes and International Instruments

The Bharatiya Nyaya Sanhita, 2023, No. 45, Acts of Parliament, 2023 (India).

The Commercial Courts Act, 2015, No. 4, Acts of Parliament, 2016 (India).

The Indian Contract Act, 1872, No. 9, Acts of Parliament, 1872 (India).

The Information Technology Act, 2000, No. 21, Acts of Parliament, 2000 (India).

Agreement on Trade-Related Aspects of Intellectual Property Rights, Apr. 15, 1994, 1869 U.N.T.S. 299.

Comprehensive Economic and Trade Agreement between India and the United Kingdom, ch. 13 (entered into force July 15, 2026).

Defend Trade Secrets Act of 2016, 18 U.S.C. § 1836 et seq.

Directive (EU) 2016/943 on the Protection of Trade Secrets, 2016 O.J. (L 157) 1.

Cases

American Express Bank Ltd. v. Priya Puri, (2006) 3 LLN 217 (Del. H.C.).

John Richard Brady v. Chemical Process Equipments Pvt. Ltd., AIR 1987 Del 372.

Niranjan Shankar Golikari v. Century Spinning & Manufacturing Co., AIR 1967 SC 1098.

Superintendence Co. of India (P) Ltd. v. Krishan Murgai, (1981) 2 SCC 246.

UBS Business Solutions v. Nisheet Singh (Bom. H.C. Mar. 30, 2026).

Zee Telefilms Ltd. v. Sundial Communications Pvt. Ltd., 2003 (5) Bom. C.R. 404 (Bom. H.C.).

Reports and Secondary Sources

Law Comm'n of India, Report No. 289, Trade Secrets and Economic Espionage (Mar. 2024).

Office of the U.S. Trade Representative, 2025 Special 301 Report (2025).

Mohini V, *Guarding the Invisible: Trade Secrets Law in India*, Managing IP (Oct. 16, 2025).

Chandni Raina, *Trade Secret Protection in India: The Policy Debate* (Ctr. for WTO Stud. 2015).

Vikrant Rana & Huda Jafri, *The India–UK CETA Comes into Force: The IP Framework Shaping a New Era of Bilateral Trade*, Bar & Bench (July 16, 2026).

REFERENCES

Alliance Center for Intellectual Property Rights. (2025, August 15). Secrets that facilitate trade: Navigating the trade secrets.

American Express Bank Ltd. v. Priya Puri, (2006) 3 LLN 217 (Delhi High Court).

Ambiance India Pvt. Ltd. v. Naveen Jain, 122 (2005) DLT 421 (Delhi High Court).

Agreement on Trade-Related Aspects of Intellectual Property Rights, Apr. 15, 1994, 1869 U.N.T.S. 299.

Arjan Dugal v. Shubham Gandhi (Delhi High Court 2025).

Aryan. (2026). Unguarded secrets: The case for a dedicated trade secret statute in India. IRCCL Blog.

Bharatiya Nyaya Sanhita, 2023 (India).

Bharatiya Sakshya Adhiniyam, 2023 (India).

Bombay Dyeing & Manufacturing Co. Ltd. v. Mehar Karan Singh, 2010 (112) Bom. L.R. 375 (Bombay High Court).

Burlington Home Shopping Pvt. Ltd. v. Rajnish Chibber, 61 (1995) DLT 6 (Delhi High Court).

Chandni Raina. (2015). Trade secret protection in India: The policy debate. Centre for WTO Studies.

Cigma Events Pvt. Ltd. v. Deepak Gupta (Delhi High Court 2024).
Code of Civil Procedure, 1908 (India).
Commercial Courts Act, 2015 (India).
Competition Act, 2002 (India).
Coco v. A.N. Clark (Engineers) Ltd., [1969] R.P.C. 41 (Ch.).
Defend Trade Secrets Act of 2016, 18 U.S.C. § 1836 et seq. (2016).
Department of Science and Technology, Government of India. (2008). Draft National Innovation Act, 2008.
Digital Personal Data Protection Act, 2023 (India).
Directive (EU) 2016/943 of the European Parliament and of the Council of 8 June 2016 on the protection of undisclosed know-how and business information (trade secrets) against their unlawful acquisition, use and disclosure, 2016 O.J. (L 157) 1.
Eastern Book Co. v. D.B. Modak, (2008) 1 SCC 1.
High Court of Delhi. (2022). The High Court of Delhi Intellectual Property Rights Division Rules, 2022.
Indian Contract Act, 1872 (India).
Indian Penal Code, 1860 (India).
Information Technology Act, 2000 (India).
John Richard Brady v. Chemical Process Equipment Pvt. Ltd., AIR 1987 Del 372.
Law Commission of India. (2024, March). Report No. 289: Trade secrets and economic espionage.
Mohini, V. (2025, October 16). Guarding the invisible: Trade secrets law in India. Managing IP.
Navigators Logistics Ltd. v. Kashif Qureshi, 254 (2018) DLT 307 (Delhi High Court).
Niranjan Shankar Golikari v. Century Spinning & Manufacturing Co., AIR 1967 SC 1098.
Office of the United States Trade Representative. (2025). 2025 special 301 report.
Official Secrets Act, 1923 (India).
Parmaar, S. S. (2026, June 19). IP proceedings or fishing expeditions? The Wire.
Press Information Bureau, Government of India. (2026). India–UK CETA set to enter into force on 15th July 2026.
Rana, V., & Jafri, H. (2026, July 16). The India–UK CETA comes into force: The IP framework. Bar & Bench.
Reddy, S., & Sandhu, G. S. (2007). Report on data protection provisions of Article 39.3 of TRIPS. Government of India.
Right to Information Act, 2005 (India).
Securities and Exchange Board of India (Prohibition of Insider Trading) Regulations, 2015 (India).
Specific Relief Act, 1963 (India).
Superintendence Co. of India (P) Ltd. v. Krishan Murgai, (1981) 2 SCC 246.
The Trade Secrets (Enforcement, etc.) Regulations 2018, SI 2018/597 (UK).
TRIPS Agreement. (1994). Agreement on Trade-Related Aspects of Intellectual Property Rights, art. 39.
UBS Business Solutions v. Nisheet Singh (Bombay High Court, March 30, 2026).
Varun Tyagi v. Daffodil Software Pvt. Ltd. (Delhi High Court 2025).
Venkateshwarlu Guduru v. Siddhardha De Bathula (Telangana High Court 2025).
Zee Telefilms Ltd. v. Sundial Communications Pvt. Ltd., 2003 (5) Bom. C.R. 404.

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RESEARCH ARTICLE

Coupled Fixed Point Theorems in Bipolar Parametric Metric Spaces with Applications to Coupled System of Differential Equations

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ABSTRACT

This paper investigates coupled fixed-point results in bipolar parametric metric spaces. The main objective is to establish the existence and uniqueness of a coupled fixed point for a covariant mapping under suitable contractive conditions. By constructing appropriate left and right iterative sequences, we show how the contraction condition leads to the Cauchy property of the resulting bisequences. Completeness of the space is then used to obtain their limits, and the contractive inequality helps establish that these limits form a coupled fixed point. A uniqueness argument is also presented to demonstrate that no other coupled fixed point can satisfy the same assumptions. A corollary is derived as a consequence of the principal theorem, and an illustrative example is provided to explain the applicability of the theoretical result. Finally, a coupled system of first-order differential equations is considered and transformed into an equivalent integral system. This formulation indicates how coupled fixed-point techniques can be used to investigate solutions of differential equations. The work highlights the role of completeness, covariant mappings, and contractive conditions in coupled fixed-point analysis.

***Mathematics Subject Classification**: 47H10; 54H25*

***Keywords:** Bipolar parametric metric space; coupled fixed point; covariant mapping; Coupled system of differential equations.*

INTRODUCTION

The "Banach contraction principle" (1922) (Banach, 1922) is the starting point of metric fixed point theory, and its extensions and applications are collected in (Agarwal et al., 2001; (Granas & Dugundji, 2013; Kirk & Shahzad, 2014); a comparison of the many contractive conditions is given in (Rhoades, 1977). The metric axioms have since been relaxed in several directions, for instance b-metric spaces (Bakhtin, 1989) (Bakhtin, 1989; Czerwik, 1993), multiplicative metric spaces (Bashirov et al., 2008; Mutlu et al., 2020), and parametric metric spaces, in which the distance depends on a parameter (Hussain et al., 2015).

A different generalization measures the distance between points of two different sets. Mutlu (2016) introduced bipolar metric spaces for this purpose and proved Banach-type theorems for covariant and contravariant mappings; further contractive conditions in this setting were studied in (Rawat et al., 2022; Gürdal et al., 2020; Mutlu et al., 2020). Extended bipolar b-metric spaces (Ganeswari & Leema Maria Prakasam, 2026), bipolar b-multiplicative metric spaces (Mercy Arokia Rani & Leema Maria Prakasam, 2024) and modular bipolar metric spaces (Maria Merlin & Leema

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Maria Prakasam, 2025) enlarge the framework further, and Hardy–Roger's type contractions are treated in (Mercy Arokia Rani & Leema Maria Prakasam, 2025).

Coupled fixed points were introduced by Guo and Lakshmikantham (1987) and were developed in partially ordered metric spaces in (Bhaskar & Lakshmikantham, 2006; Lakshmikantham & Ćirić, 2009. In bipolar metric spaces, coupled fixed point theorems were obtained in Mutlu et al., (2017) and Kishore et al., (2021), and common coupled fixed-point theorems in a parametric-type setting appear in Maria Merlin & Leema Maria Prakasam, (2026). Pasha (2024) combined the bipolar and the parametric ideas by introducing the bipolar parametric metric space (BPPMS), and related bipolar spaces were studied in (Kumar et al., 2024; Mani et al., 2023).

In this paper we prove a coupled fixed-point theorem in complete BPPMS. If $F: (P^2, Q^2) \rightrightarrows (P, Q)$ is a covariant mapping satisfying $d(F(a,b), F(p,q), C) \leq k\, d(a,p,C) + l\, d(b,q,C)$ with $k + l < 1$, then F has a unique coupled fixed point (Theorem 3.3).

The paper is organized as follows. Section 2 recalls the definitions, Section 3 contains the main result and an example, Section 4 the application, Section 5 a discussion, and Section 6 the conclusion.

PRELIMINARIES

Definition. 2.1: (Mercy Arokia Rani & Leema Maria Prakasam, 2025; Pasha et al., 2024)**:** Suppose $d: P \times Q \times (0, \infty) \to \mathbb{R}^+$ is a function defined on two non empty sets P and Q such that.

(1) If $d(p,q,C) = 0$ for all $C > 0$ then $p = q$, for all $(p,q) \in P \times Q$.

(2) If $p = q$, then $d(p,q,C) = 0$, for all $C > 0$ and $(p,q) \in P \times Q$

(3) $d(p,q,C) = d(q,p,C)$, for all $C > 0$ and $p, q \in P \cap Q$

(4) $d(p_1, q_2, C) \leq d(p_1, q_1, C) + d(p_2, q_1, C) + d(p_2, q_2, C)$, for all $C > 0$, $p_1, p_2 \in P$ and $q_1, q_2 \in Q$.

The triplet (P, Q, d) is called a BPPMS.

Example. 2.2: Let $P = [0,1]$ and $Q = [1,2]$, and define

$d: P \times Q \times (0, \infty) \to \mathbb{R}^+$ by $d(p,q,C) = \frac{|p-q|}{1+C}$.

Then (P, Q, d) is a complete BPPMS.

Definition. 2.3 (Maria Merlin & Leema Maria Prakasam, 2025; Mutlu, 2016)**:** Let (P_1, Q_1, d_1) and (P_2, Q_2, d_2) be BPPMSs and $F: P_1 \cup Q_1 \to P_2 \cup Q_2$ be a function. If $F(P_1) \subseteq P_2$ and $F(Q_1) \subseteq Q_2$, then F is termed as a covariant map and this is written as $F: (P_1, Q_1, d_1) \rightrightarrows (P_2, Q_2, d_2)$. If F is mapping from (P_1, Q_1, d_1) to $(Q_2, P_2, \overline{d}_2)$, then F is termed as a contravariant and this is denoted as $F: (P_1, Q_1, d_1) \rightleftarrows (P_2, Q_2, d_2)$.

DEFINITION. 2.4 (Ganeswari & Leema Maria Prakasam, 2026; Mutlu, 2016)**:** Let (P, Q, d) be a BPPMS. Then

(z1) The points of the sets P, Q, and $P \cap Q$ are referred to as left, right, and central points, respectively. A sequence on (P, Q, d) that consists solely of left, right, or central points is termed a left, right, or central sequence.

(z2) A left sequence $\{a_n\}$ converges to a right point q if and only if for every $\varepsilon > 0$ there exists a $n_0 \in \mathbb{N}$ such that $d(a_n, q, C) < \varepsilon$ for all $n \geq n_0$ and $C > 0$.

Similarly, a right sequence $\{p_n\}$ converges to a left point a if and only if there exists a $n_0 \in \mathbb{N}$ such that $d(a, p_n, C) < \varepsilon$ for all $n \geq n_0$ and $C > 0$.

DEFINITION. 2.5 (Mercy Arokia Rani & Leema Maria Prakasam, 2024; Mutlu, 2016): Let (P, Q, d) be a BPPMS.

(i) A sequence $(\{a_n\}, \{p_n\}) \subseteq P \times Q$ is called a bisequence on (P, Q, d).

(ii) The bisequence $(\{a_n\}, \{p_n\})$ is said to be convergent if both $\{a_n\}$ and $\{p_n\}$ are convergent. This bisequence is said to be biconvergent if $\{a_n\}$ and $\{p_n\}$ converge to the same point $u \in P \cap Q$.

(iii) $(\{a_n\}, \{p_n\})$ is a bisequence for (P, Q, d) is known as a Cauchy bisequence (CBS) if, for every $\varepsilon > 0$, we can locate a number $n_0 \in \mathbb{N}$, which, for all positive integers $n, m \geq n_0$, $C > 0$, $d(a_n, p_m, C) < \varepsilon$, is called a CBS.

Definition. 2.6 (Khan et al., 1984): Let $\mathbb{A} = \{\mathcal{A} | \mathcal{A}: [0, \infty) \to [0, \infty)\}$ be a family of altering distance functions such that $\mathcal{A}$ is continuous and monotone non-decreasing functions; $\mathcal{A}(\varepsilon) = 0 \Leftrightarrow \varepsilon = 0$;

NEW RESULTS IN COUPLED FIXED-POINT THEOREMS ON BIPOLAR PARAMETRIC METRIC SPACES

DEFINITION. 3.1: Let (P, Q, d) be a bipolar parametric metric space. $F: (P^2, Q^2) \rightrightarrows (P, Q)$ be a covariant mapping $(p,q) \epsilon P^2 \cup Q^2$ is said to be coupled fixed point of F if $F\ (a,b) = a$ *and* $F(b,a) = b$.

Definition. 3.2: The mapping $d: P \times Q \times [0, \infty) \to [0, \infty)$ is assumed to possess the following properties. Consider two nonempty sets, P and Q and

C >0

$(B1)$ For every $(p,q) \in P \times Q$, $p = q$ *if* $d\ (p,q,C) = 0$.

$(B2)$ For every $(p,q) \in P \times Q, d(p,q,C) = 0 \; if \; p = q.$

$(B3)$ If $d(p,q,C) = d(p,q,C)$, then for every $p,q \in P \cap Q$

$(B4)$ For every $p_1, p_2 \in P \; and \; q_1, q_2 \in Q, d(p_1,q_2,C) \leq d(p_1,q_1,C) +$

$$d(p_1,q_1,C) + d(p_2,q_2,C)$$

After defining the triple (P,Q,d) as a bipolar-metric space, the bipolar metric of the pair (P,Q) is defined as the mapping d.

Note: A bipolar parametric metric space is a generalization of metric space (P,Q,d) where distance is measured between elements of two distinct sets P and Q using the function $d: P \times Q \times [0,\infty) \to [0,\infty)$ is satisfying special axioms regarding distance.

Theorem. 3.3:

Let (P,Q,d) be a complete bipolar parametric metric space. $F: (P^2, Q^2) \rightrightarrows (P,Q)$ be a covaraiant mapping and k,l be non-negative constants. If F satisfies the condition

$$d(F(a,b,C),F(p,q,C) \leq k\, d(a,p,C) + ld(b,q,C), \quad k+l<1 \qquad (1)$$

$(a,b) \epsilon P, p.q \epsilon Q, then \; F: P^2 \cup Q^2 \to P \cup Q$ has a unique coupled fixed point.

Proof:

Let $a_0, b_0 \in P$ and $p_0, q_0 \in Q. We\ take \;\; a_1, b_1 \in P$ and $p_1, q_1 \in Q.$ with $F(a_0,b_0) = a_1 and\ F(b_0,a_0) = b_1, F(p_0,q_0) = p_1, F(q_0,p_0) = q_1$ and similarly we take $a_2, b_2 \in P$ and $p_2, q_2 \in Q.$ with $F(a_1,b_1) = a_2$ and $F(b_1,a_1) = b_2, F(p_1,q_1) = p_2, F(q_1,p_1) = q_2.$

In this way, we obtain a bisequences $a_n, b_n \in P$ and $p_n, q_n \in Q.$ with $F(a_n,b_n) = a_{n+1} and\ F(b_n,a_n) = b_{n+1},$

$$F(p_n,q_n) = p_{n+1}, F(q_n,p_n) = q_{n+1.}$$

For all $n \in \mathbb{N}^+$. Let $k+l = \lambda$. From (1), we get

$$d(a_n,p_{n+1,}C) = d(F(a_{n-1},b_{n-1},C),F(p_n,q_n,C) \qquad (2)$$

$$\leq k\, d(a_{n-1},p_n,C) + ld(b_{n-1},q_n,C) \quad and$$

$$d(b_n,q_{n+1,}C) = d(F(b_{n-1},a_{n-1},C),F(q_n,p_n,C) \qquad (3)$$

$$\leq k\, d(b_{n-1},q_n,C) + ld(a_{n-1},p_n,C)$$

For all $n \in \mathbb{N}^+$ and $\lambda < 1$. Let

$$e_n = d(a_n,p_{n+1},C) + d(b_n,q_{n+1},C)$$

For all $n \in \mathbb{N}^+$ .Combining (2) and (3), We observe that

$$e_n = d(a_n,p_{n+1},C) + d(b_n,q_{n+1},C)$$

$$\leq k\, d(a_{n-1},p_n,C) + ld(b_{n-1},q_n,C) + k\, d(b_{n-1},q_n,C) + ld(a_{n-1},p_n,C)$$

$$= (k+l)\, d(a_{n-1},p_n,C) + d(b_{n-1},q_n,C) = \lambda e_{n-1}.$$

Then we get

$$0 \leq e_n \leq \lambda e_{n-1} \leq \lambda^2 e_{n-1} \leq \dots\dots\dots\dots \leq \lambda^n e_{0.} \qquad \rightarrow(4)$$

On the other hand

$$d(a_{n+1},p_{n,}C) = d(F(a_n,b_n,C),F(p_{n-1},q_{n-1},C)$$

$$\leq k\, d(a_n,p_{n-1},C) + ld(b_n,q_{n-1},C) \qquad \rightarrow(5)$$

$$d(b_{n+1},q_{n,}C) = d(F(b_n,a_n,C),F(q_{n-1},p_{n-1},C)$$

$$\leq k\, d(b_n,q_{n-1},C) + ld(a_n,p_{n-1},C) \qquad \rightarrow(6)$$

For all $n \in \mathbb{N}^+$ and $\lambda < 1$. Let

$$s_n = d(a_{n+1},p_n,C) + d(b_{n+1},q_n,C)$$

For all $n \in N^+$ .Combining (5) and (6), We observe that

$$s_n = d(a_{n+1},p_n,C) + d(b_{n+1},q_n,C)$$

$$\leq k\, d(a_n,p_{n-1},C) + ld(b_n,q_{n-1},C) + k\, d(b_n,q_{n-1},C) + ld(a_n,p_{n-1},C)$$

$$= (k+l)\, d(a_n,p_{n-1},C) + d(b_n,q_{n-1},C) = \lambda s_{n-1}.$$

Then we get

$$0 \leq s_n \leq \lambda s_{n-1} \leq \lambda^2 s_{n-1} \leq \dots\dots\dots\dots\dots\dots\dots \leq \lambda^n s_{0.} \qquad \rightarrow(7)$$

Moreover,

$$d(a_n,p_{n,}C) = d(F(a_{n-1},b_{n-1},C),F(p_{n-1},q_{n-1},C)$$

$$\leq k\, d(a_{n-1},p_{n-1},C) + ld(b_{n-1},q_{n-1},C) \qquad \rightarrow(8)$$

$$d(b_n,q_{n,}C) = d(F(b_{n-1},a_{n-1},C),F(q_{n-1},p_{n-1},C)$$

$$\leq k\, d(b_{n-1},q_{n-1},C) + ld(a_{n-1},p_{n-1},C) \qquad \rightarrow(9)$$

For all $n \in \mathbb{N}^+$ and $\lambda < 1$. Let

$$t = d(a_n,p_n,C) + d(b_n,q_n,C)$$

For all $n \in \mathbb{N}^+$ .Combining (8) and (9), We observe that

$$t_n = d(a_n,p_n,C) + d(b_n,q_n,C)$$

$$\leq k\, d(a_{n-1},p_{n-1},C) + ld(b_{n-1},q_{n-1},C) + k\, d(b_{n-1},q_{n-1},C) + ld(a_{n-1},p_{n-1},C)$$

$$= (k+l)\, d(a_{n-1},p_{n-1},C) + d(b_{n-1},q_{n-1},C) = \lambda t_{n-1}.$$

Then we get

$$0 \le t_n \le \lambda t_{n-1} \le \lambda^2 t_{n-1} \le \dots\dots\dots\dots \le \lambda^n t_0. \quad \rightarrow (10)$$

Using the property (B3), we get $d(a_n, p_m, C) \le d(a_n, p_{n+1}, C) + d(a_{n+1}, p_{n+1}, C) + \dots\dots\dots\dots + d(a_{m-1}, p_m, C)$

$$d(b_n, q_m, C) \le d(b_n, q_{n+1}, C) + d(b_{n+1}, q_{n+1}, C) + \dots\dots\dots\dots + d(b_{m-1}, q_m, C) \quad (11)$$

$$d(a_m, p_n, C) \le d(a_m, p_{m-1}, C) + d(a_{m-1}, p_{m-1}, C) + \dots\dots\dots\dots + d(a_{n+1}, p_n, C)$$

$$d(b_m, q_n, C) \le d(b_m, q_{m-1}, C) + d(b_{m-1}, q_{m-1}, C) + \dots\dots\dots\dots + d(b_{n+1}, q_n, C) \quad (12)$$

For each $n, m \in \mathbb{N}^+ \text{ and } n < m$. Then from (4), (7), (10), (11) and (12), we have

$d(a_n, p_m, C) + d(b_n, q_m, C)$

$\le (d(a_n, p_{n+1}, C) + d(b_n, q_{n+1}, C)) + (d(a_{n+1}, p_{n+1}, C) + d(b_{n+1}, q_{n+1}, C)) + \cdots\dots\dots\dots + d(a_{m-1}, p_m, C) + + d(b_{m-1}, q_m, C))$

$\le e_n + t_{n+1} + e_{n+1+\dots} + t_{m-1} + e_{m-1}$

$\le \lambda^n e_0 + \lambda^{n+1} t_0 + \lambda^{n+1} e_0 + \dots\dots + \lambda^{m-1} t_0 + \lambda^{m-1} e_0$

$$\le \frac{\lambda^n}{1-\lambda} e_0 + \frac{\lambda^{n+1}}{1-\lambda} t_0 \quad \rightarrow (13)$$

$d(a_m, p_n, C) + d(b_m, q_n, C)$

$\le (d(a_m, p_{m-1}, C) + d(b_m, q_{m-1}, C)) + (d(a_{m-1}, p_{m-1}, C) + d(b_{m-1}, q_{m-1}, C)) + \dots\dots\dots\dots + d(a_{n+}, p_n, C) + + d(b_{n+1}, q_n, C))$

$\le s_{m-1} + t_{m-1} + \cdots + s_{n+1} + t_{n+1} + s_n$

$\le \lambda^{m-1} s_0 + \lambda^{m-1} t_0 + \dots + \lambda^{n+1} s_0 + \lambda^{n+1} t_0 + \lambda^n s_0$

$$\le \frac{\lambda^n}{1-\lambda} s_0 + \frac{\lambda^{n+1}}{1-\lambda} t_0 \quad \rightarrow (14)$$

For $n < m$. Since, for arbitrary $\epsilon > 0$, there exists n_0 such that

$\frac{\lambda^n}{1-\lambda} e_0 + \frac{\lambda^{n+1}}{1-\lambda} t_0 < \frac{\epsilon}{3}$ and $\frac{\lambda^n}{1-\lambda} s_0 + \frac{\lambda^{n+1}}{1-\lambda} t_0 < \frac{\epsilon}{3}$. From (13) and (14), we have

$$d(a_n, p_m, C) + d(b_n, q_m, C) < \frac{\epsilon}{3} \quad \rightarrow (15)$$

for each $n, m \ge n_0$. Then (a_n, p_m, C) and (b_n, q_m, C) are Cauchy bisequences. Because of completeness of (P, Q, d), there exists $a, b \in P$ and $p. q \in Q$ with

$\lim_{n\to\infty} a_n = p$, $\lim_{n\to\infty} b_n = q$, $\lim_{n\to\infty} p_n = a$ and $\lim_{n\to\infty} q_n = b$

Then there exists $n_1 \in \mathbb{N}$ with

$d(a_n, p, C) < \frac{\epsilon}{3}$, $d(b_n, q, C) < \frac{\epsilon}{3}$, $d(b, q_n, C) < \frac{\epsilon}{3}$ and $d(p, a_n, C) < \frac{\epsilon}{3}$. So from (1), we have

$$d(F(a,b), p, C) \le d(F(a,b), p_{n+1}, C) + d(a_{n+1}, p_{n+1}, C) + d(a_{n+1}, p, C)$$

$= d(F(a,b), F(p_n, q_n, C) + d(a_{n+1}, p_{n+1}, C) + d(a_{n+1}, p, C)$

$\le k\, d(a, p_n, C) + l\, d(b, q_n, C) + d(a_{n+1}, p_{n+1}, C) + d(a_{n+1}, p, C)$

$\le k\frac{\epsilon}{3} + l\frac{\epsilon}{3} + \frac{\epsilon}{3} + \frac{\epsilon}{3}$

$= \lambda\frac{\epsilon}{3} + 2\frac{\epsilon}{3} < \varepsilon$

For all $n \in \mathbb{N}$ and $\lambda < 1$. Then $d(F(a,b), p, C) = 0$.

$Hence, F(a, b, C) = p$. Similarly, we get

$F(b, a) = q, F(p, q) = a$ and $F(q, p) = b$. On the other hand, from (15),

we get

$$d(a, p, C) = \lim_{n\to\infty} d(a_n, p_n, C) = 0$$

$d(b, q, C) = \lim_{n\to\infty} d(b_n, q_n, C) = 0$. So $a = p$ and $b = q$.

Therefore, $(a, b, C) \in P^2 \cup Q^2$ is a coupled fixed point of F.

Now, to show the uniqueness, we begin by taking another coupled fixed point $(a*, b*, C) \in P^2 \cup Q^2$. $If\ (a*, b*, C) \in P^2$, then we get

$$d(a^*, a, C) = d\big(F(a^*, b^*, C), F(a, b, C)\big) \le k\, d(a^*, a, C) + l\, d(b^*, b, C)$$

and $d(b^*, b, C) = d\big(F(b^*, a^*, C), F(b, a, C)\big) \le k\, d(b^*, b, C) + l\, d(a^*, a, C)$

$$d(a^*, a, C) + d(b^*, b, C) \le \lambda\, d(a^*, a, C) + d(b^*, b, C) \quad \rightarrow (16)$$

Since $\lambda < 1$. This means that $d(a^*, a, C) + d(b^*, b, C) = 0$, we obtain that $a^* = a$ and $b^* = b$. $Similarly$, if $d(a^*, b^*, C) \in Q^2$ we obtain that $a^* = a$ and $b^* = b$.

Then (a, b) is a unique coupled fixed point of F.

Corollary 3.4:

Let (P, Q, d) be a complete bipolar parametric metric space. F: $(P^2, Q^2) \rightrightarrows (P, Q)$ be a covaraiant mapping and k, l be non-negative constants. If F satisfies the condition

$d(F(a,b,C), F(p,q,C) \le \frac{k}{2}(d(a,p,C) + ld(b,q,C)), \quad k < 1$

$(a, b) \epsilon P, p. q \epsilon Q, then\ F: P^2 \cup Q^2 \to P \cup Q$ has a unique coupled fixed point.

Example. 3.5: Let (P, Q, d) be the complete BPPMS of Example 2.2, that is $P = [0,1]$, $Q = [1,2]$ and $d(p,q,C) = \frac{|p-q|}{1+C}$.

Define $F: P^2 \cup Q^2 \to P \cup Q$ by $F(x,y) = \frac{2x+y+5}{8}$.

If $x, y \in P = [0,1]$, then $\frac{5}{8} \le F(x,y) \le 1$,

so $F(P^2) \subseteq P$. If $x, y \in Q = [1,2]$, then $1 \le F(x,y) \le \frac{11}{8}$, so $F(Q^2) \subseteq Q$.

Let $(a,b) \in P^2$ and $(p,q) \in Q^2$. Then

$$F(a,b) - F(p,q) = \frac{2(a-p) + (b-q)}{8},$$

so that

$$|F(a,b) - F(p,q)| \le \frac{1}{4}|a-p| + \frac{1}{8}|b-q|.$$

Dividing by $1 + C$ we obtain

$$d(F(a,b), F(p,q), C) \le \frac{1}{4}\, d(a,p,C) + \frac{1}{8}\, d(b,q,C),$$

with $k = \frac{1}{4}$, $l = \frac{1}{8}$ and $k + l = \frac{3}{8} < 1$.

All hypotheses of Theorem 3.3 hold, so F has a unique coupled fixed point. To find it, solve $F(x,y) = x$ and $F(y,x) = y$:

$$y = 6x - 5, \qquad x = 6y - 5.$$

Substituting the first into the second gives $x = 36x - 35$, hence $x = 1$ and $y = 1$.

Thus $(1,1) \in P \cap Q$ is the unique coupled fixed point, and indeed

$$F(1,1) = \frac{8}{8} = 1.$$

Take $a_0 = b_0 = 0 \in P$ and $p_0 = q_0 = 2 \in Q$. Then $a_n = b_n, p_n = q_n$

and $a_{n+1} = \frac{3a_n+5}{8}$, $p_{n+1} = \frac{3p_n+5}{8}$, which gives

$$a_n = b_n = 1 - (\frac{3}{8})^n, \qquad p_n = q_n = 1 + (\frac{3}{8})^n.$$

Hence $d(a_n, p_n, C) = \frac{2(\frac{3}{8})^n}{1+C} \to 0$, and both sequences converge to the central point 1, the coupled fixed point of F. Moreover, with $e_n = d(a_n, p_{n+1}, C) + d(b_n, q_{n+1}, C)$ we get $e_n = \lambda^n e_0$ for $\lambda = k + l = \frac{3}{8}$, which agrees with the estimate used in the proof of Theorem 3.3.

APPLICATION TO A COUPLED SYSTEM OF DIFFERENTIAL EQUATIONS

Consider the following system of first-order differential equations with initial conditions:

$$\begin{aligned} x'(t) &= (1/10)[x(t) + y(t)], \quad x(0) = 1, \\ y'(t) &= (1/10)[y(t) + x(t)], \quad y(0) = 1. \end{aligned} \tag{4.1}$$

We represent the system as a coupled fixed-point problem. The theorem-based conclusion is valid provided the function-space, distance, and mapping hypotheses in Theorem 3.3 are all satisfied.

Integrating the first differential equation from 0 to t and using $x(0) = 1$ gives

$$x(t) = 1 + \left(\frac{1}{10}\right)\int_0^t [x(s) + y(s)]ds. \tag{4.2}$$

Similarly, using y(0) = 1, we obtain

$$y(t) = 1 + \left(\frac{1}{10}\right)\int_0^t [y(s) + x(s)]ds. \tag{4.3}$$

Thus, the differential system is equivalent to the integral system (4.2)–(4.3).

Let $X = C([0,1], \mathbb{R})$, equipped with the supremum norm

$$||u||\infty = \sup_{\{t\in[0,1]\}} |u(t)|.$$

Define T : X × X → X by

$$T(u,v)(t) = 1 + \left(\frac{1}{10}\right)\int_0^t [u(s) + v(s)]ds. \tag{4.4}$$

Since u and v are continuous, the integrand is continuous; hence $T(u,v)$ is continuous and T is well-defined.

Take u, v, p, q ∈ X. Then

$$|T(u,v)(t) - T(p,q)(t)| = \left(\frac{1}{10}\right)\left|\int_0^t [(u(s) - p(s)) + (v(s) - q(s))]ds\right|.$$

By the triangle inequality,

$$|T(u,v)(t) - T(p,q)(t)| \le (1/10)\int_0^t (|u(s) - p(s)| + |v(s) - q(s)|)\, ds$$

Since $t \in [0,1]$,

$$|T(u,v)(t) - T(p,q)(t)| \le \left(\frac{1}{10}\right)(||u - p||\infty + ||v - q||\infty).$$

Taking the supremum over t gives

$$||T(u,v) - T(p,q)||\infty \le \left(\frac{1}{10}\right)||u - p||\infty + \left(\frac{1}{10}\right)||v - q||\infty. \tag{4.5}$$

This is a coupled contraction estimate with $k = l = \frac{1}{10}$, so $k + l = \frac{1}{5} < 1$. For a formal application of Theorem 3.3, this estimate must be expressed in the BPPMS distance and the required covariant mapping structure must be verified.

Subtracting the second integral equation from the first gives

$x(t) - y(t) = 0$. Hence $x(t) = y(t)$ for all $t \in [0,1]$.

Substituting into the first differential equation yields

$$x'(t) = \left(\frac{1}{5}\right)x(t), \quad x(0) = 1. \quad (4.6)$$

Separating variables gives $\frac{dx}{x} = \frac{dt}{5}$. Integrating, $\ln|x(t)| = \frac{t}{5} + C$.

From $x(0) = 1$, we obtain $C = 0$. Therefore

$$x(t) = e^{\frac{t}{5}}. \quad (4.7)$$

Since $y(t) = x(t)$, we also have

$$y(t) = e^{\frac{t}{5}}. \quad (4.8)$$

For $x(t) = y(t) = e^{\frac{t}{5}}$, we have $x'(t) = y'(t) = \left(\frac{1}{5}\right)e^{\frac{t}{5}}$. Also,

$$\left(\frac{1}{10}\right)[x(t) + y(t)] = \left(\frac{1}{10}\right)\left[2e^{\frac{t}{5}}\right] = \left(\frac{1}{5}\right)e^{\frac{t}{5}}.$$

Thus, both differential equations are satisfied. The initial conditions

$x(0) = y(0) = 1$ also hold.

The system has the solution $x(t) = y(t) = e^{\frac{t}{5}}$ on $[0,1]$.

DISCUSSION

The results obtained in this study illustrate the role of contractive mappings in establishing coupled fixed-point theorems in bipolar parametric metric spaces. The proposed framework considers the interaction between two sets through a covariant mapping and provides a systematic approach to the existence and uniqueness of coupled fixed points. In this setting, the contractive condition serves as the principal tool for controlling the behaviour of the iterative sequences.

Theorem 3.3 establishes the main theoretical result of the paper. Its proof demonstrates how suitable distance estimates can be used to study the convergence of the constructed bisequences. The use of completeness connects this convergence process with the existence of a coupled fixed point. The uniqueness argument further strengthens the result by showing that the coupled fixed point is determined uniquely under the prescribed hypotheses. Thus, the theorem brings together the contractive property, convergence, and completeness in a single mathematical argument.

Corollary 3.4 provides a consequence of the principal theorem and shows how the same fixed-point framework can be applied under the corresponding assumptions. The illustrative example in Example 3.5 gives a more direct understanding of the abstract result. By defining a specific mapping and solving the associated coupled equations, the unique coupled fixed point is identified explicitly. The example also provides an opportunity to examine the iterative process and observe its convergence towards the fixed point.

The differential-equation application presents another mathematical setting in which coupled fixed-point methods are relevant. The given system is transformed into an equivalent integral formulation by using the initial conditions. The corresponding integral operator is then studied through estimates involving the supremum norm. This approach demonstrates the connection between operator-based fixed-point techniques and the analysis of coupled differential systems.

Taken together, the theoretical results and the illustrative constructions show how the proposed framework can be used to investigate coupled fixed-point problems. The study also provides a starting point for examining more general contractive conditions and other nonlinear problems within bipolar parametric metric spaces.

CONCLUSION

This work develops coupled fixed-point results in bipolar parametric metric spaces and establishes an existence and uniqueness theorem for a covariant mapping under suitable contractive conditions. The principal contribution lies in the use of iterative sequences and completeness to obtain the coupled fixed point and establish its uniqueness.

The results are supported by a corollary and an explicit example, which illustrate the theoretical framework and its mathematical implementation. In particular, the example identifies the coupled fixed point by solving the associated equations and demonstrates the convergence of the selected iterative sequences.

The study also considers a coupled system of first-order differential equations and expresses it as an equivalent system of integral equations. This formulation illustrates the relevance of coupled fixed-point techniques in the study of nonlinear differential systems. The work therefore provides a basis for further investigations into fixed-point theory in generalized metric structures.

Future research may focus on extending the present results to other classes of bipolar metric spaces, developing alternative contractive conditions, and investigating applications to nonlinear integral equations and boundary value problems. These directions may further broaden

the scope of coupled fixed-point theory and provide additional opportunities for its application in nonlinear analysis.

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REFERENCES

Agarwal, R. P., Meehan, M., & O'regan, D. (2001). *Fixed point theory and applications* (Vol. 141). Cambridge university press.

Bakhtin, I. (1989). The contraction mapping principle in quasimetric spaces. *Functional analysis*, *30*, 26-37.

Banach, S. (1922). Sur les opérations dans les ensembles abstraits et leur application aux équations intégrales. *Fundamenta mathematicae*, *3*(1), 133-181.

Bashirov, A. E., Kurpınar, E. M., & Özyapıcı, A. (2008). Multiplicative calculus and its applications. *Journal of mathematical analysis and applications*, *337*(1), 36-48.

Bhaskar, T. G., & Lakshmikantham, V. (2006). Fixed point theorems in partially ordered metric spaces and applications. *Nonlinear analysis: theory, methods & applications*, *65*(7), 1379-1393.

Czerwik, S. (1993). Contraction mappings in $ b $-metric spaces. *Acta mathematica et informatica universitatis ostraviensis*, *1*(1), 5-11.

Ganeswari, N., & Leema Maria Prakasam, A. (2026). Common fixed point theorems in extended bipolar b-metric spaces and Applications. The Scientific Temper, 17(9), 6981–6990.

Granas, A., & Dugundji, J. (2013). *Fixed point theory*. Springer Science & Business Media.

Guo, D., & Lakshmikantham, V. (1987). Coupled fixed points of nonlinear operators with applications. *Nonlinear analysis: theory, methods & applications*, *11*(5), 623-632.

Gürdal, U. T. K. U., Mutlu, A., & Özkan, K. Ü. B. R. A. (2020). Fixed point results for α-ψ-contractive mappings in bipolar metric spaces. *J. Inequal. Spec. Funct*, *11*(1), 64-75.

Hussain, N., Salimi, P., & Parvaneh, V. (2015). Fixed point results for various contractions in parametric and fuzzy b-metric spaces. *J. Nonlinear Sci. Appl*, *8*(5), 719-739.

Khan, M. S., Swaleh, M., & Sessa, S. (1984). Fixed point theorems by altering distances between the points. *Bulletin of the Australian Mathematical Society*, *30*(1), 1-9.

Kirk, W., & Shahzad, N. (2014). *Fixed point theory in distance spaces* (Vol. 1). Cham: springer.

Kishore, G. N. V., Rao, K. P. R., IsIk, H., Srinuvasa Rao, B., & Sombabu, A. (2021). Covarian mappings and coupled fiexd point results in bipolar metric spaces. *International Journal of Nonlinear Analysis and Applications*, *12*(1), 1-15.

Kumar, M., Ege, O., Mor, V., Kumar, P., & De la Sen, M. (2024). Boyd-Wong type contractions in generalized parametric bipolar metric space. *Heliyon*, *10*(2).

Lakshmikantham, V., & Ćirić, L. (2009). Coupled fixed point theorems for nonlinear contractions in partially ordered metric spaces. *Nonlinear Analysis: Theory, Methods & Applications*, *70*(12), 4341-4349.

Mani, G., Ramaswamy, R., Gnanaprakasam, A. J., Elsonbaty, A., Abdelnaby, O. A. A., & Radenović, S. (2023). Application of fixed points in bipolar controlled metric space to solve fractional differential equation. *Fractal and Fractional*, *7*(3), 242.

Maria Merlin, S., & Leema Maria Prakasam, A. (2025). Fixed point and coupled fixed point theorems on modular bipolar metric space. The Scientific Temper, 16(12), 5328–5336.

Maria Merlin, S., & Leema Maria Prakasam, A. (2026). Theorems on common coupled fixed point in C*-algebra valued rectangular parametric metric space. The Scientific Temper, 17(2), 5707–5712.

Mercy Arokia Rani, J., & Leema Maria Prakasam, A. (2024). Fixed points of operators with multiplicative closed graphs on bipolar b-multiplicative metric spaces. Advances in Fixed Point Theory, 14(57), 1–16.

Mercy Arokia Rani, J., & Leema Maria Prakasam, A. (2025). Exploring new results on FPT for Ω-Hardy Rogers type contraction mappings. Indian Journal of Natural Sciences, 15(88), 88592–88599.

Mutlu, A. (2016). Bipolar metric spaces and some fixed point theorems. *Journal of Nonlinear Sciences and Applications*.

Mutlu, A., Ozkan, K., & Gurdal, U. (2017). Coupled fixed point theorems on bipolar metric spaces. *European journal of pure and applied Mathematics*, *10*(4), 655-667.

Mutlu, A., Özkan, K., & Gürdal, U. (2020). Locally and weakly contractive principle in bipolar metric spaces. TWMS Journal of Applied and Engineering Mathematics, 10(2), 379–388.

Mutlu, A., Özkan, K., & Gürdal, U. (2020). Locally and weakly contractive principle in bipolar metric spaces. *TWMS Journal of Applied and Engineering Mathematics*, *10*(2), 379-388.

Pasha, M. I., Rao, K. R. K., Mani, G., Gnanaprakasam, A. J., & Kumar, S. (2024). Solving a fractional differential equation via the bipolar parametric metric space. *Journal of Mathematics*, *2024*(1), 5533347.

Rawat, S., Dimri, R. C., & Bartwal, A. (2022). F-Bipolar metric spaces and fixed point theorems with applications. *J. Math. Comput. Sci*, *26*(2), 184-195.

Rhoades, B. E. (1977). A comparison of various definitions of contractive mappings. *Transactions of the American Mathematical Society*, *226*, 257-290.

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RESEARCH ARTICLE

A Multi-objective Home Health Care Fuzzy Green Vehicle Routing and Scheduling Problem with Different Types of Vehicles and Vehicle Trip Sharing Strategy

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ABSTRACT

Hospitals are facing problems due to the rapid growth of demand for services for ageing people, disabled people, people with fractured hips, different types of chronic diseases, mental illness patients, coma patients, etc. On account of this, the home health care service system is growing worldwide. In a natural-world scenario, CO_2 emission depends on some factors like traffic congestion, driver's driving behaviour, and road surface quality. Therefore, these factors create CO_2 emission that are uncertain in nature. The duration of the time window is uncertain in residential healthcare due to unexpected guests arriving, household duties, daily activities, and changes in previous appointments. In this paper, duration of time window and CO_2 emission are considered as fuzzy number. This work develops a mixed-integer linear programming model for home health care service routing and scheduling with the goal of minimising the total travel distance, travel cost, visiting cost, and CO_2 emission. The Enhanced Artificial bee colony algorithm and Enhanced Mutated cuckoo search algorithm are used to solve the home health care routing and scheduling problem. Owing to the competing nature of these objectives, these two heuristic algorithms use a normalised weighted-sum aggregated approach. A computational experiment has been conducted to test the performance of heuristic algorithms for the new modified instances, which are implemented using Python 3.12. The experiment results have shown that the Enhanced Artificial bee colony algorithm is more efficient than the Enhanced Mutated cuckoo search algorithm.

Keywords: *Home Health Care Routing and Scheduling, Single-valued Triangular Neutrosophic Fuzzy Number, Different Types of Vehicles, Vehicle Trip Sharing Strategy, weighted sum, Min-Max Normalization.*

INTRODUCTION

Home Health care (HHC) services have been developed as another method for regular clinical treatment that involves medical assessment, physiotherapist, some general hygiene care for the needed patients at their own home. In general, home health care services are essential for reducing hospitalization costs, frustrating environments, the necessity for longer stays in hospitals, and improving the satisfaction of patients. The home health care vehicle routing problem (HHC VRP) is used to find the best route for the fleet of vehicles with health care staff to serve all the assigned patient's homes within the preferred time while satisfying the objectives and considering various constraints. HHC service organizations were started in American countries and then in European countries. Home health care service system is facing a complex situation due to several factors, such as the increasing number of assigned patients and their needs, synchronization with other patients, and skills required of caregivers. Due to complexity of home health care

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system growing complexity provoke the researcher's interest to planning best suitable routing and scheduling for home health care system.

One of the earliest useful decision-support systems for everyday staff scheduling in home care organisations was presented by Eveborn et al. (2006). Various Swedish municipalities successfully implemented their LAPS-CARE system, which combined staffing, routing, and schedule planning. Bertels and Fahle (2006) solved the home health care problem by using a combination of linear and constraint programming and a heuristic approach to reduce transportation costs and increase patients and caregiver's satisfaction. Neda and Tonguc (2021) proposed new algorithm to minimize the transportation cost on Solomon instances for HHC VRP.

The aim of the multi-objective HHC VRP tends to determine routes for healthcare professionals who visit patients at their residence while simultaneously achieving a number of objectives, including minimizing travel time and costs, enhancing service quality, and balancing staff workload. Fathollahi-Fard et al. (2021) developed a bi-objective optimization model with a time window, route balancing and working time balancing and the objectives are to minimize both the cost and total service time. Decerle et al. (2019) discussed pareto-based multi-objective optimization for handling the minimum of total working time, maximum of service quality, minimum of maximum workload of caregivers and auxiliary caregivers and taking penalties for overtime working of caregivers during simultaneous service. Fathollahi Fard et al. (2020) examined a bi-objective robust optimization model and used keshtel algorithm to solved for home health care routing and scheduling problem (HHCRSP) with stochastic travel time, duration of service and gas emission.

Each vehicle in HHC-VRP faces a distinct seating or capacity limit, which affects how many employees it can accommodate. When multiple staff members travel together in the same vehicle, this is known as trip sharing. These two elements have a direct impact on route planning and the effectiveness of home healthcare services. Divsalar et al. (2023) addressed a mixed-integer nonlinear model for HHC routing service with a focus on minimising the total cost, sustainability, workload balance, and maximising service level quality. The authors proposed a multi-objective variable neighborhood search algorithm to test the instance and real-time data with different types of vehicles and different types of nurses. Sangeetha and Srinivasan (2021) investigated a new model multi-objective dynamic vehicle routing problem for simultaneous visits within preferred time slots for home health care system, and they proposed a mutated cuckoo search algorithm and tested it on randomly generated data instances with different types of vehicles.

Christian and Patrick (2015) investigated trip sharing, geographically distribution of patient's locations with different objectives concepts in HHCRSP. Yong et al. (2021) investigated a real-world case study of transportation resource sharing strategy with multi period and bi-objective model for 2-Echelon multi-period location routing problem. Ming et al. (2020) examined shared vehicle issue for two stages model problem under IoT in green logistics.

For the combined practice in HHC-VRP, synchronized visits require two or more healthcare providers to arrive at the same patient's residence at the same moment. Each staff member is required to take a specified amount of time during their shift for lunch. For schedules to remain practical and effective, both limitations must be incorporated into the routing strategy. Liu et al. (2021) tackled the situation of simultaneous care with lunch period, where caretaker begin their work from their home or HHCC for home health care service routing and scheduling problems with the help of proposed algorithm. Sohaib et al. (2016) proposed a SA-ILS for *VRP* with a time window and synchronization to test the benchmark instances. Briseida and Karl (2021) proposed a strategy of self-imposed time windows for vehicle routing problem synchronization at the delivery location to tackle this problem. Nasir and kuo (2020) addressed the challenges of synchronization, multiple visits, and multiple routes of delivery vehicle visits in routing and scheduling plan for home care problem. Liu et al. (2019) proposed an efficient adaptative large neighborhood search algorithm for home care *VRP* with synchronized visits. Andrea and Hirsch (2014) discussed HHC problems with break time, weekly rest time, and maximum working time. Coelho et al. (2016) developed a mixed-integer linear programming model for furniture delivery industry with lunch time using a multi-star randomized local search algorithm.

Uncertainty in HHC-VRP refers to unplanned events like fluctuating travel times, unexpected patient delays, urgent demands, or modifications to the time required for services. Because schedules may need to be adjusted in real time due to these uncertainties, route planning becomes more complicated. Effective approaches make an effort to manage these variations while maintaining efficient and consistent patient care. Shi et al. (2017) explore the *VRP* with a time window in home health care system and the problem of minimising the transportation cost

with uncertainty in the situation of need drugs demand. Shiri et al. (2023) proposed a multi-objective two-stage model that minimizes the cost of hhc centers while maximizing job opportunities with uncertain service times. Fariba et al. (2021) addressed the route allocation for therapists and minimising the transport and travel cost in the fuzzy environment of home health care problems. The author developed a model and solved this different size model by using MOICA, NSGA-II, and MOSEO. Shi et al. (2019) proposed a robust model for routing and scheduling problem of home health care service with uncertain travel time and service time. The authors used SA, TS, and VNS in Gurobi Solver to get the objective values. Fathollahi-Fard et al. (2020) examined jimenez's method to deal with the uncertainty in the travel time, period of service, and patient's satisfaction with multi-period, multi- depot HHCRS model problem. Adnen et al. (2022) proposed a new model for integrating home care routing and scheduling problem with uncertain travel time, dynamic behavior of patients, caregiver team. Cisse et.al (2017) describe nowadays how the home health care system frequently faces uncertainty and uncertainty parameters such as service time and travel time between two patient's locations, vehicle availability, and patient's demand.

In the past decade, HHC service system has faced numerous difficulties, and their increasing complexity has attracted many researchers to do research in the health care system. One of the earliest standard VRP frameworks with time windows, synchronisation, and precedence conditions for home healthcare visits was created by Bredström and Rönnqvist (2008). Decerle et al. (2018) examined a HHCRSP with hard and soft time-window constraints and the necessary synchronisation. To effectively manage parallel visits and different nursing skills, the authors created a memetic algorithm with unique crossover operators and a mixed-integer programming model. Their findings on benchmark and real-world French HHC data showed that the suggested algorithm produces excellent results for various kinds of instance types. An SA-ILS heuristic was created by Afifi et al. (2016) for the VRP with Time Windows and Synchronised Visits, where certain patients need multiple carers to serve them at the same time. To effectively manage both timing and synchronisation constraints, their method combines intensive local improvement techniques with simulated annealing. On benchmark datasets, their algorithm performed very effectively, achieving all known optimal outcomes and outperforming a number of previous best results. Euchi et al. (2020) create a hybrid AI-based approach that uses time windows, single-depot routing, and synchronized visits to address the HHC VRP. Their method creates effective healthcare provider plans by combining clustering and the Ant Colony System (ACS). The authors demonstrate how the hybrid approach enhances patient service and lowers overall time of completion for real HHC management.

The majority of the existing HHC-VRP research uses homogeneous vehicles and fixed parameters, neglecting real-world uncertainty and sustainability considerations. The studies Afifi et al. (2016), Bredström and Rönnqvist (2008), Decerle et al. (2018) and Euchi et al. (2020) solve healthcare routing with synchronised visits using predefined benchmark instances, and these focus on homogenous vehicles and deterministic parameters. They do not investigate how routing and staff scheduling are impacted by various vehicle sizes (small, medium, and large) with varying capacities and costs, as well as how planning quality is impacted by uncertain time-window duration. The extended HHC-VRP, which considers multiple healthcare providers and vehicles, unpredictable time duration, synchronised visits, service-level preferences, economic effectiveness, and environmental impact, which is still significantly lacking. The rest of this work is organized as follows: In section 2 discuss preliminary definition for fuzzy number. In section 3 presents the notations and description of the problem. In section 4, explains methodology. In section 5 discuss experiment result and in section 6 describe the conclusion.

METHODOLOGY

Preliminaries

Neutrosophic number

Let X is said to be a non-empty set. A Neutrosophic set $B \in R$ has the following form

$B = \{(r, T'_B(r), I'_B(r), F'_B(r)) : r \in R\}$, where the functions $T'_B, I'_B, F'_B : R \to [0,1]$ explains

the degree of truth membership, the degree of indeterminacy membership and the

degree of falsity membership as every element $r \in R$ to the corresponding set B, that is which a subset of R.

$$0 \leq T'_B(r) + I'_B(r) + F'_B(r) \leq 3$$

In specific, If X has only one element, then B as a neutrosophic number, that can be

expressed by, $B = (T'_B(r), I'_B(r), F'_B(r))$

Single-valued triangular neutrosophic fuzzy number

The single-valued triangular neutrosophic fuzzy number defined as b =

$((b_1, b_2, b_3); \alpha'_b, \beta'_b, \gamma'_b)$ is a neutrosophic set that is on R, the membership functions that are truth, uncertainty and falsity is defined as below,

$$T'_b(r) = \begin{cases} \alpha'_b\left(\frac{r - b_1}{b_2 - b_1}\right) & \text{for } b_1 \le r \le b_2 \\ \alpha'_b & \text{for } r = b_2 \\ \alpha'_b\left(\frac{b_3 - r}{b_3 - b_2}\right) & \text{for } b_2 \le r \le b_3 \\ 0 & \text{for otherwise} \end{cases}$$

$$I'_B(r) = \begin{cases} \frac{b_2 - r + \beta'_b(r - b_1)}{b_2 - b_1} & \text{for } b_1 \le r \le b_2 \\ \beta'_b & \text{for } r = b_2 \\ \frac{r - b_2 + \beta'_b(b_3 - r)}{b_3 - b_2} & \text{for } b_2 \le r \le b_3 \\ 1 & \text{for otherwise} \end{cases}$$

$$F'_B(r) = \begin{cases} \frac{b_2 - r + \gamma'_b(r - b_1)}{b_2 - b_1} & \text{for } b_1 \le r \le b_2 \\ \beta_a & \text{for } r = b_2 \\ \frac{r - b_2 + \gamma'_b(b_3 - r)}{b_3 - b_2} & \text{for } b_2 \le r \le b_3 \\ 1 & \text{for otherwise} \end{cases}$$

where $\alpha'_b, \beta'_b, \gamma'_b \in [0,1]$, $b_1, b_2, b_3 \in R$ and $b_1 \le b_2 \le b_3$.

Score function

The following score function is used to transform the neutrosophic data into crisp data

$SF'(b) = \frac{1}{2}\left((b_1 + 2b_2 + b_3)(2 + \alpha'_b - \beta'_b - \gamma'_b)\right)$,where $b = ((b_1, b_2, b_3); \alpha'_b, \beta'_b, \gamma'_b)$. The single-valued triangular fuzzy neutrosophic number where $\alpha'_b, \beta'_b, \gamma'_b \in [0,1]$, $b_1, b_2, b_3 \in R$ *and* $b_1 \le b_2 \le b_3$.

PROBLEM DESCRIPTION

This study examines an extension of the Home-Healthcare Routing Problem, in which healthcare providers visit patients in various locations within a restricted daily scheduling horizon by travelling from an organising service centre. Each healthcare worker begins the working day at the depot and is required to return when their designated visits have been completed. Every patient needs medical care that is specified by a time window and length of service. To achieve the required level of care, the provided service must start within the given window. Furthermore, healthcare staff members possess varying levels of service qualifications to cater to the diverse service needs of patients. Patients want different services from the healthcare staff members; some patients want small household services with cooking and cleaning, some bedridden patients want bathing and dressing services, some want a physiotherapist, and some want medical services. Some patients require simultaneous care due to their illness. In certain situations, synchronised care is necessary, which means that two qualified nursing staff are required to arrive at the same particular patient and begin providing care at the same moment. The travel time between HHC and the patient's home, from the patient's home to the patient's home, is denoted by $TT_{i'j'k'}$. The working schedule for the healthcare staff member is allotted as the entire day, and the lunch break is not considered a working hour. So, the lunch break duration for each healthcare staff member is assumed to be 1 hour. In this work, the capacity of the healthcare vehicle is according to the number of seating capacity of the vehicle, in addition to the driver. The different types of health care vehicles available to carry the health care staff members between HHC and the patient's home do not exceed a capacity limit.

In many studies, the healthcare staff member is allotted to the vehicle according to their service qualification level, but in this paper, some relaxation is given to this condition. Using a vehicle-sharing strategy, staff are allotted to the same or a different healthcare vehicle for synchronised visits to the locations that are geographically close to each other. This shared conveyance strategy provides that each of the patient visits is finished within the allotted time windows and synchronisation constraints while ensuring the effective use of the existing vehicle resources. Each healthcare staff member should use a single allowance and not change the good-condition allowance type during the trip. The service level of the healthcare staff member is considered by the patient satisfaction level.

In a real-world scenario, the time duration of the patient is uncertain because of the travel time and the waiting time of the healthcare staff member for simultaneous care. CO_2 emissions are also vague due to the driver's driving skill condition, road gradient, traffic congestion, using a lot of old vehicles, and varying speeds from vehicles. In this paper, the different types of time duration and emissions are considered a single-valued neutrosophic triangular fuzzy number. This problem is solved through instances with randomly generated data, some of which is real-world data, using two metaheuristic algorithms.

MATHEMATICAL MODEL

***Notations*:**

ABC - Artificial bee colony

MCSA - Mutated cuckoo search algorithm

EABCA – Enhance Artificial bee colony algorithm

EMCSA – Enhance Mutated cuckoo search algorithm

HHC – Home Health care

HHCC - Home Health care company

HHCRS - HHC routing and scheduling

HHCRSP – HHC routing and scheduling problem

i', j' – patient's node

$i', j' \in V$ – set of patient nodes including patient's home and depot

$k' \in K$ - set of different health care vehicle types

$sm' \in N$ - set of health care staff member's type

avs_1 - Average speed of the health care small vehicle

avs_2 - Average speed of the health care medium vehicle

avs_3 - Average speed of the health care large vehicle

Parameters and Their Description:

$d_{i'j'}$ - distance between depot to patient's home and patient's home to patient's home

$TC_{i'j'k'}$ - Traveling cost from patient i' to patient j' using health care vehicle type

$VCC_{sm'}$ - Staff member visiting cost of each patient for health care staff member from HHC Company

$\tilde{e}m_{i'j'k'}$ - Single-valued triangular neutrosophic CO_2 emission from health care vehicle type while traveling from patient i' to patient j' and depot to patient's home

$A_{sm'}$- capacity of the small health care vehicle

$B_{sm'}$ - capacity of the medium health care vehicle

$C_{sm'}$ - capacity of the large health care vehicle

$SL_{sm'}$ - Staff member service level

$OPT_{i'}$ - Earliest opening time of time window for patient i'

$CLT_{i'}$ - Latest Closing time of time window for patient i'

$ST_{i'}$ - Service time of patient i'

$NSM_{i'}$ - Number of sm' required at patient i'

$S_{j'}$ - Service start time at patient j'

$S_{i'}$ - Service start time at patient i'

$TT_{i'j'k'}$ - Traveling time from patient i' to patient j' and depot to patient's home by using health care vehicle type

$N_{syn\ v}$ - Set of synchronized visits

$i', j' \in N_{syn\ v}$ - every pair of synchronized visits i' and j' correlated with same locations, time windows, service time durations, service qualification level

$S_{i'}^{sm'_1}$ - Simultaneous care Start time of sm'_1

LD - lunch break duration for health care staff members

LDOT - Lunch break duration Opening time

LDCT - Lunch break duration Closing time

M' - large positive value

Decision Variables

$x_{i'j'sm'k'}$ - 1 if the health care staff member ds' of type sm' visits patient j' immediately after visiting patient i' by using health care vehicle type

- 0, otherwise

$S_{i'sm'}$ - Service starting time of sm' at patient i'

$l_{sm'}$ - lunch break starting time of sm'

Mathematical formulation for fuzzy multi-objective HHCRSP

***Objective function*:** A multi-objective optimisation model that minimises travel distance, travel cost, visiting cost, and emission is examined in this study. Min–Max normalisation is used to normalise each individual goal, and a weighted sum method is used to combine them.

Objective 1: Total Travel distance

$$Z_1 = \sum_{i' \in V} \sum_{j' \in V} \sum_{k' \in K} \sum_{sm' \in N} d_{i'j'} * x_{i'j'sm'k'} \quad ----$$

(1)

(Eqn. 1) minimizing the total travel distance on each route,

Objective 2: Total Travel cost

$$Z_2 = \sum_{i' \in V} \sum_{j' \in V} \sum_{k' \in K} \sum_{sm' \in N} TC_{i'j'k'} * x_{i'j'sm'k'} \quad ---$$

(2)

(Eqn. 2) minimizing the total travel cost on each route,

Objective 3: Total visiting cost

$$Z_3 = \sum_{i' \in V} \sum_{j' \in V} \sum_{k' \in K} \sum_{sm' \in N} VCC_{sm'} * x_{i'j'sm'k'} \quad ----$$

(3)

(Eqn. 3) minimizing health care staff visiting cost on each route,

Objective 4: Total CO_2 emission

$$Z_4 = \sum_{i' \in V} \sum_{j' \in V} \sum_{k' \in K} \sum_{sm' \in N} \tilde{e}m_{i'j'k'} * x_{i'j'sm'k'} \quad --(4)$$

(Eqn. 4) minimizing the total fuzzy CO_2 emission on each route,

Normalization Weighted sum Objective function

$$\text{Min } Z = W_1 Z_1^{norm} + W_2 Z_2^{norm} + W_3 Z_3^{norm} + W_4 Z_4^{norm} \quad ---(5)$$

Where normalization is applied

$$Z_{Objective}^{norm} = \frac{Z_{Objective} - Z_{Objective}^{min}}{Z_{Objective}^{max} - Z_{Objective}^{min}}$$

Subject to the constraints

$$\sum_{j' \in V} x_{i'j'sm'k'} = 1, \forall\, i' \in V, \forall\, k' \in K \quad ---(6)$$

$$\sum_{i' \in V} x_{i'j'sm'k'} = 1, \forall\, j' \in V, \forall\, k' \in K \quad ---(7)$$

$$\sum_{sm' \in N} \sum_{i' \in V} x_{i'j'sm'k'} = \sum_{sm' \in N} \sum_{j' \in V} x_{i'j'sm'k'} = 1, \forall\, k' \in K \quad ---(8)$$

$$\sum_{i' \in V} x_{i'j'sm'k'} = \sum_{j' \in V} x_{i'j'sm'k'}, \forall\, sm' \in N, \forall\, k' \in K \quad ---(9)$$

$$\sum_{i' \in V} NSM_{i'} \sum_{j' \in V} \sum_{sm' \in N} x_{i'j'sm'k'} \leq A_{sm'}, \forall\, k' \in K \quad ---(10)$$

$$\sum_{i' \in V} NSM_{i'} \sum_{j' \in V} \sum_{sm' \in N} x_{i'j'sm'k'} \leq B_{sm'}, \forall\, k' \in K \quad ---(11)$$

$$\sum_{i' \in V} NSM_{i'} \sum_{j' \in V} \sum_{sm' \in N} x_{i'j'sm'k'} \leq C_{sm'}, \forall\, k' \in K \quad ---(12)$$

$$\sum_{sm' \in N} x_{i'j'sm'k'} \leq 1 \;\; \forall\, i', j' \in V, \forall\, k' \in K \quad ---(13)$$

$$\sum_{j' \in V} \sum_{k' \in K} \sum_{sm' \in N} x_{i'j'sm'k'} = 2 \;\; \forall\, i' \in N_{syn\,v} \quad --(14)$$

$$OPT_{i'} \leq S_{i'} \leq CLT_{i'}, \forall i' \in V, \forall sm' \in N \quad ---(15)$$

$$S_{j'sm'} \geq S_{i'sm'} + ST_{i'} + TT_{i'j'k'} - M'(1 - x_{i'j'sm'k'}), \forall i', j' \in V, \forall sm' \in N, k' \in K \quad ---(16)$$

$$S_{0sm'} = 0 \;\; \forall sm' \in N \quad ---(17)$$

$$LDOT \leq l_{sm'} \leq LDCT \quad \forall sm' \in N \quad ---(18)$$

$$S_{j'sm'} \geq l_{sm'} + LD - M'(1 - x_{i'j'sm'k'}), \forall i', j' \in V, \forall sm' \in N, k' \in K \quad ---(19)$$

$$S_{i'sm'_1} = S_{i'sm'_2} \;\; \forall i' \in N_{syn\,v} \quad ---(20)$$

$$x_{i'j'sm'k'} \in \{0,1\}, \forall i', j' \in V, \forall sm' \in N, k' \in K \quad ---(21)$$

(Eqn. 6) and (Eqn. 7) states each vehicle start from the depot and returns to the depot after visiting the allotted patients exactly once. (Eqn. 8) indicates that each vehicle completes its route. (Eqn. 9) determine that if a vehicle serves a patient, it must also leave that patient. (Eqn. 10), (Eqn. 11), (Eqn. 12), ensure the different type of health care vehicle cannot to load more health care staff member than its capacities. (Eqn. 13) represents a vehicle may be shared by several sm′, but every move is given a distinct assignment to prevent unnecessary duplication, ensuring that each nurse can efficiently complete their tasks without overlap in responsibilities. (Eqn. 14) means every synchronised patient has a pair of sm′ assigned to them. (Eqn. 15) ensures every patient must start receiving care within the allotted time frame.

(Eqn. 16) makes sure that service at patient j′ doesn't begin until after service at node i′ is finished and it has travelled from patient i′ to patient j′. (Eqn. 17) indicates that all sm′ service starting time at HHCC are set to be zero. (Eqn. 18) guarantees that the lunch break takes place within the allocated lunch window. (Eqn. 19) confirms that the next patient will only receive care after the lunch break is over. (Eqn. 20) By enforcing the same service starting times, this constraint guarantees that synchronised patients needing several sm′ to receive simultaneous care. (Eqn. 21) describe binary variable indicating whether staff member sm′ visits patient j′ immediately after patient i′ using vehicle type k′.

ENHANCED ARTIFICIAL BEE COLONY ALGORITHM

The Artificial Bee colony algorithm is nature-inspired optimization algorithm based on foraging behaviour of honeybees. This algorithm is introduced by Karaboga (2005) [17]. The algorithm imitates how the real honeybees search for food sources and share information within a hive. ABC falls under the category of swarm intelligence algorithms and is commonly used for solving optimization problems. The artificial Bee colony algorithm which has 3 major stages is used in this work. Employer stage is redefining food sources according to neighbors nearby. Onlooker stage is updates solutions based on randomly selected sources. Scouts stage is creating random new solutions to a wide range search. In this work, ABC algorithm is enhanced by integrating the 2-OPT, multiple conflict objectives using normalization and weighted sum approach, fuzzy parameter to handle the uncertain situations of different type of time duration and CO_2 emissions in complex situation. This enhancement ABC algorithm is structured as follows:

Step 1: Initialization:

- Describe all input parameters of this problem.
- Convert the Neutrosophic triangular fuzzy data of different time duration and CO_2 emission into Crisp data by using score function.

- Initial solutions (food sources) are generated randomly. Every food source is a potential solution made up of customer-assigned priority values.
- The customers' visiting order is determined by these priority values.

Step 2: Fitness evaluation

- The customer visiting order is used to calculate the objective values for every food source, which include an overall travel distance, carbon emissions, travel cost, and visit cost. The Min-Max normalisation approach is used to scale these objective values between 0 and 1.
- Min–max normalization is used to make sure that various objective scales are related.

$$S_{no} = \frac{S - S_{o\,min}}{S_{o\,max} - S_{o\,min}}$$

where S_{no} – the objective's normalized value, S – actual value of objective, $S_{o\,min}$ – the objective's minimum value, $S_{o\,max}$ – the objective's maximum value.

- Following normalization, a weighted-sum aggregation technique is used to combine the various objectives into an aggregate scalar fitness value.

$$F_f = W_1' D_n' + W_2' TC_n' + W_3' VC_n' + W_4' E_n'$$

where F_f – Fitness function, D_n' - Normalized distance value, TC_n' - Normalized Travel cost value, VC_n' - Normalized visiting cost value, E_n' - Normalized emission value, W_1' , W_2' , W_3' , W_4' - weight parameter values. In this study, $W_1' = 0.25$, $W_2' = 0.10$, $W_3' = 0.10$, $W_4' = 0.55$.

Step 3: Employed Bee stage:

- By adding random perturbating to the current solution to generate the neighbor solution for each employed bee. Evaluating the fitness of the new solution.
- If the new solution is better, update the solution and its fitness value.

Step 4: Onlookers Stage:

- Select each solution based on its fitness value to evaluate the probability.
- Select a solution according to the calculated probability.
- Generating a new neighbor solution to evaluate the new solution.
- Update the solution along with its fitness value, if the new solution is improved.

Step 5: Scouts Stage:

- For several number of iterations, solution does not upgrade then replace the solution with new randomly generated solution.
- Update the fitness value according the new solution.

Step 6: 2-OPT

- Once the 3 bee stages are finished, the produced routes are refined using the 2-opt method.
- By eliminating overlapping routes and decreasing the needless travel distance, the 2-opt algorithm increases routing efficiency.
- To create the shortest route structures, it works by reversing specific route sections. An improved solution is retained, and its overall performance is improved if an ideal fitness value is found.

Step 7: Optimization:

The algorithm program runs for certain number of iterations to find optimal solution through the above 3 stages.

Step 8: Best solution:

The outcome with the lowest fitness value is chosen as the best solution once all iterations have been completed. The best customer priority order is represented by this solution.

Step 9: Priority Sorting

The priority values derived from the best answer are used to sort the customers. This arranged sequence establishes the customers' visiting order.

Step 10: Synchronized Visit

To ensure certain patients need synchronized visits, these visits are randomly selecting the patients and are included in the routes.

Step 11: Constructing Routes

Forming routes starting from depot and end at depot, staff member in each vehicle does not exceed vehicle's capacity limit and time window constraints.

***Step 12*:** The final outcome shows the optimised routes as well as all related outcomes.

ENHANCED MUTATAED CUCKOO SEARCH

The cuckoo search algorithm is a nature-inspired metaheuristic algorithm and it is mimics the behaviour of cuckoo bird. This algorithm is developed by Xin and Deb (2009). The 3 main rule for CS implementation and they are a single egg is laid by each cuckoo at time and it is placed in randomly chosen nest, the best nest with the highest-quality eggs will be promoted to the new generation, the number of available host nest is fixed and host bird identifies cuckoo eggs with probability $P_a \in (0,1)$. The new variant called mutated cuckoo search algorithm was introduced by Sangeetha and Srinivasan (2021). In this mutated cuckoo search algorithm, host nest is

selected randomly. The present study enhances the mutated cuckoo search algorithm through the incorporation of normalized weighted sum technique for multi-objective function and fuzzy parameters to deal with complex scenarios involving varying types of time duration and CO_2 emissions. The conceptual framework of this enhanced Mutated cuckoo search algorithm is as follows:

Step 1: Initialization

- Define input parameter and also some of the input data are generate random.
- Apply the score function to transform the Neutrosophic triangular fuzzy data with varying time durations and CO_2 emissions into Crisp data.
- A list of patient nodes should be shuffled randomly to create a variety of possible routes for population.

Step 2: Evaluation of fitness function:

- For every route, multiple objectives are calculated, such as distance, travel expenses, visiting costs, and emissions.
- The fitness function solutions that are used in this algorithm are determined using the same normalisation and weighted sum technique as in the Enhanced ABC algorithm.

Step 3: Neighborhood Local search 2-Opt

- Initialize a host nest. Choose a host nest to deposit fresh cuckoo egg.
- Find a nest at random from the population to serve as the host. Perhaps a new and improved solution will occupy the place of this nest.
- The 2-opt method reverses (swapping) the order of patient nodes in a particular section of the route in order to decrease the total distance and enhance initial solution quality and route efficiency.

Step 4: Levy flight

- Levy flight facilitates an investigation of the search space by avoiding local minima through the use of larger jumps.
- The existing route is modified to create a new route.

Step 5: Path relinking

- The process evaluates intermediate solutions as it progressively converts from one route to another.
- To find solutions between two routes by using path relinking. This process combines Diversification and local search.

Step 6: Inversion mutation

Routes can be mutated to produce new solutions by flipping a section of the routes.

Step 7: Abandon nest

- Worse solutions are handled by the abandon nest function, which replaces them with new routes created by inversion mutation.
- This guarantees that, in order to preserve population diversity, less than ideal solutions are eliminated and replaced with new ones.

Step 8: Merge route

By modifying routes to include any missing patients and allocating the number of routes to correspond with the number of vehicles, it provides that every patient is visited.

Step 9: Synchronized visit

Synchronized visit are incorporated for selected patients randomly and indicate this on the routes in order to verify that certain patient's simultaneous requirement. Each staff member does not exceed vehicle capacity and time window constraints.

Step 10: Update Best Solution

The best solution is updated if the currently generated solution yields a smaller fitness value than the best solution that had already been saved.

$$S_{Cur} < S_{Best}$$

Step 11: Termination Condition

All optimisation steps are continuously performed by the algorithm until the desired number of generations is attained. The best routes are listed as the final optimal solution once each iteration has been completed.

COMPUTATIONAL EXPERIMENTS

From the literature review, the instances were taken from Euchi et al. (2020), then the instance was modified and tested with randomly generated data. This experiment has been solved for more than 1000 patients. In this work, the dataset is organized into three categories, specifically small, medium, and large healthcare vehicles, which denote various instance classifications developed for computational testing. To evaluate the implementation of the suggested model under distinct levels of routing difficulty, different problem sizes, including 20, 50, and 80 patients, are considered for every data set type. To analyse the health care staff members sharing health care small, medium, and large vehicles with their capacities for trips to serve the patients and synchronised visits, include them in the route plan.

To investigate and handle the uncertainty in different types of time duration and CO_2 emission, they are taken as a single-valued neutrosophic fuzzy number. It is transformed into a crisp number by using the score function. This study's

fuzzy numbers and score function were taken from Srinivas & Prabakaran (2023). The datasets have been modified to incorporate different types of vehicles and uncertainty data because these parameters are absent from existing benchmarks. This experiment is considered for a one-day trip, including a lunch break in the route plan. Table 1 explains the modified set of instances, heterogeneous vehicles, fuzzy time duration used in this study and Table 2 describes the required parameters for this specific problem. To the best of our knowledge, there are no existing modified instances like this for the HHC scheduling and routing problem.

Table 1: Modified Instance Dataset

Vehicle Type	Instance	Number of patients	Number of health care staff members	Synchronized visits	Time windows		
					Small Time Duration	Medium Time Duration	Large Time Duration
Small Vehicle	1	20	4	2	[1.4,1.5,1.7; 0.98,0.05,0.03]	[1.8,2.1,3.1; 0.89,.12,0.09]	[2.6,2.9,3.8; 0.91,0.04,0.02]
	2	20	4	2	[1.5,1.8,2.8; 0.88,0.1,0.05]	[2.6,2.9,3.8; 0.95,0.06,0.04]	[3.6,3.9,4.8; 0.98,0.07,0.02]
	3	20	4	2	[1,1.6,2.5; 0.9,0.09,0.07]	[2.3,2.5,3.4; 0.79,0.02,0.01]	[3.1,3.4,4.2; 0.91,0.02,0.01]
	4	20	4	2	[1.2,1.5,2.3.; 0.73,0.02,0.01]	[2,2.4,3.2; 0.95,0.4,0.3]	[2.6,3.0,3.9; 0.9,0.04,0.01]
	5	20	4	2	[1.2,1.6,2.5; 0.81,0.02,0.01]	[2.2,2.5,3.4; 0.89,0.04,0.02]	[3,3.4,4.3; 0.94,0.04,0.01]
	6	50	10	5	[1.1,1.4,2.2; 0.76,0.03,0.01]	[2,2.3,3.1; 0.89,0.04,0.01]	[2,3.1,3.9; 0.93,0.03,0.02]
	7	50	10	5	[1.2,1.5,2.3; 0.82,0.1,0.02]	[1.9,2.2,3.0; 0.09,0.06,0.01]	[2.7,3.0,3.9; 0.87,0.4,0.01]
	8	50	10	5	[1.3,1.6,2.4; 0.78,0.04,0.01]	[2.2,2.5,3.4; 0.9,0.06,0.03]	[3.1,3.4,4.3; 0.88,0.05,0.04]
	9	80	16	8	[1.2,1.5,2.3; 0.72,0.01,0.01]	[2,2.3,3.1; 0.88,0.02,0.02]	[2.6,2.9,3.9; 0.84,0.02,0.01]
	10	80	16	8	[1.2,1.5,2.3; 0.8,0.03,0.02]	[2,2.3,3.2; 0.83,0.01,0.01]	[2.6,2.9,3.8; 0.88,0.02,0.02]
Medium Vehicle	11	20	4	2	[1.4,1.7,2.6; 0.8,0.09,0.01]	[1.9,2.2,3.1; 0.83,0.06,0.01]	[2.7,3,3.9; 0.9,0.04,0.03]
	12	20	4	2	[1,1.3,2.1; 0.8,0.05,0.01]	[1.8,2.1,2.9; 0.91,0.04,0.04]	[2.8,3.2,4.1; 0.96,0.04,0.04]
	13	20	4	2	[1.1,1.5,2.4; 0.85,0.1,0.05]	[2.1,2.4,3.3; 0.9,0.05,0.03]	[2.9,3.2,4.2; 0.89,0.03,0.02]
	14	20	4	2	[1.5,1.8,2.7; 0.83,0.05,0.02]	[2.6,2.9,3.8; 0.9,0.05,0.02]	[3.6,3.9,4.8; 0.97,0.05,0.02]
	15	20	4	2	[1.2,1.5,2.3; 0.77,0.04,0.04]	[2.1,2.4,3.1; 0.94,0.03,0.03]	[2.9,3.2,4.1; 0.9,0.02,0.02]
	16	50	10	5	[1.2,1.6,2.6; 0.79,0.05,0.05]	[2.2,2.5,3.6; 0.88,0.06,0.03]	[3,3.4,4.4; 0.89,0.02,0.01]
	17	50	10	5	[1.3,1.7,2.7; 0.79,0.03,0.02]	[1.7,2.1,3.0; 0.86,0.03,0.03]	[2.5,2.9,3.9; 0.89,0.03,0.03]
	18	50	10	5	[1.1,1.5,2.4; 0.8,0.1,0.01]	[2,2.4,3.2; 0.88,0.01,0.01]	[2.8,3.2,4.2; 0.88,0.03,0.02]
	19	80	16	8	[1.3,1.6,2.5; 0.77,0.1,0.01]	[2.3,2.6,3.5; 0.85,0.02,0.02]	[3.3,3.6,4.4; 0.93,0.03,0.03]
	20	80	16	8	[1.4,1.8,2.9; 0.9,0.09,0.09]	[2.2,2.6,3.6; 0.87,0.03,0.03]	[3.0,3.4,4.5; 0.9,0.03,0.03]
Large Vehicle	21	20	4	2	[1.2,1.5,2.5; 0.79,0.06,0.06]	[2.1,2.4,3.4; 0.89,0.07,0.06]	[2.7,3.0,4; 0.9,0.06,0.04]
	22	20	4	2	[1,1.4,2.3; 0.8,0.03,0.03]	[1.9,2.3,3.2; 0.94,0.07,0.04]	[2.8,3.1,4.0; 0.92,0.08,0.02]
	23	20	4	2	[1.4,1.7,2.8; 0.8,0.06,0.06]	[1.8,2.2,3.2; 0.79,0.02,0.02]	[2.6,3.0,4.0; 0.86,0.03,0.02]
	24	20	4	2	[1,1.3,2.2; 0.75,0.05,0.02]	[1.8,2.1,3.1; 0.87,0.08,0.07]	[2.9,3.2,4.3; 0.88,0.04,0.03]
	25	20	4	2	[1.4,1.7,2.9; 0.69,0.02,0.01]	[1.9,2.2,3.3; 0.78,0.05,0.04]	[2.7,3.0,4.2; 0.86,0.05,0.04]
	26	50	10	5	[1.3,1.5,2.5; 0.6,0.02,0.02]	[2.2,2.4,3.4; 0.83,0.04,0.04]	[3.0,3.2,4.4; 0.87,0.06,0.06]
	27	50	10	5	[1.1,1.4,2.4; 0.8,0.09,0.09]	[2,2.3,3.3; 0.89,0.06,0.05]	[2.8,3.1,4.1; 0.9,0.04,0.04]
	28	50	10	5	[1.2,1.4,2.4; 0.79,0.09,0.09]	[2.1,2.3,3.3; 0.9,0.07,0.07]	[2.9,3.1,4.1; 0.9,0.05,0.05]

	29	80	16	8	[1.5,1.7,2.9; 0.78,0.08,0.08]	[2.3,2.4,3.4; 0.87,0.08,0.08]	[3.3,3.5,4.4; 0.94,0.06,0.05]
	30	80	16	8	[1.4,1.6,2.6; 0.8,0.08,0.08]	[2.3,2.5,3.6; 0.87,0.07,0.07]	[3.5,3.8,4.7; 0.88,0.05,0.03]

Table 2: Parameter Setting

Parameters	**Surfaces**
(X_j, Y_j)	U|3,9|
d_{ij}	$\sqrt{(Y_i - Y_j)^2 + (Z_i - Z_j)^2}$
opt_i	(8,10)
clt_i	(14,17)
svc_{ij}	(250,650)
avs_1	40
avs_2	50
avs_3	60
$A_{sm'}$	(3+1) seaters
$B_{sm'}$	(5+1) seaters
$C_{sm'}$	(9+1) seaters
travel cost for small vehicle	(13, 20)
travel cost for medium vehicle	(20, 30)
travel cost for large vehicle	(25, 40)
sl_s	(0, 1)
Lunch duration	1 hour
Service time	(0.4, 1.4)
CO_2 emission of vs_1	[(0.1159,0.1161,0.1170; 0.99,0.01,0.01)]
CO_2 emission of vs_2	[(0.1211,0.1213,0.1225; 0.99,0.01,0.01)]
CO_2 emission of vs_3	[(0.145,0.147,0.157; 0.98,0.01,0.01)]

RESULT AND DISCUSSION

This study's computational results are based on the healthcare routing and scheduling model described in Euchi et al. (2020), which takes synchronised visits, healthcare providers' routing, and time window constraints into account to reduce the total time. The Euchi et al. (2020) study's benchmark instance structure is derived from standard datasets presented in Bredström and Rönnqvist (2008), where time window classifications for small, medium, and large were established. To make improvements that reflect variations in operation across the real world, the initially developed instances were expanded in the current work by adding uncertain time window durations and randomly generated travel distances, service time, travel cost, and visiting cost parameters. To improve allocating resources efficiently and representing actual healthcare transporting environments, predetermined vehicle capacity limitations and heterogeneous vehicle arrangements—such as vehicle size, seating capacity, and staff vehicle-sharing techniques—were also included. The outcomes produced by algorithms EABCA and EMCSA show that both approaches were successful in producing effective routes that met time window limitations, prescribed vehicle capacity restrictions, and synchronization requirements. Meanwhile, by reducing an inefficient travel distance and increasing scheduling effectiveness in an unpredictable operating environment, EABCA constantly outperformed EMCSA in terms of routing efficiency. These results are consistent with previous research, including Afifi et al. (2016) and Decerle et al. (2018), where improved outcomes for healthcare routing environments were attributed to improvements in planning adaptability and routing effectiveness. Since direct numerical comparison with deterministic Euchi et al. (2020) study results was not possible due to the incorporation of uncertainty, heterogeneous vehicles, and additional operational factors in the current work, performance analysis was conducted according to route performance, travel distance, travel cost, visiting cost, CO_2 emission is minimised, scheduling effectiveness and capacity usage.

In this paper, a mathematical model is incorporated into the EMCSA and the EABCA and the computational experiments were performed by Python 3.12. For every benchmark instance, EABCA and EMCSA have been executed several times separately, and the optimal objective values from each run was noted. The weighted sum approach is used to address the problem's multiple objectives. Tables 3-5 present each objective value in the original units of ABC algorithm, while tables 6-8 show each objective value along with the corresponding units of MCS algorithm for heterogeneous vehicles.

Table 3 Enhancing ABC Algorithm Result for small vehicle

Instance	Distance (km)	Travel Cost	Visiting Cost for all staff members	Travel time for all staff members (hrs)	Service time for all staff members (hrs)	Service level for all staff members	CO_2 emission (kg)	CPU (Sec)
1	61.984	867.933	4905.395	1.549	13.35	3.122	7.196	0.000
2	64.259	926.225	4863.95	1.605	13.23	1.88	7.459	0.0051
3	65.404	925.92	4723.5091	1.626	11.33	2.77	7.594	0.0469
4	58.954	833.317	4686.378	1.477	14.69	1.68	6.84	0.000
5	56.117	768.098	5205.179	1.4027	11.25	1.457	6.515	0.0312
6	61.795	877.697	5121.479	1.545	13.85	2.67	7.175	0.000
7	69.716	1050.817	14083.727	1.918	35.17	2.05	8.907	0.0625
8	60.54	825.394	5056.56	1.5	13.94	1.78	7.018	0.0156
9	84.423	1213.77	7738.901	2.09	20.95	3.185	9.78	0.000
10	86.883	1201.107	7316.784	2.171	21.71	4.63	10.086	0.0156

Table 4 Enhancing ABC Algorithm Result for medium vehicle

Instance	Distance (km)	Travel Cost	Visiting Cost for all staff members	Travel time for all staff members (hrs)	Service time for all staff members (hrs)	Service level for all staff members	CO_2 emission (kg)	CPU (sec)
11	57.696	1215.946	1494.101	1.154	23.66	2.61	6.998	0.0312
12	35.604	786.401	1652.54	0.712	16.65	1.365	4.318	0.000
13	33.267	800.544	1833.502	0.6653	13.2	0.874	4.035	0.0156
14	32.6337	702.574	1956.336	0.653	13.83	0.704	4.026	0.000
15	37.859	778.615	1868.78	0.7573	12.41	0.675	4.592	0.000
16	59.836	1263.403	2910.68	1.197	26.12	1.612	7.257	0.0469
17	78.606	1689.718	2608.787	1.571	24.73	2.258	9.535	0.0625
18	63.034	1336.165	8188.992	1.26	25.99	2.109	7.645	0.0156
19	93.802	2103.623	12267.761	1.876	40.22	4.717	11.377	0.0469
20	99.706	2275.338	11713.513	1.994	38.5	2.395	12.099	0.0469

Table 5 Enhancing ABC Algorithm Result for large vehicle

Instance	Distance (km)	Travel Cost	Visiting Cost for all staff members	Travel time for all staff members(hrs)	Service time for all staff members (hrs)	Service level for all staff members	CO_2 emission (kg)	CPU (sec)
21	37.838	974.388	7015.231	0.632	12.519	1.225	5.562	0.0312
22	40.817	1176.167	6346.726	0.68	31.15	1.701	6.001	0.0156
23	37.278	1065.382	6569.635	0.622	28.54	1.276	5.48	0.0156
24	36.165	953.618	6366.042	0.603	24.4	0.677	5.316	0.000
25	41.091	1157.573	6910.528	0.685	27.92	1.105	3.041	0.000
26	80.463	2067.698	14451.881	1.348	59.18	1.8	11.828	0.0469
27	73.556	2069.171	14132.791	1.226	61.869	2.038	10.811	0.0938
28	78.191	2040.53	14431.354	1.302	63.15	2.159	11.494	0.0625
29	123.624	3353.658	21693.88	2.06	69.06	3.615	18.171	0.0625
30	114.428	3278.102	21140.1486	1.904	87.52	2.137	16.807	0.0469

Table 6 Enhancing MCSA Result for small vehicle

Instance	Distance (km)	Travel Cost	Visiting Cost for all staff members	Travel time for all staff members(hrs)	Service time for all staff members (hrs)	Service level for all staff members	CO_2 emission (kg)	CPU (sec)
1	64.192	868.949	5054.82	1.6046	12.36	1.25	7.454	0.0156
2	66.031	933.545	4980.3026	1.649	14.94	2.64	7.6651	0.0156
3	68.561	1018.277	5021.416	1.713	13.72	1.376	7.955	0.0151
4	63.177	949.182	4898.72	1.580	15.44	1.287	7.334	0.0312
5	59.958	852.772	5259.105	1.499	11.82	0.947	6.96	0.0469
6	61.795	923.332	5227.13	1.632	14.3	2.331	7.587	0.1250
7	79.952	1296.891	14256.596	1.999	36.18	2.098	9.282	0.2031
8	60.542	825.394	5606.272	1.514	16.75	2.322	7.028	0.000

9	88.865	1289.152	7738.901	2.221	20.95	3.774	10.3173	0.0312
10	95.889	1369.746	7995.954	2.39	22.55	3.983	11.133	0.0938

Table 7 Enhancing MCSA Result for medium vehicle

Instance	Distance (km)	Travel Cost	Visiting Cost for all staff members	Travel time for all staff (hrs)	Service time for all staff members (hrs)	Service level for all staff members	CO_2 emission (kg)	CPU (sec)
11	64.96	1823.107	6738.6	1.29	27.5	1.51	7.885	0.0156
12	82.688	2346.234	3976.899	1.65	18.61	1.54	10.024	0.0938
13	74.201	2025.242	1833.502	1.477	25.68	1.377	9.03	0.0469
14	83.441	2448.782	3728.977	1.668	24.68	1.386	10.121	0.0625
15	87.094	1953.402	3944.223	1.742	21.52	1.033	10.566	0.000
16	67.321	1587.411	8869.272	1.346	29.3	1.738	8.167	0.2031
17	79.213	1741.073	8086.856	1.58	32.93	1.989	9.608	0.2344
18	63.099	1402.88	8504.28	1.26	29.68	1.909	7.655	0.0166
19	102.793	2209.225	12716.725	2.056	46.11	3.393	12.469	0.0469
20	104.611	2446.93	11754.653	2.093	40.72	2.168	12.689	0.0625

Table 8 Enhancing MCSA Result for large vehicle

Instance	Distance (km)	Travel Cost	Visiting Cost for all staff members	Travel time for all staff (hrs)	Service time for all staff members (hrs)	Service level for all staff members	CO_2 emission (kg)	CPU (Sec)
21	39.557	1220.692	7236.038	0.659	25	1.301	5.815	0.0625
22	43.914	1221.326	7196.916	0.732	29	1.388	6.456	0.0156
23	41.267	1118.433	7235.804	0.687	28.6	0.264	6.066	0.0625
24	37.002	1119.209	7083.707	0.617	29.7	0.988	5.439	0.03 12
25	41.741	1225.203	7034.939	0.695	28.81	1.087	6.137	0.0412
26	80.805	2244.636	14639.2098	1.337	60.88	2.453	11.878	0.1250
27	77.659	2368.193	14218.359	1.294	65.61	2.778	11.416	0.1094
28	78.194	2110.835	14966.602	1.303	64.2	2.541	11.494	0.0938
29	131.643	3959.928	21815.994	2.192	76.2	2.168	19.36	0.0938
30	123.02	3445.162	21366.741	2.051	89.47	3.131	18.082	0.1719

To describe the algorithm's performance, the best values from each instance were used to calculate the overall mean μ′ and standard deviation σ′, and the Tables 9,10 and 11 display the normalised weighted sum values (Z), which serve as a common metric for comparing the algorithms overall objective values. Both the EABCA and EMCSA are solved and provide their output values for multi-objective functions such as distance, health care staff visiting cost, travel cost, and CO_2 emission. The normalization weighted-sum aggregation method is used to solve the multi-objective function. The EABCA gives better results in comparison to the EMCSA for small, medium, and large vehicle types.

Table 9 Comparison table for small vehicle

Enhance ABC Algorithm			Enhance Mutated Cuckoo Search Algorithm	
Instance	**Z**	**CPU (sec)**	**Z**	**CPU (sec)**
1	0.3605	0.000	0.3687	0.0156
2	0.4248	0.0051	0.4348	0.0156
3	0.4014	0.0469	0.4152	0.0151
4	0.3871	0.000	0.3989	0.0312
5	0.3837	0.0312	0.4451	0.0469
6	0.1164	0.000	0.1719	0.1250
7	0.2166	0.0625	0.2232	0.2031
8	0.1627	0.0156	0.1649	0.000
9	0.1376	0.000	0.1393	0.0312
10	0.1386	0.0156	0.1453	0.0938

Mean μ′	0.2729	0.0176	0.2907	0.0577
SD σ′	0.1219	0.0211	0.1251	0.0609

Table 10 Comparison table for medium vehicle

Enhance ABC Algorithm			Enhance Mutated Cuckoo Search Algorithm	
Instance	**Z**	**CPU (sec)**	**Z**	**CPU (sec)**
11	0.4151	0.0312	0.4232	0.0156
12	0.2074	0.000	0.2192	0.0938
13	0.2217	0.0156	0.2721	0.0469
14	0.2205	0.000	0.2382	0.0625
15	0.2273	0.000	0.2441	0.000
16	0.1635	0.0469	0.1782	0.2031
17	0.1807	0.0625	0.1836	0.2344
18	0.1662	0.0156	0.1727	0.0166
19	0.1542	0.0469	0.1645	0.0469
20	0.1554	0.0469	0.1664	0.0625
Mean μ′	0.2112	0.0266	0.2262	0.0782
SD σ′	0.0732	0.0222	0.0747	0.0752

Table 11 Comparison table for large vehicle

Enhance ABC Algorithm			Enhance Mutated Cuckoo Search Algorithm	
Instance	**Z**	**CPU (sec)**	**Z**	**CPU (sec)**
21	0.2766	0.0312	0.2826	0.0625
22	0.2946	0.0156	0.3176	0.0156
23	0.2744	0.0156	0.2895	0.0625
24	0.296	0.000	0.3001	0.0312
25	0.3026	0.000	0.3145	0.0412
26	0.2025	0.0469	0.2228	0.1250
27	0.2091	0.0938	0.2235	0.1094
28	0.2351	0.0625	0.2372	0.0938
29	0.2045	0.0625	0.2092	0.0938
30	0.1994	0.0469	0.2026	0.1719
Mean μ′	0.01769	0.0375	0.05775	0.08069
SD σ′	0.0211	0.0289	0.0609	0.0452

CONCLUSION

This work presents multi-objective HHC vehicle routing and scheduling problems in uncertain situations, along with synchronised visits and vehicle sharing strategies. In this work, a mixed-integer mathematical formulation was created, and two existing heuristic algorithms were combined with a normalization weighted-sum technique to address this multi-objective problem. The numerical experiment was solved by enhanced ABCA and enhanced MCSA for the modified instances. The outcomes of the computational experiment with enhanced ABCA provide better performance compared to enhanced MCSA. Comparison of objectives shows that better routing and distribution choices can lower travel distance, travel expenses, visiting costs and emissions without affecting service quality. The benchmark instances were extended and modified because the existing benchmark did not contain the required information. The extensions presented in this paper offer home healthcare organisations a more effective and efficient planning framework. In the future, the work can be extended to IoT technology, multi-modal, real-life case studies, dynamic planning with time synchronization, and AI and ML optimisation techniques for home health care management systems.

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REFERENCES

Afifi, S., Dang, D. C., & Moukrim, A. (2016). Heuristic solutions for the vehicle routing problem with time windows and synchronized visits. *Optimization Letters*, *10*(3), 511-525. https://doi.org/10.1007/s11590-015-0878-3

Bertels, S., & Fahle, T. (2006). A hybrid setup for a hybrid scenario: combining heuristics for the home health care problem. *Computers &*

operations research, *33*(10), 2866-2890. https://doi.org/10.1016/j.cor.2005.01.015

Bredström, D., & Rönnqvist, M. (2008). Combined vehicle routing and scheduling with temporal precedence and synchronization constraints. *European journal of operational research*, *191*(1), 19-31. https://doi.org/10.1016/j.ejor.2007.07.033

Cissé, M., Yalçındağ, S., Kergosien, Y., Şahin, E., Lenté, C., & Matta, A. (2017). OR problems related to Home Health Care: A review of relevant routing and scheduling problems. *Operations research for health care*, *13*, 1-22. https://doi.org/10.1016/j.orhc.2017.06.001

Coelho, L. C., Gagliardi, J. P., Renaud, J., & Ruiz, A. (2016). Solving the vehicle routing problem with lunch break arising in the furniture delivery industry. *Journal of the Operational Research Society*, *67*(5), 743-751. https://doi.org/10.1057/jors.2015.90

Decerle, J., Grunder, O., El Hassani, A. H., & Barakat, O. (2019). A memetic algorithm for multi-objective optimization of the home health care problem. *Swarm and evolutionary computation*, *44*, 712-727. https://doi.org/10.1016/j.swevo.2018.08.014

Decerle, J., Grunder, O., El Hassani, A. H., & Barakat, O. (2018). A memetic algorithm for a home health care routing and scheduling problem. *Operations research for health care*, *16*, 59-71. https://doi.org/10.1016/j.orhc.2018.01.004

El-Amraoui, A., Harbi, S., & Moh, A. N. S. (2022). Home health care scheduling problem under uncertainty: Robust optimization approaches. *Computing and Informatics*, *41*(1), 288-308. https://doi.org/10.31577/cai_2022_1_288

Euchi, J., Zidi, S., & Laouamer, L. (2020). A hybrid approach to solve the vehicle routing problem with time windows and synchronized visits in-home health care. *Arabian journal for science and engineering*, *45*(12), 10637-10652. https://doi.org/10.1007/s13369-020-04828-5

Eveborn, P., Flisberg, P., & Rönnqvist, M. (2006). Laps Care—an operational system for staff planning of home care. *European journal of operational research*, *171*(3), 962-976. https://doi.org/10.1016/j.ejor.2005.01.011

Fathollahi-Fard, A. M., Hajiaghaei-Keshteli, M., & Tavakkoli-Moghaddam, R. (2018). A bi-objective green home health care routing problem. Journal of Cleaner Production, 200, 423-443. https://doi.org/10.1016/j.jclepro.2018.07.258

Fathollahi-Fard, A. M., Ahmadi, A., & Karimi, B. (2020). A robust optimization for a home healthcare routing and scheduling problem considering greenhouse gas emissions and stochastic travel and service times. In *Green Transportation and New Advances in Vehicle Routing Problems* (pp. 43-73). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-45312-1_2

Fathollahi-Fard, A. M., Ahmadi, A., Goodarzian, F., & Cheikhrouhou, N. (2020). A bi-objective home healthcare routing and scheduling problem considering patients' satisfaction in a fuzzy environment. *Applied soft computing*, *93*, 106385. https://doi.org/10.1016/j.asoc.2020.106385

Fikar, C., & Hirsch, P. (2015). A matheuristic for routing real-world home service transport systems facilitating walking. *Journal of Cleaner Production*, *105*, 300-310. https://doi.org/10.1016/j.jclepro.2014.07.013

Goodarzian, F., Goodarzian, A., Abraham, A., & Dastgoshade, S. (2020, December). Home health care network management under fuzzy environment using meta-heuristic algorithms. In *International Conference on Soft Computing and Pattern Recognition* (pp. 320-332). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-73689-7_31

Goodarzian, F., Abraham, A., & Fathollahi-Fard, A. M. (2021). A biobjective home health care logistics considering the working time and route balancing: a self-adaptive social engineering optimizer. *Journal of Computational Design and Engineering*, *8*(1), 452-474. https://doi.org/10.1093/jcde/qwaa089

Karaboga, D. (2005). *An idea based on honey bee swarm for numerical optimization* (Vol. 200, pp. 1-10). Technical report-tr06, Erciyes university, engineering faculty, computer engineering department.

Kordi, G., Divsalar, A., & Emami, S. (2023). Multi-objective home health care routing: a variable neighborhood search method: Gh. Kordi et al. *Optimization Letters*, *17*(9), 2257-2298. https://doi.org/10.1007/s11590-023-01993-y

Lim, M. K., Wang, J., Wang, C., & Tseng, M. L. (2020). A novel method for green delivery mode considering shared vehicles in the IoT environment. *Industrial Management & Data Systems*, *120*(9), 1733-1757. https://doi.org/10.1108/IMDS-02-2020-0078

Liu, R., Tao, Y., & Xie, X. (2019). An adaptive large neighborhood search heuristic for the vehicle routing problem with time windows and synchronized visits. *Computers & Operations Research*, *101*, 250-262. https://doi.org/10.1016/j.cor.2018.08.002

Liu, W., Dridi, M., Fei, H., & El Hassani, A. H. (2021). Hybrid metaheuristics for solving a home health care routing and scheduling problem with time windows, synchronized visits and lunch breaks. *Expert Systems with Applications*, *183*, 115307. https://doi.org/10.1016/j.eswa.2021.115307

Nasir, J. A., & Kuo, Y. H. (2020). A decision support framework for home health care transportation with simultaneous multi-vehicle routing and staff scheduling synchronization. *Decision Support Systems*, *138*, 113361. https://doi.org/10.1016/j.dss.2020.113361

Sangeetha, R. V., & Srinivasan, A. G. (2021). Mutated cuckoo search algorithm for dynamic vehicle routing problem and synchronization occurs within the time slots in home healthcare. *International Journal of System Assurance Engineering and Management*, 1-17. https://doi.org/10.1007/s13198-021-01300-x

Sarasola, B., & Doerner, K. F. (2021). Solving a Multi-objective Vehicle Routing Problem with Synchronization Constraints. In *International Conference on Computational Logistics* (pp. 532-546). Cham: Springer International Publishing. DOI:10.1007/978-3-030-87672-2_35

Shi, Y., Boudouh, T., & Grunder, O. (2017). A hybrid genetic algorithm for a home health care routing problem with time window and fuzzy demand. *Expert Systems with Applications*, *72*, 160-176. https://doi.org/10.1016/j.eswa.2016.12.013

Shi, Y., Boudouh, T., & Grunder, O. (2019). A robust optimization for a home health care routing and scheduling problem with consideration of uncertain travel and service times. *Transportation Research Part E: Logistics and Transportation Review*, *128*, 52-95. https://doi.org/10.1016/j.tre.2019.05.015

Shiri, M., Ahmadizar, F., Thiruvady, D., & Farvaresh, H. (2023). A sustainable and efficient home health care network design model under uncertainty. *Expert Systems with Applications*, *211*, 118185. https://doi.org/10.1016/j.eswa.2022.118185

Srinivas, S., & Prabakaran, K. (2023). Optimization of single-valued triangular neutrosophic fuzzy travelling salesman problem. *Neutrosophic Sets & Systems*, *60*, 366.

Trautsamwieser, A., & Hirsch, P. (2014). A Branch-Price-and-Cut approach for solving the medium-term home health care planning problem. *Networks*, *64*(3), 143-159. https://doi.org/10.1002/net.21566

Tanoumand, N., & Ünlüyurt, T. (2021). An exact algorithm for the resource constrained home health care vehicle routing problem. *Annals of Operations Research*, *304*(1), 397-425. https://doi.org/10.1007/s10479-021-04061-9

Wang, Y., Sun, Y., Guan, X., Fan, J., Xu, M., & Wang, H. (2021). Two-echelon multi-period location routing problem with shared transportation resource. *Knowledge-Based Systems*, *226*, 107168. https://doi.org/10.1016/j.knosys.2021.107168

Yang, X. S., & Deb, S. (2009, December). Cuckoo search via Lévy flights. In *2009 World congress on nature & biologically inspired computing (NaBIC)* (pp. 210-214). Ieee. https://doi.org/10.1109/NABIC.2009.5393690

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RESEARCH ARTICLE

Low-Power Tuneable Operational Transconductance Amplifier Low-Pass Filter at 90nm CMOS

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ABSTRACT

Analog circuits for biomedical applications often have low power and low voltage requirement for processing low-frequency and low-amplitude EEG, ECG, and EMG signals. Existing Operational amplifier (Op-Amp) based analog circuits suffer from high power consumption and lack electronic tuneability. Consequently, Operational Transconductance Amplifiers (OTAs) have emerged as a suitable replacement, offering lower power consumption, better linearity, and carries external bias control connection to tune circuital parameters. In this regard, this work showcases a complementary-input, fully differential, CMOS, OTA based low-pass filter for low power biosignal processing application. The filter is designed with the help of 90nm CMOS technology and applies a bias voltage control technique in which tuning voltage regulates the bias current and transconductance through NMOS current sink transistor. At a voltage V_{bais}= 500 mV and supply voltage of 1V, the filter has achieved a maximum gain of 22.56 dB, a cut-off frequency of about 270.8 Hz, an input referred noise (IRN) of 665 nV/sqrt(Hz) and power consumption of only 32.91 µW which indicates that the low-frequency response can be effectively tuned by varying the bias voltage. Monte carlo simulation demonstrates negligible deviation of total power consumption against their respective mean value, establishing insensitivity of the filter to the process and mismatch variations. Compared to previously reported filters, the proposed filter offers a low cut-off frequency f_c , low input referred noise (IRN), low power consumption and provide a basis for selecting a bias condition for the low frequency biosignal applications.

Keywords *- OTA (Operational Transconductance Amplifier), Fully Differential OTA, Bias-Voltage Control, Low-Power CMOS.*

INTRODUCTION

The use of portable and wearable healthcare systems has increased the demand for compact and low-power analog circuits (Lou, Z., et al. 2026 & Xu, J., et. al. 2025). Biosignals such as EEG (electroencephalogram), ECG (electrocardiogram) and EMG (electromyogram) are generally small in amplitude and contain low-frequency information (Yan, F. and Liu, J., 2025; Liu, F. and Lorenzelli, L. 2024; Mehrabi Moghadam, Z., et al. 2025; Emon, M. Z. A., et al. 2024). Analog circuits used to process these signals require sufficient gain for proper signal amplification. At the same time, low noise, low power consumption, and low distortion are important for maintaining the signal quality and reliable operation (Kledrowetz, V., et al. 2023; Kulej, T., et. al. 2026; Lo, T.-Y., et al. 2007; Rezaei, F., et al. 2011).

The performance of CMOS operational transconductance amplifiers (OTAs) is dependent

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on the transistor operating point and bias conditions. In OTA-based continuous-time filters, the transconductance g_m directly influences the filter cutoff frequency, while the bias current affects power consumption (Moosaei, A., et al 2015; Maheshwari, S. and Pandya, J. P., et al. 2018; Kumngern, M., et. al. 2024). Therefore, varying the bias voltage or current provides an effective way to electronically tune the filter frequency response without changing the supply voltage (Yin, Y., et al. 2024; Choi, J., et al. 2023). Various CMOS OTA and electronically tunable filters have been previously reported in the literature for low-power and tunable analog signal-processing applications. (Kulej, T., et al 2024) presented a multiple-input fully differential OTA operating at a 0.5 V supply and evaluated its used in a fifth-order Chebyshev low-pass filter designed for bio-signal processing applications. The reported filter achieved a power consumption of 60 nW while operating at a 0.5-V supply voltage, with a total harmonic distortion of 0.97%. The Monte Carlo simulations, and temperature dependent evaluation were also done to assess the circuits performance under varying operating conditions. The OTA operated at a 0.4-V supply with power consumption below 30 nW, and its application as a low pass filter with a cutoff frequency of 250-Hz. (Khateb, F., et al. 2022) reported multiple input OTA-based filter designed to suppress noise and motion related disturbances in the biosignal acquisition, including low-pass and band-pass filtering functions for biomedical signal-processing applications. (Kumngern, M., et al. 2025) reported a tunable third order elliptic low-pass filter based on an OTA-C architecture, operating at a supply voltage of 450-mV for biosignal application. The reported filter consumed 40.5 nW of power, and achieved a cutoff frequency of 112.9 Hz, and a dynamic range reached 66.7 dB under 1% THD condition. Monte Carlo analysis and PVT analysis have also been performed. Other a low-voltage OTA-C and Gm-C filter techniques have also been reported for biomedical and low-frequency signal-processing applications (Phatsornsiri, P., et al. 2025; Srinivasagan, R., 2025; Ram Babu, R., Et al. 2017).

In this work, a fully differential CMOS OTA is configured as a low-pass filter for the low-frequency biosignal-processing applications. The proposed architecture employs complementary PMOS and NMOS differential input stages for differential signal processing. Current-mirror and current-steering structures are used to establish the signal-processing paths and differential output operation. A controllable NMOS current-sink transistor is incorporated to provide bias control. By varying the voltage $V_{bias,}$ applied to this transistor, the operating current and small-signal transconductance g_m of given OTA can be controlled, resulting in a tunable filter response. The influence of the bias voltage on gain, cutoff frequency, noise, total harmonic distortion, and power consumption is investigated.

The proposed circuit is designed in Cadence Virtuoso with a 90-nm CMOS technology, at supply voltage of 1-V. The bias voltage is varied from 100 mV to 900 mV to investigate its effect on the main circuit parameters. DC, AC, transient, noise, harmonic-distortion, and Monte Carlo analyses are performed under different bias conditions. The investigated parameters include gain, cutoff frequency, noise, total harmonic distortion, and power consumption.

PROPOSED MODIFIED OTA ARCHITECTURE

The proposed OTA based filter, implemented using 90-nm CMOS technology, is reported in Figure 1. It uses bias-voltage-controlled technique to optimize parameters at a 1 V supply voltage and 500 mV bias voltage.

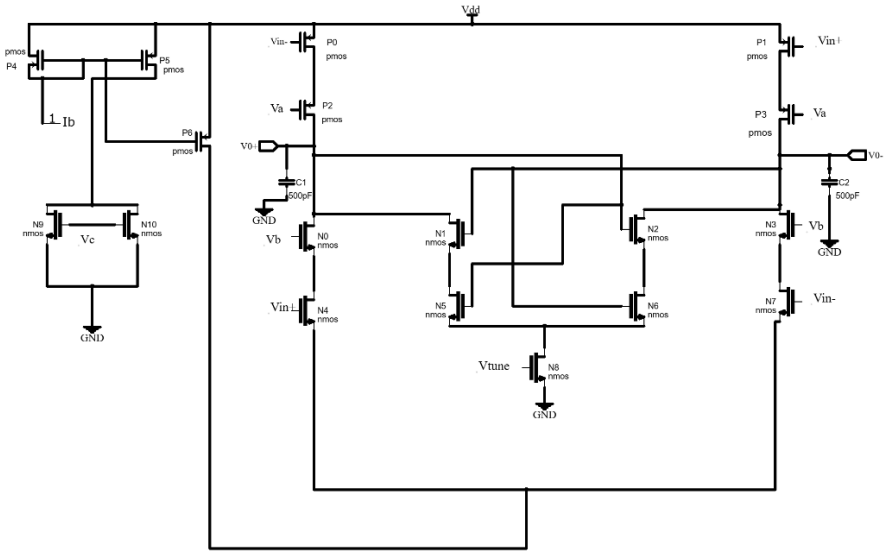

Figure 1. Proposed fully differential CMOS OTA-based low-pass filter with bias control.

The filter uses complementary PMOS and NMOS differential input stages where input signals are applied at V_{in+} and V_{in-} through PMOS transistor P_1 and NMOS transistor N_7 while bias voltage V_a and V_b controls the active load and gain stages. The PMOS transistors from P_0 to P_6 forms upper current mirror network, NMOS transistor from N_0 to N_7 shows differential amplifier, current-steering and gain stages, transistor N_8 represents controllable current sink device, capacitor C_1 and C_2 (=500pF) at input and output terminals is used for capacitive loading respectively while output is taken across V_O.

Differential current mirrors and output branches are used to obtain a fully differential output. The voltage V_{bias} applied at the gate terminal of NMOS transistor N8, and this voltage changes the operating current of the associated transistor network. The circuit does not use a separate bias-voltage-controlled technique. Instead, the main control used in this work is bias-voltage control. The voltage applied to N8 is varied to change the transistor operating condition and the current in the corresponding bias path. This changes the small-signal operating point of the OTA and, consequently, affects parameters, such as cutoff frequency, gain, noise, and power-consumption. As the bias voltage changes, the current and transconductance of the associated devices can change. The resulting change in the OTA operating point affects the frequency response and power consumption. The simulated results are therefore presented for several bias-voltage values to show this behaviour.

The main technique used in the proposed circuit is bias-voltage-controlled tuning of the OTA operating point. This approach is simple because the variation in cutoff-frequency is obtained by changing the bias voltage applied to N8, while the supply voltage remains fixed at 1 V.

DESIGN METHODOLOGY

The dimensions of transistors and other details are precisely selected, shown in Figure 2, for low-voltage operation.

CIRCUIT PARAMETERS & BIAS CONDITIONS

V_a = 600 mV I_B = 250 nA
V_b = 500 mV C_L = 500 pF
V_Bias = 0.1 to 0.9 V
V_c = 400 mV

Transistor	W / L
P0 - P1	500 n / 180 n
P2 - P3	300 n / 180 n
P4, P5	500 n / 180 n
P6	2 µ / 180 n
N0 - N10	1 µ / 180 n

Figure 2. Circuital Parameters and bias condition

The main variable in the study is the bias voltage applied to transistor N8. This voltage was varied from 100 mV to 900 mV while the supply voltage and other simulation conditions were kept unchanged.

For each of the bias-voltage values, the DC operating-point analysis has been done to check the transistor operating conditions. AC analysis was then used to obtain the voltage gain and cutoff frequency. Transient analysis has been used to observe the time domain response. Noise analysis was used to obtain the noise power spectral density. These analyses were repeated for the selected bias-voltage values.

The results for different bias voltages were compared with other State-of-Art designs to understand how the bias voltage changes the main performance parameters of the OTA.

RESULTS AND DISCUSSIONS

The transient response is evaluated using 1 KHz sine wave, with an input signal of 1 mV peak-to-peak (p-p). The simulated output waveform, shown in Figure 3, has an amplitude of approximately 1.3 mV (p-p). The output amplitude is greater than the input amplitude, showing amplification under the performed simulation condition.

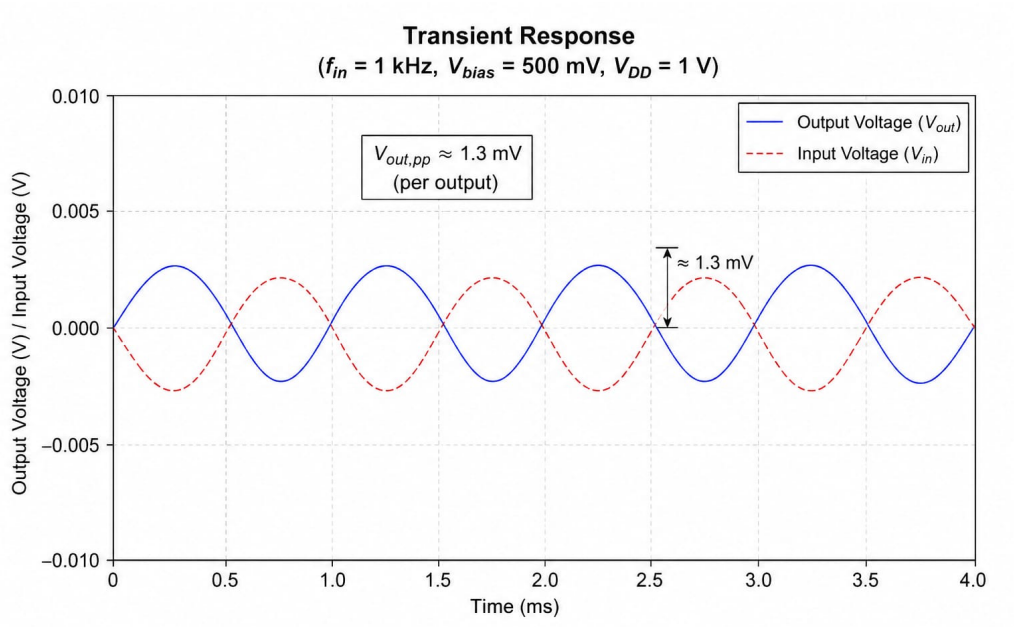

Figure. 3. Transient response of proposed CMOS OTA circuit.

The DC gain and frequency- dependent behaviour are also studied for different bias voltages. At a 500-mV bias voltage, the simulated DC gain is 22.56 dB, which corresponds to about 13.43 V/V which was highest among different bias voltages shown in Figure 4. The corresponding 3 dB cut off frequency is approximately 270.8 Hz, and the unity-gain bandwidth (UGB) is approximately 3.679 kHz.

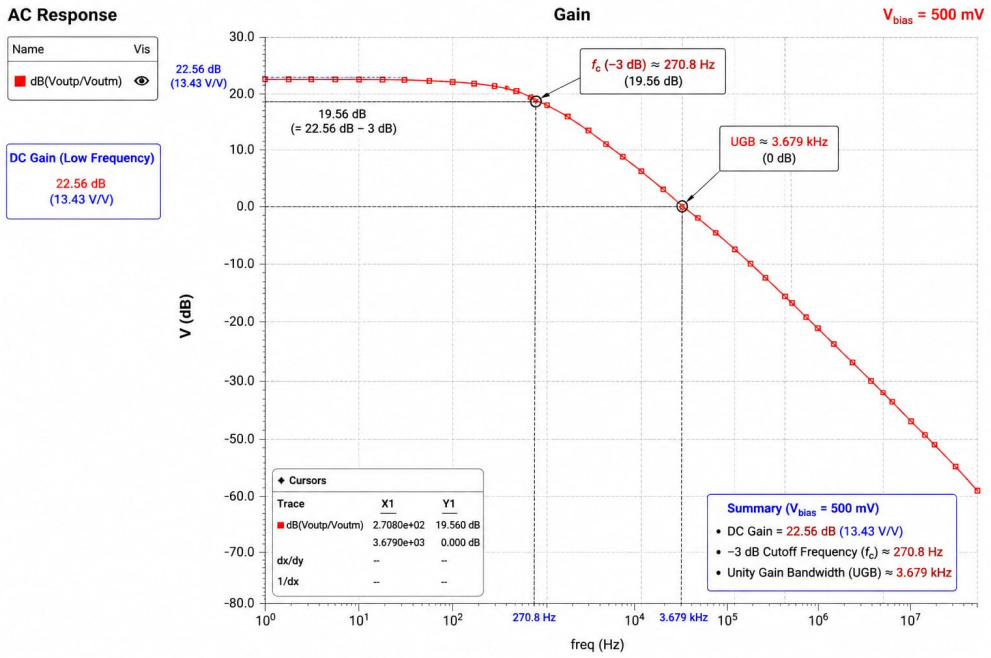

Figure 4. AC response of proposed fully differential, CMOS OTA based low-pass filter.

Figure 5 and 6 depicts the gain characteristics of OTA-based low-pass filter at bias voltages of 500 mV, 600 mV, and 700 mV and variation of total power consumption of circuit at different bias voltage respectively.

It is found that as the bias voltage is increased beyond 500mV, the gain decreases to approximately 19.91 dB (9.9 V/V), while the cutoff frequency increases to approximately 363 Hz. At 700 mV, the gain decreases further to approximately 15.70 dB (6.1 V/V), while the cutoff frequency increases to approximately 524 Hz.

These results show that the cutoff frequency and gain changes with the applied bias voltage which indicates that bias-voltage control can be used to adjust the low-frequency response without changing the 1 V supply voltage, however, practical operating point can be selected according to the required gain, cutoff frequency, noise, and power consumption.

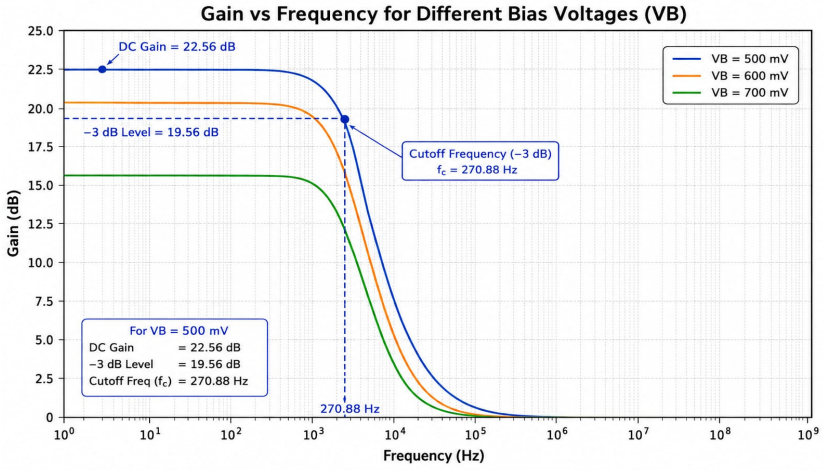

Figure 5. Gain variation with frequency under different bias voltage values.

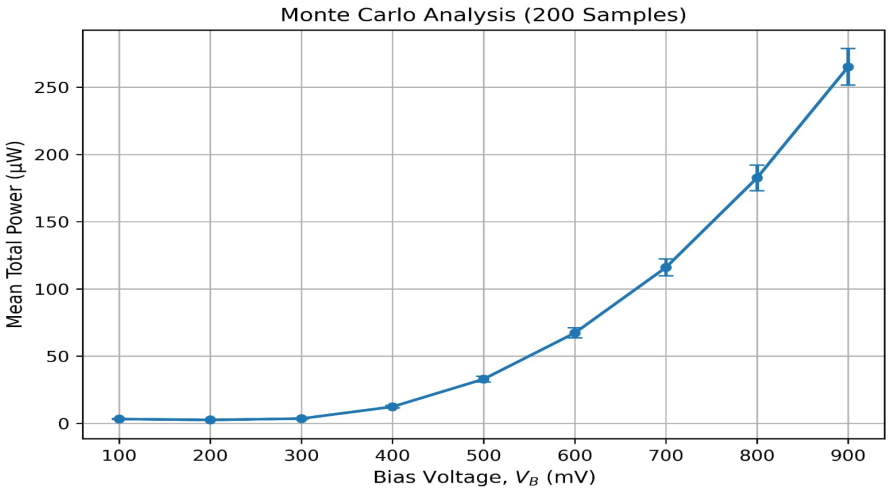

Figure 6. Monte Carlo analysis of total power consumption under varying bias condition.

Figure 7 represents the noise power spectral density (PSD) of the proposed circuit for bias voltage values of 500 mV, 600 mV, and 700 mV.

In the frequency range 1 Hz to 1 GHz, the simulated noise is higher at low frequencies, where flicker-noise effects are important, and becomes more nearly constant at higher frequencies as the white-noise contribution becomes more dominant. At 1 kHz, the simulated PSD values are approximately 5.09 pV²/Hz at 500 mV, 4.80 pV²/Hz at 600 mV, and 3.72 pV²/Hz at 700 mV.

At 700mV bias voltage, lowest value of PSD is obtained, however, power consumption increased simultaneously. This result shows that increasing the bias voltage can reduce the simulated PSD in the selected operating range and the bias voltage should be selected by considering both noise and power consumption.

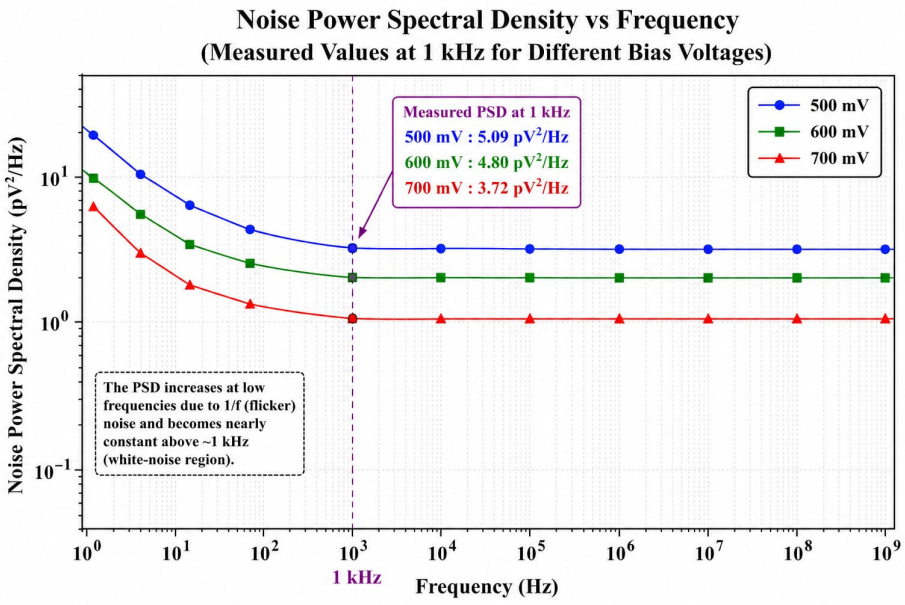

Figure 7. Noise PSD of the proposed circuit at different bias voltages.

Figure 8(a) represents the Monte Carlo analysis of total power consumption using 200 samples. The mean power consumption increased from approximately 3.26 µW at 100 mV to 265.2 µW at 900 mV while the standard deviation increased from approximately 357 nW to 13.49 µW. This indicates that the mean power consumption increased as the bias voltage increased. The increase in power consumption with bias voltage is consistent with the increase in circuit current under the tested operating conditions. The larger standard deviation at higher bias voltages also represents a larger absolute variation in power.

Table 1. Monte Carlo results of total power consumption.

Bias Voltage V_B (mV)	Nominal Total Power (µW)	Yield (%)	Minimum (µW)	Maximum (µW)	Mean (µW)	Standard Deviation
100	3.30	100	2.48	4.44	3.26	357 nW
200	2.60	100	2.12	3.07	2.59	188.9 nW
300	3.58	100	2.94	4.52	3.59	308.1 nW
400	12.38	100	10.46	14.93	12.41	956 nW
500	32.91	100	28.57	38.34	32.96	2.10 µW
600	67.22	100	59.16	76.93	67.28	3.80 µW
700	116.70	100	103.00	132.00	116.00	6.33 µW
800	182.50	100	161.70	205.60	182.60	9.53 µW
900	265.00	100	235.00	297.00	265.20	13.49 µW

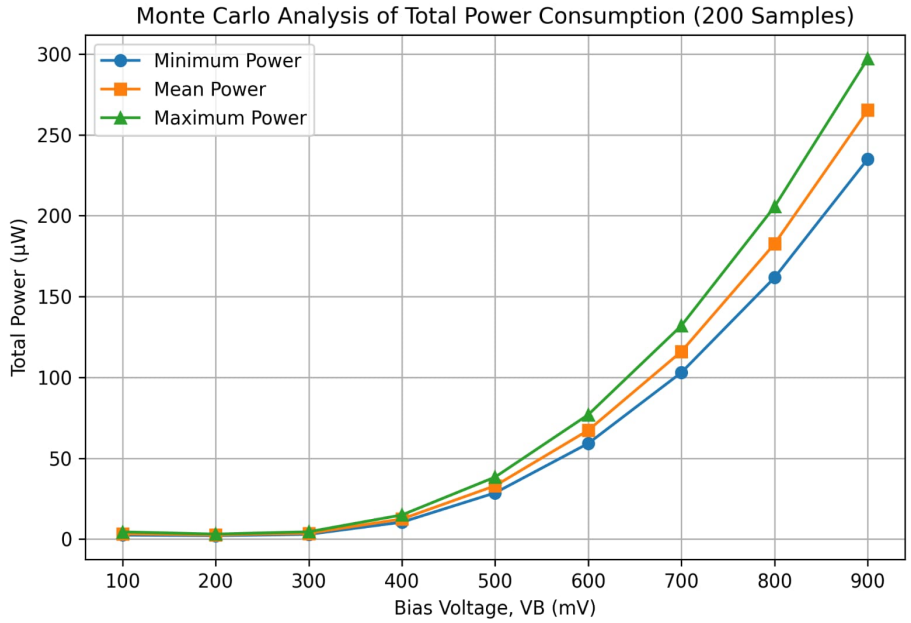

Figure 8(a). Monte Carlo analysis of total power consumption using 200 samples

Figure 8(b) shows the Monte Carlo distribution of total power consumption at a bias voltage of 500 mV using 200 samples.

The analysis includes process and mismatch variations. The distribution shows how the simulated power consumption varies around the nominal operating point for the selected samples. The result gives the spread of power consumption at 500 mV under the simulated variation conditions. It provides an additional check of the power-consumption variation at the selected operating point.

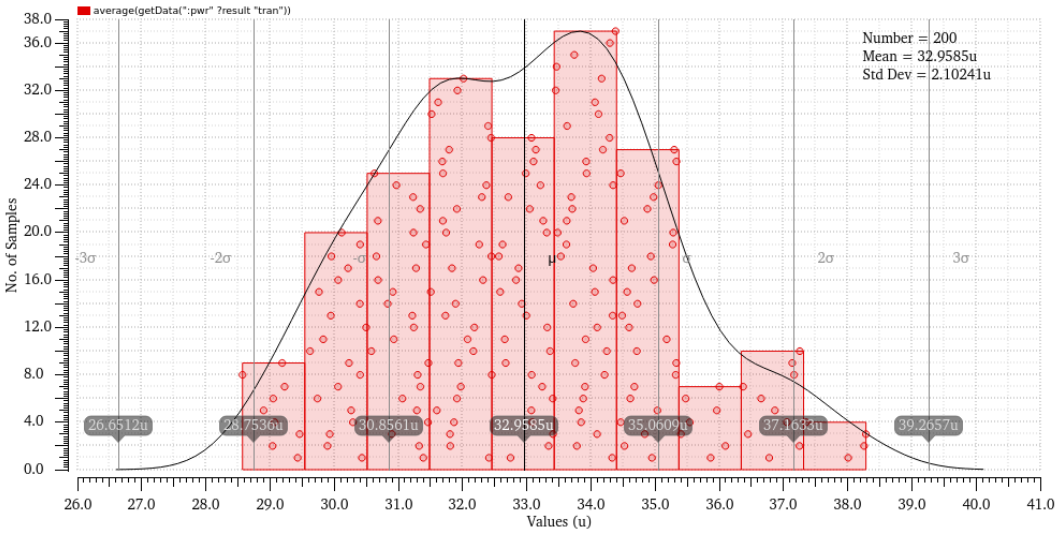

Figure 8(b). Monte Carlo analysis of total power consumption at 500 mV bias voltage.

Total harmonic distortion (THD) was calculated using the transient analysis for bias voltages from 100 mV to 900 mV. The THD is approximately 1.058% over most of the investigated bias-voltage range. At 900 mV, the THD is approximately 1.05966%. The change in THD over the investigated range is small. This indicates that the simulated harmonic distortion is not strongly affected by the bias-voltage change under the selected test conditions.

The THD results therefore show similar simulated linearity for the tested bias voltages. The result is limited to the input signal and simulation conditions used for the THD analysis. The pre-layout of the fully differential CMOS OTA us shown in Figure 9 using 90-nm GPDK090 CMOS technology. The layout dimensions are approximately 9.52 µm × 9.52 µm, giving an area of about 90.63 µm². The layout contains the OTA core and the required input, output, power, and bias connections. External voltage sources, current sources, and capacitors used during simulation were not included in the physical layout.

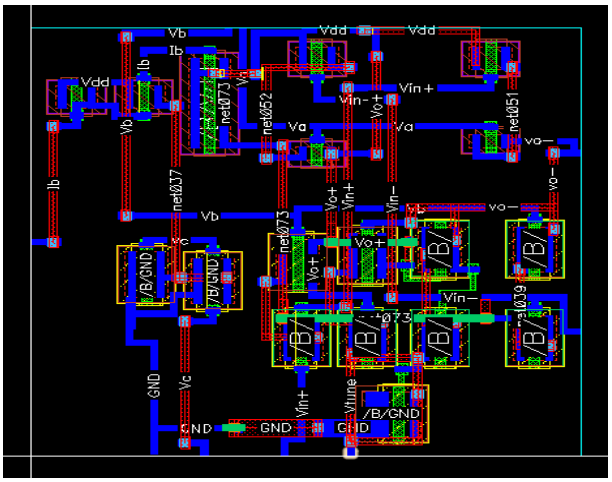

Figure 9. Layout Design of filter (9.52 µm × 9.52 µm)

Table 2 compares proposed filter with the previously published designs. The comparison includes technology, order, supply voltage, DC gain, cutoff frequency, power consumption, THD and IRN. This filter exhibits higher DC gain than (Ismail, S. H., et. al. 2011; Kumar, R., et. al. 2016; Póvoa, R., et. al. 2020), lower cut-off frequency than (Ismail, S. H., et. al. 2011; Elamien, M. B., et. al. 2018; Kumar, R., et. al. 2016; Póvoa, R., et. al. 2016; Póvoa, R., et. al. 2020), and lower power dissipation than (Ismail, S. H., et. al. 2011). These characteristics are essential for the low-frequency biomedical applications. Key contribution of the present work is the attainment of tuning in the low-frequency response with the applied bias voltage.

Table 2: Comparison of the proposed filter with previously published designs

Parameter	Ismail, S. H., et. al. (2011).	Elamien, M. B., et. al. (2018)	Póvoa, R., et. al. (2020)	Kumar, R., et. al. (2016)	Póvoa, R., et. al. (2020)	Proposed Work
Technology	180 nm	90 nm	90 nm	180 nm	130 nm	90 nm
Order	3	3	4	—	2	1
Operating voltage	0.9 V	1 V	1.2 V	0.85 V	0.9 V	1 V
DC Gain	5–21 dB	—	—	2 dB	7 dB	22.56 dB
Cutoff frequency	>1 MHz	4.57–12.59 MHz	814Hz–12 MHz	500 Hz	415 Hz	270.8 Hz
Power consumption	411.6 µW	1.16 mW	11.83 mW	1.2 µW	0.55 µW	32.91 µW
Total Harmonic Distortion (THD)	<–40 dB	—	<–60 dB	—	–60 dB	1.058%
Input Referred Noise (IRN)	167 nV at 1 MHz	—	293.6 nV	23 µV	—	665 nV at 1 kHz

CONCLUSION

A bias-voltage-controlled OTA low-pass filter is designed using 90nm CMOS technology. The circuit work at a 1 V power supply and the main control variable is the bias voltage applied to transistor N8, which was varied from 100 mV to 900 mV.

At 500 mV bias voltage, the simulated gain is 22.56 dB, the cutoff frequency is approximately 270.8 Hz, and the unity-gain bandwidth is approximately 3.679 kHz. The power consumption at this operating point is approximately 32.91 µW, while the simulated THD is close to 1.058%. When the bias voltage is increased, the cutoff frequency also increases in the selected range. The cutoff frequency is approximately 363 Hz at 600 mV and 524 Hz at 700 mV, while the gain decreases. Thus, the bias voltage affects both gain and cutoff frequency. Monte Carlo analysis with 200 samples was used to observe power-consumption variation under the selected process and mismatch conditions. The reported 100% yield is based on the acceptance criterion used in the simulation and should not be taken as a general reliability result.

The overall simulation demonstrate that the operating characteristics of the proposed OTA can be adjusted through bias voltage applied to N8. The main contribution of this work is the study of the resulting changes in gain, cutoff frequency, noise, THD, and power consumption.

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Conflict of interest: None

Source of support: None

REFERENCES

Abbasalizadeh, S., Sheikhaei, S., & Forouzandeh, B. (2013). A 0.9 V Supply OTA in 0.18 [mu] m CMOS Technology and Its Application in Realizing a Tunable Low-Pass Gm-C Filter for Wireless Sensor Networks. *Circuits and Systems*, *4*(1), 34.

Choi, J., Kweon, S. J., & Jeon, H. (2023). Single-stage CMOS operational transconductance amplifiers (OTAs): a design tutorial. *Electronics*, *12*(18), 3833.

Elamien, M. B., & Mahmoud, S. A. (2018). An 114 Hz–12 MHz digitally controlled low-pass filter for biomedical and wireless applications. *IET Circuits, Devices & Systems*, *12*(5), 606-614.

Emon, M. Z. A., Salim, K. M., & Chowdhury, M. I. B. (2024). Design and analysis of a high-gain, low-noise, and low-power analog front end for electrocardiogram acquisition in 45 nm technology using gm/id method. *Electronics*, *13*(11), 2190.

Ismail, S. H., Soliman, E. A., & Mahmoud, S. A. (2011). Cascaded third-order tunable low-pass filter using low voltage low power OTA. In *2011 International Symposium on Integrated Circuits*. 488-491.

Khateb, F., Kumngern, M., Kulej, T., & Arbet, D. (2026). MI-OTA Based First Order Filters for Biomedical Applications. *Circuits, Systems, and Signal Processing*, 1-17.

Khateb, F., Prommee, P., & Kulej, T. (2022). MIOTA-based filters for noise and motion artifact reductions in biosignal acquisition. *IEEE Access*, *10*, 14325-14338.

Kledrowetz, V., Prokop, R., Fujcik, L., & Haze, J. (2023). A fully differential analog front-end for signal processing from EMG sensor in 28 nm FDSOI technology. *Sensors*, *23*(7), 3422.

Kulej, T., Khateb, F., & Kumngern, M. (2024). 0.5 V multiple-input fully differential operational transconductance amplifier and its application to a fifth-order Chebyshev low-pass filter for bio-signal processing. *Sensors*, *24*(7), 2150.

Kulej, T., Kumngern, M., & Khateb, F. (2026). Nano-power OTA-based low-pass filter for ultra-low-energy biomedical signal processing. *Sensors*, *26*(9), 2586.

Kumar, R., Sharma, S., & Singh, A (2016). A Low Power Low Transconductance OTA in 180nm CMOS Process for Biomedical Applications. *International Journal of Electronics and Technical Achievements*, 9(11), 5427-5434.

Kumngern, M., Khateb, F., Kulej, T., & Langhammer, L. (2024). 1 V electronically tunable differential difference current conveyors using multiple-input operational transconductance amplifiers. *Sensors*, *24*(5), 1558.

Kumngern, M., Kulej, T., & Khateb, F. (2025). A 450 mV tunable low-frequency OTA-C third-order elliptic low-pass filter for bio-signal applications. *IEEE Access*, *13*, 36224-36232.

Liu, F., & Lorenzelli, L. (2024). Toward all flexible sensing systems for next-generation wearables. *Wearable Electronics*, *1*, 137-149.

Lo, T. Y., & Hung, C. C. (2007). A Wide Tuning Range $ G_ {m} $–$ C $ Continuous-Time Analog Filter. *IEEE Transactions on Circuits and Systems I: Regular Papers*, *54*(4), 713-722.

Lou, Z., Wang, R., Belmekki, B. E. Y., & Alouini, M. S. (2026). Towards bioelectric signal-enabled human healthcare monitoring: state-of-the-art, design strategies, challenge, and future. *npj Biomedical Innovations*, *3*(1), 7.

Maheshwari, S. (2018). Tuning approach for first-order filters and new current-mode circuit example. *IET Circuits, Devices & Systems*, *12*(4), 478-485.

Moghadam, Z. M., Salehi, M. R., Gordi, M., & Abiri, E. (2025). An Ultra-Low Noise, Power-Efficient AFE based on Current-Reuse and splitting techniques for Multibiosignal acquisition. *AEU-International Journal of Electronics and Communications*, 156051.

Phatsornsiri, P., Kumngern, M., Khateb, F., Torteanchai, U., Wongprommoon, N., & Kulej, T. (2025). 16-nW 0.5-V low-pass filter for bio-signal applications. *AEU-International Journal of Electronics and Communications*, *188*, 155570.

Póvoa, R., Arya, R., Canelas, A., Passos, F., Martins, R., Lourenço, N., & Horta, N. (2020). Sub-µW Tow-Thomas based biquad filter with improved gain for biomedical applications. *Microelectronics Journal*, *95*, 104675.

R. Ram Babu et al. (2017). A high-speed gain enhanced operational transconductance amplifier using positive feedback technique. Proceedings of 2nd International Conference on Communication and Electronics Systems (ICCES), IEEE, 560-563.

Rezaei, F., & Azhari, S. J. (2011). Ultra low voltage, high performance operational transconductance amplifier and its application in a tunable Gm-C filter. *Microelectronics Journal*, *42*(6), 827-836.

Rezaei, F., & Azhari, S. J. (2015). A new controllable adaptive biasing linearization technique for a CMOS OTA and its application to tunable Gm-C filter design. *Microelectronics Journal*, *42*(9), 810-818.

Srinivasagan, R. (2025). Advanced low-power filter architecture for biomedical signals with adaptive tuning. *Plos one*, *20*(1), e0311768.

Xu, J., Qu, T., Pan, Q., Li, Y., Liu, L., Li, Y., ... & Hong, Z. (2025). Analog front-end circuit techniques for wearable ExG, BioZ, and PPG signal acquisition: A review. *IEEE Open Journal of the Solid-State Circuits Society*.

Yan, F., & Liu, J. (2024). Analog front-end input-impedance boosting techniques for bio-potential monitoring—A review. *IEEE Transactions on Instrumentation and Measurement*, *73*, 1-14.

Yin, Y., Zhang, X., Feng, Z., Qi, H., Lu, H., He, J., & Luo, Y. (2024). An ultra-low-voltage transconductance stable and enhanced OTA for ECG signal processing. *Micromachines*, *15*(9), 1108.

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