Breast Cancer: Exploring Causes, Deciphering Molecular Signaling Pathways, Identifying Therapeutic Targets, and Developing Treatment Strategies

Jyoti Dinkar Bhosale[1], Priti V. Pancholi[2], Varsha B Raule[3], Bharat Madhavrao Pawar[4]
[1]*Assistant Professor, Computer Engineering Department, Vilasrao Deshmukh Foundations Group of Institutions, Latur, Maharashtra*
[2]*Assistant Professor, Computer Science and Engineering, M.S. Bidve Engineering College, Latur, Maharashtra*
[3]*Department Electronics Engg. (VLSI), Anantrao Pawar College of Engineering & Research (APCOER), Maharashtra, India*
[4]*Computer Engineering Department, Vilasrao Deshmukh Foundations Group of Institutions, Latur, Maharashtra, India*

Abstract- Breast cancer remains the most prevalent malignancy among women worldwide, driven by genetic, hormonal, and environmental factors. Advances in molecular biology have led to improved classification based on molecular subtypes, receptor status, and tumor characteristics, allowing for more precise diagnostic and therapeutic strategies. Traditional treatments such as surgery, chemotherapy, and radiation remain fundamental, but targeted therapies, including monoclonal antibodies and kinase inhibitors, have significantly improved patient outcomes. Despite progress, challenges like metastasis, drug resistance, and tumor heterogeneity persist. Research into molecular signaling pathways, genetic mutations, and non-coding RNAs continues to provide new therapeutic insights. Future advancements should focus on early detection, predictive biomarkers, and personalized medicine to enhance survival rates and quality of life. A multidisciplinary approach integrating genetics, immunotherapy, and advanced diagnostics is crucial for improving breast cancer treatment outcomes.

Keywords: Breast cancer, molecular classification, genetic mutations, signaling pathways, targeted therapy, receptor status, tumor heterogeneity, personalized medicine

I. INTRODUCTION

Worldwide Breast cancer represents the leading malignancy in women because it constitutes 23% of all occurrences in female cancer cases. The condition creates substantial health problems because of its difficult origins together with its multiple ways of expressing at the molecular level as well as its unpredictable treatment outcomes. Breast cancer formation results from various elements which combine genetic abnormalities with hormonal imbalances and environmental elements and life-style habits. The development of breast cancer susceptibility mainly stems from genetic predisposition which is significantly influenced by BRCA1 and BRCA2 mutations. Molecular biology together with biomedical research advances have enabled researchers to better understand breast cancer signal networks that drive disease progression. Early tumour formation in breast tissue requires the critical participation of the estrogen receptor pathway together with HER2 and Wnt/β-catenin and Notch and Hedgehog together with PI3K and mTOR pathways. Research indicates that cyclin-dependent kinases (CDKs) and breast tumor kinases (BRKs) help control the cell cycle pathway through cell regulation which makes them prime targets for therapy. Research into non-coding RNAs during breast cancer development has become important because it creates fresh possibilities for biomarker detection and treatment methods. The accurate identification of breast cancer types through molecular and histopathological evaluation enables healthcare professionals to make important prognostic predictions along with treatment decision guidance. The current care approaches in breast cancer treatment include targeted monoclonal antibodies and kinase inhibitors as well as traditional

chemotherapy methods and hormonal medication. The benefits from recent developments in breast cancer treatment must be enhanced while scientists work to decrease the spread of cancer and increase the response to medical interventions.

Breast cancer represents a substantial worldwide medical issue which remains the leading type of cancer among female patients. During 2020 statistical data revealed that the worldwide total number of breast cancer cases reached 2.3 million and the mortality from breast cancer surpassed 685,000 deaths. The statistics for breast cancer incidents keep increasing in spite of recent developments in screening methods and treatment protocols. Results showing improved survival appear mostly due to mammographic screening and adjuvant therapies yet advanced disease now increasingly depends on highly effective systemic treatments. Breast cancer development occurs after modifications between hereditary and environmental elements. The risk for disease development substantially rises when BRCA1 and BRCA2 genes experience genetic mutations. Two essential groups of causal factors develop breast cancer: genetic elements together with non-genetic elements consisting of age, reproductive history, hormonal influences, lifestyle choices, radiation exposure and histological abnormalities. Genetic predisposition tends to increase the susceptibility to environmental and lifestyle factors that lead to breast cancer development. The medical field identifies breast cancer as a complex disease that contains several distinctive biological forms showing different pathologic characteristics and genomic mutations and changes in tumor ecological environments. Different factors that work together guide how diseases advance and how patients respond to treatment and their overall health outcomes. The standard clinical criteria which direct treatment strategies mainly include cancer measurements and classification of cancer cell features yet prove ineffective against therapy resistance development in complex breast cancer cases. Current advances in molecular biology together with genomics research have advanced our understanding of tumor heterogeneity along with genetics and cell complexity. Through high-throughput sequencing analysis together with multiple analytical platforms scientists have discovered new biomarkers and therapeutic targets that result in enhanced personalized care. Breast cancer treatment achievements in molecular signaling pathway research enabled scientists to develop targeted therapies leading to more effective care and resistance enhancement.

1.1 TRADITIONAL BREAST CANCER CLASSIFICATION

Histopathological traits and clinical criteria have been the mainstays of traditional breast cancer categorization. Invasive ductal carcinoma (IDC) and invasive lobular carcinoma (ILC) are the two most prevalent kinds of breast cancer, according to this classification. The tumor's grade, which evaluates the cancer cells' appearance and resemblance to normal cells, and its stage, which takes into account the tumor's size and whether it has spread to neighboring lymph nodes or other body areas, are usually the basis for these classifications. Furthermore, human epidermal growth factor receptor 2 (HER2) expression and hormone receptor status, such as estrogen receptor (ER) and progesterone receptor (PR) positive, are often used to categorize breast tumors. Although this conventional method helps forecast patient outcomes and direct treatment plans, it has drawbacks, especially when it comes to addressing tumor heterogeneity and the molecularly changing nature of breast cancer. In order to represent the intricate biological behaviors and treatment responses of many breast cancer subtypes, it has become more crucial in recent classifications to include genomic and transcriptome data. This change to a more complex classification system recognizes the different molecular subtypes of breast cancer, including triple-negative breast cancer (TNBC), luminal A, luminal B, and HER2-enriched. Each of these subtypes influences treatment choices and results because they vary not only in biological traits but also in clinical responses to therapy. Because of their low rates of proliferation and high estrogen receptor positivity, luminal A cancers typically have a better prognosis and react favorably to hormone treatments. On the other hand, even though they are hormone receptor-positive, luminal B tumors proliferate more and frequently need more intensive therapy. Targeted treatments like trastuzumab, which selectively blocks the HER2 signaling pathway, are beneficial for HER2-enriched cancers, which are identified by an overexpression of the HER2 protein. Triple-negative breast cancers, which lack ER, PR, and HER2 expressions, are

particularly difficult to treat because they are usually more aggressive and do not respond to hormonal therapies or HER2-targeted treatments.

The shortcomings of conventional histology-based classifications have made the necessity of precision medicine approaches in the treatment of breast cancer increasingly apparent. This includes using genomic profiling to find particular actionable mutations or vulnerabilities and to customize treatments according to the tumor characteristics of the individual. All things considered, although conventional categorization techniques established the foundation for our knowledge of breast cancer, current studies and technical developments are pushing the envelope in the direction of a more individualized and successful strategy for the management and treatment of this complicated illness.

A multifaceted framework that combines clinical features, histological categorization, and sophisticated genetic analysis is used to stratify human breast carcinomas. Based on the migration of cancerous cells from breast lobules or ducts into the surrounding stroma, tumors are often categorized by histology upon diagnosis as either invasive or in situ carcinomas (Figure 1) (reviewed in WHO Classification of Tumours).

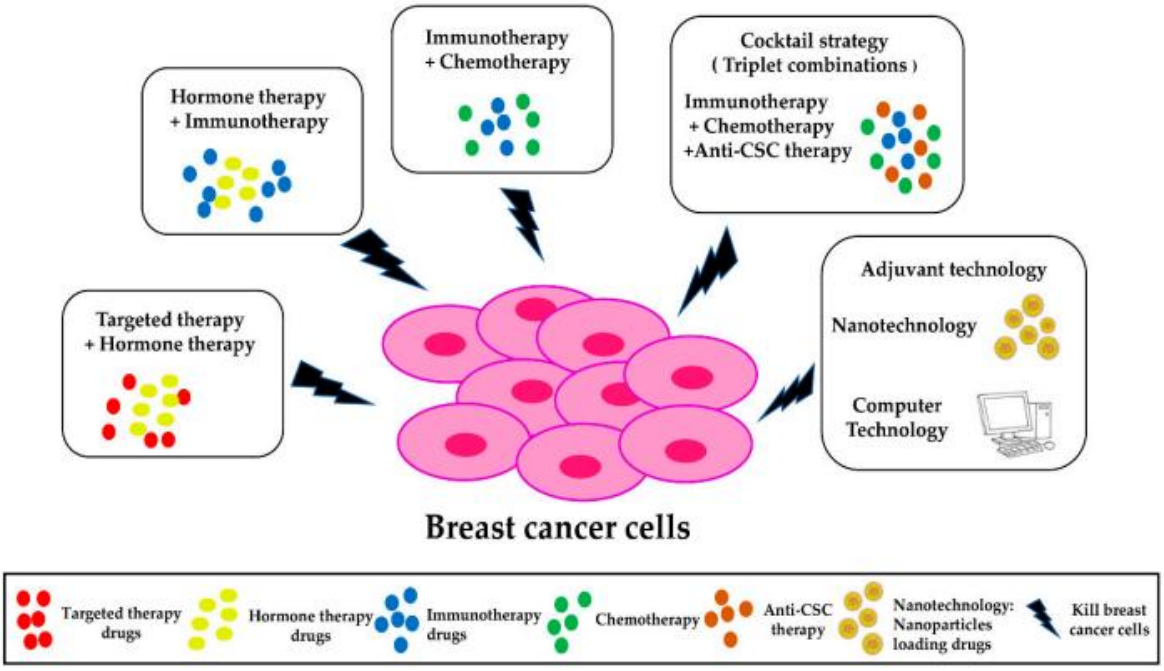

Figure 1. Overview of Breast Cancer Treatment Approaches
Source: https://www.mdpi.com/1422-0067/23/19/11046

1.2 Natural compounds targeting Notch signaling pathway in breast cancer

Notch signaling activity is correlated with aggressive tumors, poor clinical outcomes, and drug resistance in individuals with breast cancer. Small molecule inhibitors that target Notch signaling could be a more practical method of explaining anticancer drugs. Naturally occurring phytochemicals in TNBCs have the ability to target and modify oncogenic, anti-apoptotic, EMT-, and metastasis-related signaling pathways, including the Wnt, Notch, NF-kB, PI3K/Akt/mTOR, MAPK, and Hedgehog pathways. Several studies have shown that plant-derived medicinal bioactive compounds, including bioflavonoids and polyphenols, may be used to treat breast cancer because of their efficacy and absence of adverse effects. Here, we highlight how the notch signaling system, which targets phytochemicals, may be used to treat TNBCs. With the aid of the membrane-bound enzyme complex γ-secretase, the Notch receptor-ligand complex initiates a signaling cascade. The NICD complex, which is created when the enzyme γ-secretase breaks down the intracellular domain of the Notch receptor-ligand complex, enters

the nucleus and regulates Notch-responsive genes, such as Hes1 and Hey1, as well as anti-apoptotic proteins like Bcl2 and survivin, which results in increased cell proliferation. The expression of E-cadherin, which includes the epithelial-to-mesenchymal transition, is likewise regulated by notch signaling. Research indicates that Notch signaling controls the integrity of the mitochondrial membrane and the generation of reactive oxygen species. The Notch signaling system is linked to sphere-forming cells' capacity for self-renewal.

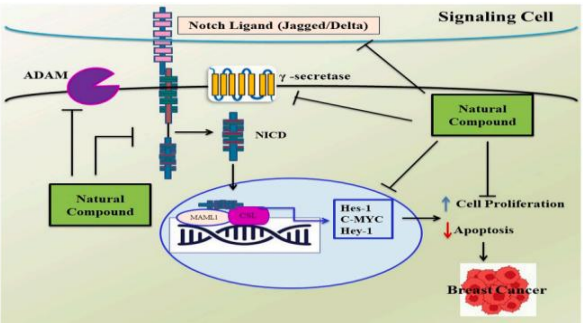

Figure 2. Notch Signaling Pathway and the Role of Natural Compounds in Breast Cancer
Source:https://www.sciencedirect.com/science/article/pii/S075333222300728X

1.3 Understanding Breast Cancer Etiology

The average lifetime risk for a woman in the United States to get a breast cancer diagnosis is 12.3% (1). After skin cancer, this condition is now the second most frequent cancer among women in the US. Numerous risk factors, such as a positive family history, obesity, tall height, smoking, alcohol use, early menarche, late menopause, sedentary lifestyle, nulliparity, hormone replacement treatment, and a past history of breast cancer, interact intricately to cause breast cancer. Multiparity, nursing history, physical exercise, and weight reduction are factors linked to a lower risk of breast cancer. The ongoing rise in breast cancer incidence rates of around 0.5% per year, which has been linked to a national increase in body weight and a decline in fertility, demonstrates the impact of variables like obesity and fertility on the etiology of breast cancer. In addition to being far more common in women than in men, breast cancer is also strongly correlated with both age and race, with White women having the highest overall rates, followed by Black, Asian, and Hispanic women, in that order. Women are twice to three times more likely to have breast cancer in their lifetime if they have a first-degree relative who has had the disease. In order to better understand the risk factors for breast cancer and maybe support future research into its treatment and prevention, this chapter aims to examine the genesis of the illness.

FACTORS AFFECTING BREAST CANCER RISK

As noted, there are multiple interactive factors that impact breast cancer occurrences and in the subsequent sections the main features of these will be discussed.

Gender

In the US, 280,000 women and 3,000 men get a breast cancer diagnosis each year. Thus, the risk of breast cancer is about 100 times higher in women than in males. The increased stimulation of estrogen and progesterone is the primary cause of the greater incidence of breast cancer in women. It has been shown that the level of circulating androgens and estrogens in postmenopausal women is positively connected with their risk of developing breast cancer. The risk of breast cancer in males is positively connected with the rise in the estrogen to androgen ratio, which may be attributed to either an excess of estrogen or an androgen deficit. Additionally, women who are premenopausal or postmenopausal have a greater lifetime risk of breast cancer due to larger fluctuations in their sex hormone levels than males.

Age

The majority of breast cancer diagnoses occur in women over 50, and the chance of developing breast cancer rises with age. According to the Surveillance, Epidemiology, and End Results (SEER) database, a woman's risk of breast cancer is 2.4% if she is between the ages of 50 and 59, 3.5% if she is between the ages of 60 and 69, and 7.0% if she is 70 years of age or older. Age-dependent increases in carcinogenesis and the accumulation of cellular alterations over time are partially responsible for the rising prevalence of breast cancer, which is similar to the age dependency of many prevalent malignancies (11). Additionally, there is a correlation between the result prognosis with the age of diagnosis. Breast cancer survival rates are lower for women diagnosed before the age of 50 than for those diagnosed between the ages of 50 and 70 (9). The higher incidence of very aggressive triple negative breast cancer in patients 40 years of age or younger is

probably the cause of the shorter survival rate in younger patients.

Heritable factors and cancer genetics

Heritable factors play a significant role in breast cancer risk. Women with a personal history of breast cancer have a slightly increased risk of developing cancer in the opposite breast, rising by 0.5% annually. A first-degree family history, including a mother, sister, or daughter with breast cancer, doubles the risk, while having two first-degree relatives with the disease triples it. Second-degree relatives, such as grandmothers, aunts, or nieces, also contribute to a moderately increased risk. Genetic mutations, particularly in BRCA1 and BRCA2 genes, significantly elevate breast cancer risk, with BRCA1 carriers facing a higher lifetime risk than BRCA2 carriers.

Geography, ethnicity and race

The incidence of breast cancer varies globally. Australia, New Zealand, North and West Europe, and North America all have higher incidences of breast cancer. Nonetheless, the global breast cancer mortality rate is comparable. The risk of breast cancer varies by race in the United States, with White women having the greatest overall incidence of the disease (131.8 per 100,000), followed by Black women (124.7 per 100,000). Asian/Pacific Islander, Hispanic, and American Indian/Alaskan Native women are less likely to be at risk. Notably, Black women are at the greatest risk of developing early-onset breast cancer before the age of 45, even though white women are at the highest risk overall. Additionally, Black women are more likely to arrive with advanced illness and have a higher breast cancer death rate.

Obesity

Obesity increases breast cancer risk. BMI is linked to estrogen-positive breast cancer in post-menopausal women. The association between obesity and breast cancer risk varies by menopause. Several studies link a BMI of ≥30 kg/m2 to increased post-menopausal breast cancer risk. A meta-analysis of multiple studies found that obese post-menopausal women had a 1.1 per 5 BMI unit relative risk of breast cancer (95% CI 1.1–1.2). This is linked to obese women's greater estrogen levels. The fact that women with normal BMIs had a greater breast cancer risk with a higher body fat percentage supports this argument (29). In premenopausal women, greater BMI reduces breast cancer risk. The reason of this inverse association is unknown.

Stature

Tallness also increases breast cancer risk (3, 31). Seven prospective cohort studies of over 337,000 women found that height is an independent risk factor for breast cancer. The relative risk of breast cancer for women 1.75 meters (69 inches) or higher compared to women shorter than 1.60 meters (63 inches) was 1.22 for all women, 1.42 for premenopausal women, and 1.28 for postmenopausal women. Height and breast cancer are linked, although the cause is unknown. There are theories that dietary, genetic, and environmental variables in early infancy affect growth hormone release and breast cancer development.

Alcohol Consumption and Smoking

Alcohol consumption is linked to an increased risk of breast cancer, with even low intake (3–4 drinks per week) showing a positive association. The risk rises with higher consumption and is most strongly linked to drinking habits in early and late adulthood. Alcohol may contribute to breast cancer by affecting estrogen metabolism, leading to higher blood estrogen levels. Smoking also increases breast cancer risk, particularly for women who started smoking in adolescence.

Menarche and Menopause

Early menarche and late menopause are associated with a higher risk of breast cancer due to prolonged exposure to estrogen. The risk increases slightly for each year earlier at menarche or later at menopause. Studies suggest that early menarche has a greater impact on breast cancer risk than late menopause, though further research is needed to clarify the underlying mechanisms.

Reproductive History and Breastfeeding

Both multiparity and breastfeeding have a protective effect against breast cancer. Breastfeeding for at least six months is linked to a lower risk, with each year of breastfeeding reducing the risk by approximately 4.3%. The protective effect is more pronounced in aggressive, receptor-negative breast cancer subtypes.

Endogenous Estrogen and Hormonal Therapy
Higher estrogen levels in both premenopausal and postmenopausal women are associated with increased breast cancer risk. Postmenopausal hormone therapy, especially combined estrogen-progestin therapy, increases breast cancer risk when used for long periods. Short-term use (four years or less) does not significantly raise the risk, but prolonged use, particularly over ten years, is linked to a higher likelihood of breast cancer and difficulty in mammographic detection.

1.4 Molecular Signaling Pathways in Breast Cancer
The review on "Molecular Signaling Pathways in Breast Cancer" provides a comprehensive overview of the genetic alterations and signaling pathways involved in breast cancer progression and treatment options. Here are the key details:

1. Genetic Factors:
Oncogenes: Genes such as HER2, c-MYC, and RAS are implicated in promoting uncontrolled cell growth. Their mutations lead to the activation of signaling pathways that favor tumorigenesis.

Tumor Suppressor Genes (TSGs): Genes like p53, RB, and PTEN, which normally regulate cell growth and prevent tumor formation, are found to be mutated or downregulated in breast cancer, contributing to cancer progression.

2. Signaling Pathways:
MAPK Pathway: Involved in transmitting growth signals, contributing to cell proliferation and differentiation.

PI3K/AKT/mTOR Pathway: This pathway is essential for cell survival and metabolism, and it is frequently activated in breast cancer, promoting tumor growth.

p53 Pathway: The guardian of the genome, this pathway is crucial in responding to DNA damage. Mutations in the TP53 gene often lead to unchecked cell division.

3. Evolution of Targeted Therapies:
The understanding of these pathways has led to the development of targeted therapies that specifically inhibit the molecular changes characteristic of breast cancer. For instance, HER2-targeted therapies, like trastuzumab (Herceptin), focus on blocking the signals from the overexpressed HER2 protein to halt cancer progression.

Other therapies aim to target the hormonal receptors (e.g., estrogen and progesterone receptors) influencing the growth of hormone-responsive breast cancers.

4. Challenges and Future Directions:
The complexity of breast cancer genetics and heterogeneity between tumors presents significant challenges. Ongoing research is aimed at developing better classification systems based on genetic profiles and refining therapies to enhance efficacy while minimizing side effects. The role of cancer stem cells (CSCs) poses an additional challenge, as they may contribute to recurrence and metastasis. Targeting these cells could be vital for long-term treatment success.

5. Trends in Research:
The incorporation of pharmacogenetics and DNA microarray analysis is enhancing the ability to predict patient responses to specific therapies, tailoring treatments to individual genetic profiles.

Overall, the intricate interplay of genetic factors and signaling pathways reflects the multifaceted nature of breast cancer, guiding the development of personalized medicine approaches in treatment. For more in-depth exploration, researchers continue to focus on specific pathways and gene interactions to improve therapeutic strategies

1.5 Identification of Therapeutic Targets for Breast Cancer
The quest to improve breast cancer (BC) treatment is imperative given the disease's high prevalence and associated healthcare burden. This study presents a comprehensive approach to identify novel therapeutic targets for breast cancer through Mendelian randomization (MR) techniques. By analyzing data from 2,004 circulating proteins alongside extensive genome-wide association study (GWAS) datasets from the Breast Cancer Association Consortium, the researchers identified five promising drug targets: TLR1, A4GALT, SNUPN, CTSF, and specifically TLR1 for estrogen receptor-positive breast cancer. The research utilized various analytical strategies to ensure the robustness of the findings. These included sensitivity analyses to address reverse causation and genetic confounding, as well as Bayesian

colocalization to confirm shared variability between the identified proteins and breast cancer. The protein-protein interaction (PPI) network analysis revealed important relationships between these novel targets and existing breast cancer therapies, particularly highlighting TLR1's interaction with current treatment modalities.

To further enhance the drugability of the targets, the study employed phenome-wide MR (Phe-MR) to evaluate potential side effects associated with the identified proteins, thus providing a safer therapeutic profile. The identification of these targets not only sheds light on potential advancements in breast cancer treatment but also emphasizes the role of genetic approaches in unveiling new therapeutic avenues. In conclusion, the findings advocate for additional clinical exploration of these identified targets, particularly TLR1, A4GALT, SNUPN, and CTSF, which hold promise for developing innovative therapeutic strategies against breast cancer. This study serves as a significant step toward leveraging genetic insights for better intervention strategies, ultimately aiming to enhance patient outcomes in breast cancer treatment

Engineering-Based Strategies in Breast Cancer Treatment

1. Structural Health Monitoring (SHM) Analogy in Tumor Detection

Structural Health Monitoring (SHM) in civil engineering involves detecting and assessing damage in buildings and bridges using sensors and imaging techniques. A similar approach is applied in breast cancer detection through advanced imaging methods such as MRI, CT scans, and ultrasound. Techniques like machine learning-based anomaly detection in SHM can be adapted to identify tumors in their early stages, improving diagnosis accuracy and treatment planning.

2. Tissue Engineering and Biomaterials in Breast Reconstruction

Civil engineering principles contribute to tissue engineering by guiding the development of biomedical materials for breast reconstruction. Concepts from materials science, load-bearing structures, and fluid dynamics are used to create scaffolds that mimic natural breast tissue. Innovations in bioengineered materials improve implant biocompatibility, durability, and patient outcomes.

3. 3D Printing and Smart Materials in Personalized Medicine

3D printing, widely used in civil engineering for constructing complex structures, is revolutionizing personalized medicine. In breast cancer treatment, 3D-printed implants, prosthetics, and customized drug delivery systems enhance patient-specific treatment. Smart materials, inspired by self-healing and adaptive structures in engineering, enable responsive implants and prosthetics that adapt to physiological conditions, improving post-surgical recovery and quality of life.

II.LITERATURE SURVEY

Author and Year	Topic	Method	Findings
Emma Nolan et al. (2023)	Deciphering breast cancer: from biology to the clinic	Integrated genomic and transcriptomic data, single-cell and spatial technologies	Identified distinct cancer subtypes, molecular drivers, and prognostic signatures; emphasized importance of the tumor microenvironment; highlighted therapy resistance as a challenge.
Pratibha Pandey et al. (2023)	Targeting Notch signaling pathway in breast cancer	Review of natural products affecting cancer microenvironment and signaling pathways	Natural compounds show potential in targeting multiple cancer pathways, including apoptosis and autophagy; emphasizes further research for multi-targeted therapy.
Pilar Eroles et al. (2012)	Advances in breast cancer classification and pathways	Review of high-throughput technologies and gene expression profiling	Identified six intrinsic breast cancer subtypes; molecular studies reshaped diagnosis and treatment; ongoing clinical trials testing targeted therapies.
Venketesh K. Panda et al. (2025)	Breast tumor microenvironment and signaling networks	Review of various signaling pathways in breast cancer, including EGFR, Notch, and Hedgehog	Dysregulation in pathways leads to drug resistance and cancer stem cell enrichment; metabolic reprogramming contributes to therapy failure.

Riya Thapa et al. (2023)	Long-chain non-coding RNAs (lncRNAs) and breast cancer	Review of lncRNAs interacting with AKT/PI3K/mTOR, Wnt/β-catenin, Notch, and NF-κB pathways	lncRNAs play a crucial role in breast cancer progression and metastasis; potential for developing targeted therapies.
Rocío García-Becerra et al. (2015)	Endocrine resistance in ER-positive breast cancer	Review of resistance mechanisms, including genetic polymorphisms, miRNA regulation, and signal transduction modifications	Endocrine resistance limits therapy effectiveness; new strategies are needed to restore tamoxifen sensitivity in resistant cancer cells.

III FUTURE DIRECTIONS AND CHALLENGES

Bridging the Gap Between Civil Engineering and Medical Research

Integrating civil engineering principles with breast cancer research can lead to innovative diagnostic and treatment solutions. Applying structural health monitoring (SHM) techniques to tumor detection, optimizing biomaterials for reconstruction, and enhancing imaging technologies through engineering-driven innovations can improve patient outcomes.

Potential Research Areas

AI-Based Diagnostics: Leveraging artificial intelligence for early and accurate breast cancer detection, predictive modeling, and treatment optimization.

Bio-Inspired Structural Materials: Developing advanced biomaterials for breast reconstruction and prosthetics, inspired by civil engineering principles such as self-healing concrete and adaptive structures.

Smart Monitoring Systems: Implementing IoT-based wearables and real-time health monitoring tools to track disease progression and treatment responses.

Ethical Considerations and Interdisciplinary Collaboration

Advancing engineering-driven medical solutions requires addressing ethical concerns such as patient data privacy, accessibility, and the implications of AI-driven diagnostics. Strong collaboration between engineers, medical researchers, and policymakers is essential to ensure responsible development and application of these technologies in breast cancer treatment.

IV. CONCLUSION

Breast cancer remains a significant global health challenge, influenced by genetic, hormonal, and environmental factors. Advances in molecular biology have enhanced our understanding of its complexity, leading to improved classification, targeted therapies, and early detection strategies. Traditional treatments such as surgery, chemotherapy, and radiation remain essential, but newer approaches, including monoclonal antibodies, kinase inhibitors, and hormone-based therapies, have significantly improved patient outcomes. Research into genetic mutations, molecular signaling pathways, and non-coding RNAs continues to drive innovation in breast cancer diagnosis and treatment. Despite progress, challenges such as tumor heterogeneity, drug resistance, and metastatic progression persist. Future efforts should focus on refining personalized medicine, identifying predictive biomarkers, and developing more effective combination therapies. The integration of proteomics, genomics, and advanced screening methods will be crucial in reducing breast cancer mortality. A multidisciplinary approach incorporating genetics, immunotherapy, and precision medicine will be key to improving survival rates and enhancing the quality of life for breast cancer patients.

Funding

“The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.”

Competing Interests

“The authors have no relevant financial or non-financial interests to disclose.”

Availability of data and materials

“The authors confirm that the data supporting the findings of this study are available within the article.”

Acknowledgements

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCE

[1] García-Becerra, R., Santos, N., Díaz, L., & Camacho, J. (2012). Mechanisms of resistance to endocrine therapy in breast cancer: focus on signaling pathways, miRNAs and genetically based resistance. International journal of molecular sciences, 14(1), 108-145.

[2] García-Becerra, R., Santos, N., Díaz, L., & Camacho, J. (2013). Mechanisms of resistance to endocrine therapy in breast cancer: Focus on signaling pathways, miRNAs and genetically based resistance. *International Journal of Molecular Sciences*, *14*(1), 108–145. https://doi.org/10.3390/ijms14010108

[3] Panda, V. K., Mishra, B., Mahapatra, S., Swain, B., Malhotra, D., Saha, S., Khanra, S., Mishra, P., Majhi, S., Kumari, K., Nath, A. N., Saha, S., Jena, S., & Kundu, G. C. (2025). Molecular Insights on Signaling Cascades in Breast Cancer: A Comprehensive Review. *Cancers*, *17*(2), 1–41. https://doi.org/10.3390/cancers17020234

[4] Thapa, R., Afzal, O., Gupta, G., Bhat, A. A., Almalki, W. H., Alzarea, S. I., Kazmi, I., Altamimi, A. S. A., Subramaniyan, V., Thangavelu, L., Singh, S. K., & Dua, K. (2023). Unveiling the connection: Long-chain non-coding RNAs and critical signaling pathways in breast cancer. *Pathology - Research and Practice*, *249*, 154736. https://doi.org/https://doi.org/10.1016/j.prp.2023.154736

[5] Eroles, P., Bosch, A., Alejandro Pérez-Fidalgo, J., & Lluch, A. (2012). Molecular biology in breast cancer: Intrinsic subtypes and signaling pathways. *Cancer Treatment Reviews*, *38*(6), 698–707. https://doi.org/10.1016/j.ctrv.2011.11.005

[6] Momenimovahed, Z., & Salehiniya, H. (2019). Epidemiological characteristics of and risk factors for breast cancer in the world. *Breast Cancer: Targets and Therapy*, *11*, 151–164. https://doi.org/10.2147/BCTT.S176070

[7] Preeti Tanaji Mane, Sangram Prakash Patil, Balaji Sopanrao Wakure, & Pravin Shridhar Wakte. (2021). Breast cancer: understanding etiology, addressing molecular signaling pathways, identifying therapeutic targets and strategizing the treatment. *International Journal of Research in Pharmaceutical Sciences*, *12*(3), 1757–1769. https://doi.org/10.26452/ijrps.v12i3.4779