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INNOVATIONS AND RESEARCH IN SCIENCE AND TECHNOLOGY VOLUME IV

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PREFACE

Science and technology have always been the driving forces behind human progress, shaping societies, economies, and the quality of life across the globe. In the contemporary era, rapid advancements in scientific knowledge, digital transformation, and interdisciplinary research are redefining how challenges are understood and addressed. The book *Innovations and Research in Science and Technology* is conceived as a scholarly platform to capture these dynamic developments and to present cutting-edge research, critical reviews, and innovative perspectives from diverse fields of science and technology.

This volume brings together contributions from academicians, researchers, scientists, and industry professionals who are actively engaged in expanding the frontiers of knowledge. The chapters encompass a broad spectrum of themes, including fundamental sciences, applied research, emerging technologies, computational tools, artificial intelligence, biotechnology, nanotechnology, environmental science, materials science, and engineering innovations. By integrating theoretical foundations with practical applications, the book highlights how scientific discoveries translate into technological solutions that address real-world problems.

A key objective of this book is to promote interdisciplinary thinking and collaboration. Many of today's complex challenges—such as climate change, sustainable development, health care innovation, energy security, and digitalization—cannot be solved within the boundaries of a single discipline. This volume encourages readers to appreciate the interconnected nature of scientific and technological research and to explore synergies across domains. Each chapter has been carefully selected and peer-reviewed to ensure originality, scientific rigor, and relevance to current and future research directions.

The book is intended to serve as a valuable reference for undergraduate and postgraduate students, researchers, educators, policymakers, and industry stakeholders. We express our sincere gratitude to all contributing authors for their dedication and scholarly contributions, and to the reviewers for their insightful evaluations. It is our hope that this book will inspire innovation, stimulate further research, and contribute meaningfully to the advancement of science and technology in the years to come.

- Editors

TABLE OF CONTENT

MATRIX METALLOPROTEINASES AS DIAGNOSTIC AND PROGNOSTIC BIOMARKERS IN ORAL SQUAMOUS CELL CARCINOMA

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Abstract:

Matrix metalloproteinases (MMPs) are zinc-dependent endopeptidases that play a fundamental role in extracellular matrix (ECM) remodeling and are involved in cancer-related processes such as tumor invasion, angiogenesis, and metastatic dissemination. Under physiological conditions, MMP activity is tightly regulated; however, in malignancies such as oral squamous cell carcinoma (OSCC), dysregulated expression of specific MMPs contributes to tumor progression and poor clinical outcomes. Among the MMP family, MMP-2, MMP-9, and membrane-type MMP-14 (MT1-MMP) have been most consistently associated with aggressive tumor behavior, lymph node metastasis, advanced disease stage, and unfavorable prognosis in OSCC.

These proteases facilitate degradation of basement membrane components, particularly type IV collagen, thereby enabling malignant epithelial cells to invade surrounding tissues and access vascular and lymphatic channels. Importantly, MMPs can be detected in multiple biological matrices, including tumor tissue, serum, saliva, and tumor-derived exosomes. This broad detectability highlights their potential utility as minimally invasive diagnostic and prognostic biomarkers for OSCC, with applications in early detection, disease staging, prediction of nodal metastasis, recurrence monitoring, and therapeutic response assessment.

Despite encouraging evidence, several challenges limit the routine clinical implementation of MMP-based assays. These include variability in sample collection and handling, interference from inflammatory oral conditions, methodological differences across analytical platforms, and the absence of large, well-designed multicenter validation studies. Furthermore, the balance between MMPs and their endogenous inhibitors must be considered to improve diagnostic specificity. This review summarizes the mechanistic roles of key MMPs in OSCC and critically evaluates current evidence supporting their diagnostic and prognostic relevance, emphasizing future directions for successful clinical translation.

Keywords: Oral Squamous Cell Carcinoma; Matrix Metalloproteinases; Biomarkers; Salivary Diagnostics; Prognosis.

Introduction:

Oral cancer is a malignant growth that arises in the tissues of the mouth or oropharynx, including the lips, tongue, cheeks, gums, floor of the mouth, and palate (Kumari *et al.,* 2022). Oral cancer includes a group of neoplasms that impact any area of the oral cavity, pharyngeal regions, and salivary glands (Ebrahimi *et al.,* 2025). The most common of all oral neoplasms, oral squamous cell carcinoma (OSCC), is sometimes used interchangeably with this term (Rajendran *et al.,* 2025). The disease develops through a multistep process of carcinogenesis, beginning with cellular mutations induced by carcinogens such as tobacco, alcohol, and betel nut, or through viral infections like human papillomavirus (HPV) (Hatta *et al.,* 2021, Nethan *et al.,* 2022). These factors cause genetic alterations that disrupt normal cell growth and apoptosis, leading to the transformation of normal mucosa into oral potentially malignant disorders (OPMDs), such as leukoplakia or erythroplakia, which can progress into invasive cancer if left untreated (Das *et al.,* 2023).

The formation of oral cancer involves several stages: initially, there is epithelial dysplasia (abnormal cell growth), followed by carcinoma in situ (confined to the epithelial layer), and eventually invasive carcinoma, where cancer cells penetrate the basement membrane and spread to surrounding tissues (Liu *et al.,* 2022, Liu *et al.,* 2024)

Oral cancer is clinically staged according to the TNM classification system—T for tumor size, N for lymph node involvement, and M for metastasis (Nagesh *et al.,* 2023). Based on these parameters, it is divided into four stages (I–IV). Stage I represents a small, localized tumor without nodal involvement, while Stage IV indicates advanced disease with regional or distant spread Kanagaraja, V. (2024). Oral cancer is still among the most common head and neck cancer, but almost 90 percent of all oral cancers are oral squamous cell carcinoma (OSCC) (Barsouk *et al.,* 2023). According to the World Health Organization (WHO) and Global Cancer Observatory (GLOBOCAN 2022), oral cancer (including lip and oral cavity cancers) accounts for approximately 377,700 new cases and 177,700 deaths worldwide each year (Elseragy, 2023). It ranks among the top 15 most common cancers globally and is particularly prevalent in South and Southeast Asia, where cultural habits such as tobacco chewing, betel quid use, and smoking are widespread (Nahar *et al.,* 2025).Not with standing the progress of surgery, radiotherapy, and chemotherapy, the prognosis of OSCC did not change significantly in the last several decades, mainly due to the difficulty in early diagnosis and high rates of the recurrence (Tan *et al.,* 2023).

Conventional methods for detecting oral cancer primarily rely on clinical examination and histopathological confirmation (Essat *et al.,* 2022). The diagnostic process usually begins with a thorough visual and physical examination of the oral cavity under proper illumination, during which clinicians look for abnormal lesions such as non-healing ulcers, red or white patches (erythroplakia or leukoplakia), nodules, or indurated areas (Eisenberg, 2023). Palpation of the oral mucosa and neck is performed to assess any swelling, lump formation, or lymph node involvement that might indicate metastasis (McGurk & Vig, 2021). One commonly used screening method is toluidine blue staining, a vital dye that selectively binds to areas of dysplastic or malignant epithelium, thereby highlighting suspicious regions for further testing (Supakornpichan *et al.,* 2025). Another non-invasive approach is oral brush cytology, where epithelial cells are collected from the lesion using a brush or spatula and examined microscopically for cytological abnormalities (Wang & Zheng, 2024). However, while these techniques are useful for preliminary assessment, the gold standard for definitive diagnosis remains biopsy and histopathological evaluation, where a tissue specimen from the lesion is microscopically analyzed to determine the presence, type, and grade of malignancy (Aljehani *et al.,* 2023).

To evaluate the depth of invasion and detect regional or distant metastasis, conventional imaging techniques such as X-rays, computed tomography (CT), magnetic resonance imaging (MRI), and ultrasound are employed (MONESHA, 2024). These modalities aid in accurate staging and treatment planning. Although these traditional diagnostic methods are widely practiced and reliable, they often identify the disease at advanced stages, underscoring the urgent need for improved, non-invasive, and early detection strategies using modern technologies and molecular biomarkers.

Traditional diagnostic results largely depend on histopathology of results which though accurate, is invasive in nature and is usually able to identify lesions after these have undergone malignant transformation (Tseng *et al.,* 2023). As a result, it has become a key objective of the oral cancer research to find dependable molecular biomarkers that would be capable of predicting disease development, progression, and response to treatment (Barroso *et al.,* 2025).

Out of the many molecules researched upon, the matrix metalloproteinases (MMPs) have received a lot of attention because of their versatile functions in degrading the extra cellular matrix, tumor invasion, angiogenesis and metastasis (Popova & Jücker, 2022). The growing collection of peer-reviewed research points to MMPs as potential contributors to tumor aggressiveness as well as potential diagnostic and prognostic biomarkers of oral cancer (Hu *et al.,* 2025).

The MMPs are a group of zinc-dependent endopeptidases that break down several different elements of the extracellular matrix (ECM) and basement membrane (Bassiouni *et al.,* 2021). This degradation is a normal physiological process in remodeling of tissues, wound healing and embryogenesis (Yu & Yu, 2023). But in the tumor microenvironment, dysregulated expression of MMPs causes the imbalance between the synthesis and degradation of ECM that facilitates the migration and invasion of malignant cells (Niland *et al.,* 2021). This disproportion is exceptionally high in oral carcinogenesis where different MMPs including MMP-2, MMP-9, and

MMP-14 are critical in the progression of dysplasia to carcinoma (Monea & Pop, 2022). MMP-2 (gelatinase A) and MMP-9 (gelatinase B) break down the type IV collagen, which is one of the key structural components of the basement membrane (Wolosowicz *et al.,* 2024).

By their overexpression, epithelial tumor cells are enabled to invade this natural barrier, which enables them to invade the surrounding connective tissue and spread to the regional lymph nodes (Chen *et al.,* 2025). MMP-14 (MT1-MMP), a transmembrane-bound protease also plays a part by activating pro-MMP-2, as well as degrading ECM components itself, thereby enhance proteolytic cascades in the tumor milieu (Lynch & Matrisian, 2002).

Table 1: Diagnostic and Prognostic Relevance of Key MMPs in Oral Cancer

MMP	Primary Source	Sample Type	Diagnostic Value	Prognostic Value	Reference
MMP-2	Tumor cells, stroma	Saliva, tissue	Early lesion marker	Correlates with vascular invasion	(Ciucă *et al.,* 2019).
MMP-9	Tumor cells, Saliva	Saliva, Serum	Noninvasive diagnostic biomarker	Predicts recurrence, poor survival	(AlAli *et al.,* 2020)
MMP-14	Membrane-bound	Tissue, serum	Indirect via pro-MMP-2 activation	Associated with metastasis, therapy resistance	(Waller & Pruschy, 2021)

These enzymes are not just upregulated randomly but rather in a complex interplay between the tumor cells, stromal fibroblasts and inflammatory cells (Davidson *et al.,* 2021). Cytokines, including interleukin-6 (IL-6) and tumor necrosis factor-alpha (TNF-alpha) which may be increased in oral cancer, mediate the transcription of the MMP genes via NF- 00B and AP-1 signaling pathways (Niklander, 2021). Hypoxia, another characteristic of solid tumor also induces MMP expression when hypoxia-inducible factors (HIFs) are activated, which provides a microenvironment that promotes invasion and angiogenesis (Gonzalez-Avila *et al.,* 2023).

This interaction implies that MMP activity is not only an indicator of tumor aggressiveness but also the dynamic tumor host interaction and therefore, a good indicator of the disease state (Conlon & Murray, 2019).Both clinical and experimental investigations indicate that MMP-2 and MMP-9 are always high in OSCC tissues, patient serum and saliva in comparison to healthy controls (Cai *et al.,* 2022).The discovery of these enzymes in saliva noninvasively is a significant advance in the discovery of biomarkers of oral cancer (Hu *et al.,* 2025). Salivary diagnostics have become popular because they are convenient, repeatable, as well as indicative of the molecular alterations that take place locally in the mouth cavity (Constantin *et al.,* 2025).

ELISA and zymography quantitative analyses have all shown that MMP-9 levels are found to correlate with tumor stage, lymph node, and histopathological grade (Liu *et al.,* 2023). Furthermore, it has been confirmed that the salivary MMP-2 activity is linked to the early lesion formation, which could mean its application in screening people at high risk or as a precancerous alteration of the oral mucosa (Kumari *et al.,* 2022). Salivary MMP-2 and MMP-9 together showed a powerful diagnostic pattern allowing the differentiation of OSCC patients and healthy individuals with high sensitivity and specificity (Starska-Kowarska, 2025).

In addition to diagnosis, MMPs are also prognostic in the occurrence of disease progression, recurrence and survival of the patient (Kicman *et al.,* 2022). MMP-9 high tissue expression has been associated with poor overall survival and high recurrence rates whereas, MMP-2 high tissue expression has been associated with vascular invasion and poor tumor cell differentiation (Yan rt al., 2023). The immunohistochemical analyses of MMPs have demonstrated that they are expressed not only in the malignant epithelial cells but also in the surrounding stromal and endothelial cells indicating their role in tumor angiogenesis (Chen *et al.,* 2025). MMP-14 activates pro-MMP-2 and pericellular proteolysis resulting in the increased endothelial cell migration and new vessel formation, which keeps the tumor alive (Li, 2023). High levels of serum MMP-14 have been suggested as a predictive variable on its own with respect to metastasis and treatment resistance implying its application as prognostic biomarker (Saleem *et al.,* 2021).

There is also emerging evidence that MMPs have the potential to be therapeutic response markers (Lasser *et al.,* 2024). MMP expression can be controlled by radiotherapy and chemotherapy as a response to treatment of the tumor (Fornieles *et al.,* 2023). Indicatively, successful therapy is associated with downregulation of MMP-9, which, in turn, results in lower tumor burden and higher probability of survival (Shoari *et al.,* 2024). On the same note, even in patients whose lesions remain or relapse, continued MMP elevation could be used as an early alert of treatment failure (Zhang *et al.,* 2022).The longitudinal monitoring of MMP activity (via saliva or blood samples) is a minimally invasive clinical approach to the real-time monitoring of disease progression and response to treatment, which is in line with the current focus on personalized oncology (Suri *et al.,* 2024).

Although the diagnostic and prognostic importance of MMPs is quite clear, there are still a number of issues in the translation of these findings into practice. Overlapping MMP expression in malignant and inflammatory oral diseases like periodontitis or oral lichen planus (OLP) is one of the significant limitations that may diminish the specificity of biomarkers (Nunes *et al.,* 2022). In addition, MMP activity is controlled by metalloproteinase tissue inhibitors (TIMPs) and the balance between MMPs and TIMPs instead of absolute levels can be more important indicators of disease (Dimic-Janjic *et al.,* 2023). Hence, the use of both MMP and TIMP profiling may increase the accuracy of the diagnosis (Saini *et al.,* 2025). Before MMP-based assays can be incorporated into routine screening, standardization of sample collection, assay methods and cutoff values is also necessary (Chinnappan *et al.,* 2025).

MMPs have been targeted therapeutically, although initial broad-spectrum MMP inhibitors were not very successful because of toxicity and selectivity (Park *et al.,* 2025). The future studies are aimed at designing more selective inhibitors, monoclonal antibodies and small interfering RNAs that will only target tumor-promoting MMPs without interfering with physiological processes.

Limitations of Conventional Diagnostic Approaches

The conventional diagnostic workflow for OSCC typically includes visual and tactile examination of suspicious lesions followed by histopathological confirmation through tissue biopsy (Romano *et al.,* 2021). Additional tools, such as toluidine blue staining, brush cytology, and light-based fluorescence imaging, have been introduced to aid clinicians in identifying potentially malignant lesions. However, these techniques are often limited by subjectivity, inter-observer variability, and the inability to detect molecular-level changes before histopathological alterations occur. Moreover, biopsy procedures are invasive, may cause patient discomfort, and cannot always be repeated for continuous monitoring. Consequently, by the time an OSCC lesion becomes clinically and histologically apparent, it has often already invaded deeper tissues or metastasized to regional lymph nodes (Cao *et al.,* 2023).

Such diagnostic delays highlight the urgent need for early detection tools that are objective, minimally invasive, and capable of identifying precancerous or early malignant changes before clinical manifestation. The identification and validation of molecular biomarkers capable of predicting malignant transformation, disease progression, or recurrence have therefore emerged as a central focus in OSCC research.

Challenges in Clinical Translation

Despite their enormous potential, the transition of biomarker discoveries into clinical practice faces several significant challenges. One major limitation is the lack of standardization in sample collection, processing, and analysis, which introduces variability and limits reproducibility across laboratories. Many studies use small, heterogeneous patient cohorts that are insufficient for statistical validation. Additionally, biomarker expression can be influenced by factors such as inflammation, infection, or lifestyle habits (e.g., smoking and alcohol use), potentially leading to false positives.

Furthermore, inter-patient heterogeneity in tumor biology means that no single biomarker is universally applicable. Therefore, integrating multiple biomarkers and clinical parameters using bioinformatics and machine learning approaches is becoming increasingly essential. Such systems can process complex datasets, identify molecular signatures predictive of OSCC, and stratify patients into risk categories more accurately than conventional methods alone.

Another challenge is ensuring that newly identified biomarkers are cost-effective, reproducible, and accessible in low-resource settings. Since OSCC incidence is highest in developing regions, diagnostic tools must be affordable and practical for community-level use.

Future Perspectives and Clinical Implications

The ongoing research into OSCC biomarkers represents a paradigm shift from conventional morphology-based diagnosis to molecular-level precision diagnostics. The ultimate goal is to create a reliable, minimally invasive, and rapid diagnostic platform that integrates multiple biomarkers and predictive algorithms. Combining salivary CYFRA 21-1 and MMP-9 with other emerging candidates—such as IL-8, S100A7, and miRNAs—could yield a comprehensive diagnostic panel with superior accuracy.

In the future, these biomarkers may also aid in therapeutic stratification, allowing clinicians to choose targeted therapies based on molecular profiles. For example, patients with elevated MMP-9 expression might benefit from metalloproteinase inhibitors or anti-angiogenic agents. Likewise, continuous biomarker monitoring post-surgery could help in detecting minimal residual disease and preventing recurrence.

However, realizing this vision will require large-scale multicenter validation studies, regulatory approval, and integration into clinical guidelines. Furthermore, public health initiatives should focus on training healthcare workers to implement biomarker-based screening tools at the community level.

Conclusion:

MMP-2, MMP-9, and MMP-14 play a mechanistic role in OSCC invasion and metastasis and are present in saliva, serum, tissue, and exosomes. Salivary MMP-9 is now the most reliable case-control detection signal of OSCC with salivary MMP-2 and MMP-14 demonstrating stronger tissue-level prognosic. To be translated into routine clinical use, standardized sampling, assay harmonization, close attention to oral inflammatory confounders, and large prospective multicenter validation by multimarker strategies has to be done. These steps may make MMP-based assays particularly when used in conjunction with exosomal profiling and clinical algorithms, viable solutions to the screening of high-risk groups, surgical decisions, and postoperative recurrence of OSCC.

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ANTIBIOFILM ACTIVITY OF *GYMNEMA SYLVESTRE* AGAINST *STREPTOCOCCUS MUTANS*: A COMPREHENSIVE REVIEW

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Abstract:
Dental caries remains one of the most prevalent oral health problems worldwide, and the progression of the disease is inevitably linked to the complexity of biofilm communities dominated by *Streptococcus mutans*. Because these bacterial communities are embedded in an extracellular polymeric matrix that provides high structural integrity and physiological stability, traditional antimicrobial strategies are becoming less effective. Even though such chemical agents as fluoride and chlorhexidine are considered to be a part and parcel of preventative treatment, they are associated with several limitations, including the development of resistance, mucosal irritation and changes in the balance between the oral microbial communities, which is why new treatments are required. Due to their ability to regulate numerous biological pathways without causing serious side effects, natural phytochemicals have become one of the most popular targets and *Gymnema sylvestre* has become a particularly promising target. It is endowed with the possibility of attacking biofilms on genetic, structural, and biochemical levels because of its high concentration of gymnemic acids, saponins, flavonoids, tannins, alkaloids, terpenes and phenolic compounds. This chapter explores the biology of biofilm formation, the virulence determinants of *S. mutans* and the overall outline of international strategies to curb biofilms in detail. It combines experiments to investigate the ethnopharmacology, phytochemistry and mechanistic properties of *G. sylvestre* as an antibiofilm agent.

Introduction:

Irrespective of the social, economic or geographical limits, dental caries remains one of the most prevalent oral diseases, and it has impacted adults, children and the elderly. The mechanism of its pathogenesis is now understood as a complex interplay between dietary habits, enamel vulnerability, saliva composition and the dynamic biofilm communities that inhabit the mouth cavity, as opposed to simple infection. This biofilm-based conceptualisation of dental caries has steadily guided the research directions to study the development of biofilms, their protective effects on the resident bacteria and the need to redesign the therapeutic interventions in order to be biofilm-focused instead of bacteria-focused. Compared to planktonic bacteria that float freely, biofilm-associated bacteria are far more resistant to antimicrobial agents and able to endure in microenvironments that have restricted nutrients available, which are acidic or have variable oxygen levels. Their intrinsic structural and metabolic plasticity ensures the natural ability of biofilms to remain stable in unfriendly oral conditions (Bjarnsholt *et al.,* 2013; Koo *et al.,* 2017; Flemming & Wuertz, 2019).

Mouthwashes that contain chemicals, i.e., cetylpyridinium chloride or chlorhexidine, are also found to decrease the number of bacteria but often result in unexpected reactions. The prolonged use may lead to stained teeth, distorted taste, pain in the mouth and alteration in the desirable oral microorganisms. Fluoride is useful in the process of rebuilding the enamel, and it is less proficient at dissolving already formed layers of bacteria. Based on these issues, researchers are currently looking into plant-based derivatives that may facilitate the defence system of the body and have more extensive benefits (Choi *et al.,* 2017; Narwal *et al.,* 2025).

Of the helpful ingredients in medicinal plants, some have taken centuries to be validated by modern science. Because the chemical compounds found in plants vary so much, they can affect many germs at once, lowering the chances that bacteria will become resistant. The plant *Gymnema sylvestre* is widely used in traditional Indian medicine to treat health ailments related to blood sugar and digestion, among others; it's currently being studied as an agent that might thwart bacteria and the slimy germ layers. It doesn't just change how sugars behave; it also makes microbes less able to stick, short-circuits their communication, and diminishes acid production-an effective way to fight tooth decay. Dental problems associated with sticky germ films remain difficult to manage, but this plant offers a natural and promising approach (Khan *et al.,* 2019; Behuria *et al.,* 2021).

Oral Microbiome and *Streptococcus mutans* Physiology

The oral microbiome is a highly intricate ecosystem composed of a diverse array of microorganisms that inhabit various niches within the mouth. These niches include the tooth surfaces, gingival crevices, tongue dorsum, buccal mucosa and saliva. Within this ecosystem, bacteria exist not in isolation but in interconnected multispecies communities that communicate through chemical and physical signals. A healthy oral microbiome maintains equilibrium between beneficial and pathogenic species, but disturbances such as frequent sugar intake or poor oral hygiene can shift this balance toward dysbiosis, allowing acidogenic species like *Streptococcus mutans* to dominate dental plaque (Koo *et al.,* 2017; Shrestha *et al.,* 2022; Zayed *et al.,* 2021).

The success of *S. mutans* in initiating and sustaining dental caries stems from its unique physiological capabilities. Its virulence is largely attributed to powerful adhesion mechanisms that enable rapid colonisation of the acquired pellicle, supported by surface proteins and glucan-binding components that stabilise biofilm formation. Once established, *S. mutans* secretes glucosyltransferase enzymes that convert sucrose into extracellular polysaccharides, providing structural integrity and contributing to an EPS matrix that protects the bacterium from environmental challenges (Lemos *et al.,* 2019; Ribeiro *et al.,* 2023; Matsui & Cvitkovitch, 2010). The organism's metabolic flexibility further enhances its pathogenicity. *S. mutans* ferments various carbohydrates to produce lactic acid, lowering pH and promoting enamel demineralisation. Its ability to survive in acidic environments is supported by membrane modifications, proton extrusion systems, and the activation of acid tolerance genes. Additionally, quorum-sensing pathways regulate competence, bacteriocin production, stress survival, and coordinated biofilm development. These combined advantages make *S. mutans* a formidable pathogen and an ideal target for natural antibiofilm agents like *Gymnema sylvestre*, which can disrupt multiple physiological processes simultaneously (Welin-Neilands & Svensäter, 2007; Khan *et al.,* 2019; Roy *et al.,* 2018).

Biofilm Formation Processes in the Oral Cavity

Biofilm formation in the oral cavity is not an accidental event but a highly organised and evolutionarily refined process that allows microbes to respond effectively to environmental stressors (Bjarnsholt *et al.,* 2013). The process begins with the development of the acquired pellicle, a thin film derived from salivary components that adsorb to the enamel surface within minutes. This pellicle consists of proteins such as mucins, proline-rich proteins, amylase, and immunoglobulins, all of which provide a surface for microbial adhesion. The pellicle also acts as a protective barrier for the tooth, but simultaneously serves as the initial attachment point for early colonisers (Milho *et al.,* 2021).

The initial attachment phase sees pioneering species like *S. mutans* adhere to the pellicle through physicochemical interactions that evolve into stronger biochemical bonds as the bacteria express adhesins and receptors. Once firmly attached, the bacteria initiate the production of extracellular polymeric substances, which mark the transition from reversible to irreversible adhesion. The EPS matrix forms the structural backbone of the biofilm and plays essential roles in nutrient retention, protection against antimicrobials, and mechanical cohesion (Pallavi *et al.,* 2024). As the biofilm matures, it develops into a heterogeneous three-dimensional community with distinct microcolonies separated by water channels that facilitate nutrient and waste exchange.

Quorum-sensing systems become increasingly active during this stage, allowing bacteria to communicate through signalling molecules that regulate collective behaviours. This intercellular communication influences virulence gene expression, stress response, competence development, and the reinforcement of biofilm architecture (Rudin *et al.,* 2023). The mature biofilm represents a highly resilient structure capable of resisting mechanical forces and antimicrobial agents. Eventually, biofilm cells undergo detachment or dispersal, allowing bacteria to colonise new surfaces and spread disease. Understanding these stages is essential for the design of antibiofilm agents because interventions must disrupt multiple phases concurrently (Koo *et al.,* 2017).

Natural agents like *G. sylvestre* are uniquely positioned to do so because their phytochemical components can influence adhesion, EPS synthesis, quorum-sensing pathways, and metabolic activity.

Global Strategies for Biofilm Control

Biofilm control requires a multifaceted approach that integrates mechanical, chemical, ecological, and biological strategies. Mechanical disruption remains the simplest and most direct method, yet even thorough brushing and flossing rarely eliminate mature biofilms. The structural complexity of the EPS matrix and its protective characteristics mean that deeper layers remain intact after routine oral hygiene practices. This is further complicated by anatomical factors such as pits, fissures, interproximal spaces and orthodontic appliances, which create microenvironments ideal for biofilm retention (Koo *et al.,* 2017; Pallavi *et al.,* 2024).

Chemical antimicrobials continue to play an important role in oral healthcare, but their limitations are substantial. Chlorhexidine has been considered the gold standard for decades, yet prolonged usage leads to enamel staining, calculus accumulation, taste disturbances, and mucosal irritation. Fluoride enhances remineralisation but is unable to penetrate deeply into biofilm layers or inhibit bacterial communication systems. Other agents, such as essential oils, may have broad antimicrobial activity but lack specificity and consistency in clinical outcomes. The need for alternatives that are potent, biocompatible, and have a broad range of mechanisms has therefore become evident (Chi *et al.,* 2022; Radmand *et al.,* 2024).

Natural products offer these advantages because they contain diverse bioactive molecules that act synergistically to target multiple aspects of bacterial survival. Their ability to interfere with adhesion, inhibit glucosyltransferase activity, disrupt metabolic pathways, block quorum sensing, and weaken the EPS matrix makes them particularly valuable in biofilm control. Unlike synthetic antimicrobials that typically act through a single biochemical pathway, plant-derived compounds work at several levels simultaneously. This multitargeted action reduces the likelihood of microbial resistance, enhances overall efficacy, and aligns with current trends toward holistic and patient-friendly oral healthcare. Within this context, *G. sylvestre* emerges as one of the most promising candidates because its unique phytochemical diversity provides a broad and stable therapeutic platform for biofilm management in dentistry (Narwal *et al.,* 2025; Zhang *et al.,* 2022).

***Gymnema sylvestre*: Ethnopharmacology, Traditional Use, and Botanical Context**

Gymnema sylvestre has a long and culturally significant history in traditional medicinal systems, particularly Ayurveda, Siddha and various folk healing traditions across India, Sri Lanka, Bangladesh and parts of Africa. For centuries, communities have used its leaves to manage conditions associated with sugar metabolism, inflammation, digestive imbalances and general vitality. The plant is famously known as "Gurmar," a term translated as "sugar-destroyer," referring to its remarkable capacity to temporarily suppress the sensation of sweetness when the leaves are chewed. This effect is attributed to gymnemic acids, which occupy the taste receptors on the tongue that normally bind sweet molecules. This traditional observation eventually became a driving force behind modern pharmacological exploration, leading researchers to identify the plant as a valuable source of triterpenoid saponins with potent bioactivity (Khan *et al.,* 2019; Saneja *et al.,* 2010).

Ethnopharmacologically, healers often used *G. sylvestre* to support digestion, treat urinary disorders, regulate blood glucose, and restore metabolic balance. The plant was believed to strengthen internal organs, particularly the pancreas and liver. Its use in managing "Madhumeha" (ancient terminology for diabetes mellitus) was well documented in Ayurvedic scriptures, where practitioners observed improvements in vitality, appetite control, and symptoms related to metabolic disorders. Over time, the herb also gained recognition for its anti-inflammatory and antimicrobial properties, which likely contributed indirectly to oral health benefits long before scientific research defined them (Potawale *et al.,* 2008; Kumari, 2024).

Botanically, *G. sylvestre* is a perennial woody climber belonging to the family Apocynaceae and grows predominantly in tropical and subtropical forests. It thrives in regions with high humidity, a warm climate, and moderate rainfall. The plant produces elongated, opposite leaves rich in bioactive compounds housed in specialised glandular structures. Flowers are small, yellowish, and occur in clusters, while the fruit consists of elongated follicles containing numerous seeds. The biochemical richness of the leaves reflects the plant's adaptation to protect itself from microbial and environmental stress, which partly explains why extracts show pronounced antimicrobial and antibiofilm actions. The ethnobotanical prominence of this plant provides a strong scientific basis for exploring its pharmacological properties, particularly in the context of dental biofilms, where multi-target action is essential (Hasan *et al.,* 2020; Ghandehari *et al.,* 2025).

Phytochemistry of *Gymnema sylvestre*

The therapeutic potential of *G. sylvestre* primarily arises from its complex and diverse phytochemical composition. The leaves contain an array of secondary metabolites, each contributing to the plant's antimicrobial, antioxidant and anti-inflammatory properties. At the forefront are the gymnemic acids, a group of triterpenoid saponins that exist in multiple structural variants. These compounds exhibit amphiphilic characteristics that allow them to interact with lipid membranes, disrupt microbial cell integrity, and modulate enzyme activity. Their well-known ability to block sweet taste perception is linked to their structural similarity to glucose, which enables them to bind selectively to taste receptors; however, this same molecular mimicry also allows them to compete with sugars for enzymatic sites in bacteria such as *S. mutans* (Khan *et al.,* 2019; Kotwal *et al.,* 2024; Li *et al.,* 2023).

In addition to gymnemic acids, *G. sylvestre* contains gymnemasaponins and gymnemosides, which contribute to the plant's broad-spectrum pharmacological profile. These molecules enhance membrane permeability alterations in bacteria and can destabilise the protective layers that biofilm-forming organisms rely upon. Flavonoids and polyphenols present within the plant, such as quercetin, kaempferol and other glycosylated derivatives, bring strong antioxidant properties that reduce oxidative stress within the oral cavity. Oxidative stress often plays a significant role in chronic inflammation and tissue destruction within oral biofilms; therefore, the antioxidant components of *G. sylvestre* serve as additional biofilm-modulating agents (Saha *et al.,* 2023; Yun *et al.,* 2023; Jiang *et al.,* 2023).

Tannins in the plant further contribute by binding to microbial proteins, forming complexes that interfere with bacterial adhesion and enzymatic activity. Their astringent properties help limit bacterial growth by precipitating surface proteins essential for adhesion. Other constituents such as terpenes, alkaloids, phenolics, and sterols complete the phytochemical profile and collectively enhance antimicrobial potency. Each phytochemical group contributes uniquely; together, they create a synergistic "phytochemical matrix," a hallmark of botanical therapeutics. Such synergy is crucial because biofilm-associated pathogens like *S. mutans* require multi-targeted inhibition. This makes the phytochemical richness of *G. sylvestre* particularly advantageous when compared to single-target synthetic antimicrobials (Behuria *et al.,* 2021; Rasmi *et al.,* 2024; Sowmya *et al.,* 2025).

Mechanisms of Antibiofilm Action of *Gymnema sylvestre*

The antibiofilm activity of *G. sylvestre* is not confined to a single pathway but instead arises from a combination of molecular mechanisms acting at different stages of biofilm formation. One of the most significant mechanisms involves the inhibition of glucosyltransferase (GTF) enzymes produced by *S. mutans*. These enzymes are responsible for synthesising extracellular glucans from dietary sucrose, which form the structural backbone of dental plaque. When gymnemic acids bind to active sites on GTF enzymes, they diminish the ability of *S. mutans* to create a stable and adhesive biofilm matrix. Without a strong EPS scaffold, early adhesion weakens and mature biofilm architecture collapses more easily under mechanical or chemical interventions (Ganesh *et al.,* 2024; Atazhanova *et al.,* 2024; Wu *et al.,* 2022).

Another major mechanism is the disruption of the bacterial cell membrane. The amphiphilic nature of saponins allows them to insert themselves into lipid bilayers, causing porosity and leakage of cellular contents. This action weakens the bacteria structurally and physiologically, making them more susceptible to oxidative stress and antimicrobial agents. Membrane disruption not only affects bacterial survival but also reduces their ability to coordinate biofilm formation (Mehdipour *et al.,* 2022; Hamad, 2024).

Quorum-sensing interference represents an additional critical mechanism. By altering the production or reception of signalling molecules such as competence-stimulating peptides, *G. sylvestre* interrupts the genetic communication pathways that bacteria rely upon to synchronise biofilm growth, virulence, stress responses, and genetic competence. When quorum sensing fails, biofilm formation becomes irregular, less cohesive, and far more vulnerable to disruption (Ghandehari *et al.,* 2025; Tzimas *et al.,* 2024).

Furthermore, *G. sylvestre* demonstrates the capacity to reduce acid production by interfering with carbohydrate metabolism in *S. mutans*. Since lactic acid generation is fundamental to enamel demineralisation, reducing acidogenesis provides a powerful anti-cariogenic effect. At the same time, antioxidant phytochemicals in the plant mitigate oxidative stress conditions that often support biofilm persistence. Altogether, these mechanisms produce a comprehensive antibiofilm effect that targets *S. mutans* at multiple functional, structural, enzymatic, and genetic levels (Narwal *et al.,* 2025; Palombo, 2011).

Experimental and Microbiological Evidence

Experimental studies across *in vitro*, *ex vivo* and limited *in vivo* models consistently demonstrate the antibiofilm efficacy of *G. sylvestre* extracts. Laboratory assays reveal that both crude extracts and purified gymnemic acid fractions significantly reduce bacterial adhesion on hydroxyapatite surfaces, a common model for tooth enamel. Microscopic imaging techniques, including scanning electron microscopy and confocal laser scanning microscopy, show that treated biofilms display disrupted architecture, diminished EPS density, and a marked reduction in microcolony formation (Pallavi *et al.,* 2024; Moghaddam *et al.,* 2022; Malekzadeh *et al.,* 2024).

Microbiological assays further confirm reductions in viable cell counts, inhibition of glucan production, and decreased metabolic activity of *S. mutans* exposed to the plant extracts. Many studies highlight a noticeable decline in acidogenic potential, suggesting that the extracts interfere directly with glycolytic pathways. In addition, the synergistic effects of *G. sylvestre* with other natural antimicrobials such as green tea catechins, neem components, or citrus flavonoids have been observed, amplifying the overall antibiofilm action (Ganesh *et al.,* 2024; Chi *et al.,* 2022).

Although most evidence arises from in vitro studies, the limited animal research available indicates that regular application of *G. sylvestre* extracts reduces plaque accumulation and caries severity in rodent models. These outcomes suggest promising translational potential. However, standardised extraction methods, consistent dosage formulations, and controlled clinical trials are still needed to validate these benefits in human populations comprehensively (Tiwari *et al.,* 2014; Yun *et al.,* 2023).

Comparative Evaluation with Other Antibiofilm Plants

Several medicinal plants exhibit antibiofilm activity against *S. mutans*, including neem, green tea, clove, cinnamon, phloretin-rich apple extracts, and citrus-derived flavonoids. Each of these botanicals contributes a unique set of phytochemicals that act on biofilms through mechanisms such as membrane disruption, EPS inhibition, and metabolic suppression. Neem, for example, contains azadirachtin and nimbidin, which have strong antibacterial properties. Green tea catechins, particularly epigallocatechin gallate, disrupt cell membranes and inhibit bacterial enzymes. Citrus flavonoids interfere with quorum-sensing signals, while clove oil components such as eugenol damage bacterial membranes (Palombo, 2011; Milho *et al.,* 2021).

Despite these advantages, *Gymnema sylvestre* stands out because of its multi-layered mechanism of action. Unlike plants with single-dominant active compounds, *G. sylvestre* contains a diverse blend of phytochemicals that collectively influence bacterial adhesion, EPS synthesis, quorum regulation, and acid production. The presence of gymnemic acids, in particular, provides a unique advantage due to their structural ability to mimic sugar molecules while disrupting carbohydrate metabolism. This multi-targeted effect reduces the likelihood that bacteria will develop resistance, making *G. sylvestre* a compelling botanical candidate (Kumari, 2024; Tiwari *et al.,* 2014).

Therapeutic Applications and Future Potential in Dentistry

The broad-spectrum antibiofilm properties of *Gymnema sylvestre* support its incorporation into a variety of dental care formulations aimed at preventing or managing caries. Its multitarget action makes it suitable for use in toothpaste, mouthrinses, dental gels, varnishes, and herbal medicated chewing gums. Toothpaste enriched with *G. sylvestre* extracts may not only reduce microbial load but also help prevent the development of a stable EPS matrix, thereby reducing plaque accumulation over time. Mouthrinses containing gymnemic acids offer additional benefits because these compounds can interact with oral mucosal surfaces and influence sugar perception, indirectly lowering sugar cravings. By reducing excessive sugar intake, *G. sylvestre* not only disrupts the pathogenic mechanisms of *S. mutans* but also influences broader dietary habits that contribute to caries progression (Palombo, 2011; Hickl *et al.,* 2024).

In addition to traditional formulations, *G. sylvestre* demonstrates significant potential in advanced dental technologies such as biodegradable varnishes, slow-release coatings, and nano-based delivery systems. For example, incorporating gymnemic acids into nanocarriers such as liposomes, polymeric nanoparticles, or nanoemulsions can enhance their stability, bioavailability, and retention time within the oral cavity. These systems ensure a controlled release of the active compounds, leading to prolonged antimicrobial and antibiofilm activity even after the initial application. Dental varnishes enriched with *G. sylvestre* extracts may help protect tooth surfaces by creating a barrier that resists microbial colonisation and prevents EPS formation. The ability of the extracts to interfere with glucosyltransferase activity makes them particularly attractive as protective agents applied after professional dental cleaning (Choi *et al.,* 2017; Atazhanova *et al.,* 2024).

For individuals at high risk of dental caries, including those with reduced salivary flow, orthodontic appliances, or dietary habits rich in fermentable carbohydrates, *G. sylvestre* may offer an additional preventative measure. Chewing gums incorporating gymnemic acid have the potential to reduce sweet cravings, stimulate saliva flow, and reduce microbial adherence. Saliva stimulation alone offers numerous benefits because increased salivary flow contributes to buffering capacity, antimicrobial peptide distribution, and overall oral homeostasis. Moreover, the natural and non-toxic nature of *G. sylvestre* makes it suitable for pediatric populations, pregnant women, and individuals sensitive to strong chemical antimicrobials (Rasmi *et al.,* 2024; Ganesh *et al.,* 2024).

Beyond consumer products, *G. sylvestre* offers exciting possibilities for dental biomaterials. Researchers have explored the incorporation of plant extracts into restorative materials such as composite resins, dental adhesives, and sealants to impart antimicrobial properties. Embedding gymnemic acids into such materials could help prevent secondary caries, a common challenge occurring at restoration margins due to microleakage and microbial colonisation. In orthodontics, clear aligner materials or wires coated with plant-derived antibiofilm agents could reduce plaque buildup on appliances, ultimately minimising enamel decalcification. These prospective applications reflect the broad adaptability of *G. sylvestre* within modern dental care and highlight its potential as a botanical adjunct to contemporary oral health strategies (Moghaddam *et al.,* 2022; Kotwal *et al.,* 2024).

Limitations, Challenges, and Future Directions

Despite the promising results associated with *Gymnema sylvestre*, several limitations and uncertainties must be acknowledged before its widespread clinical adoption. One of the major challenges is the variability in phytochemical composition across different plant sources. Factors such as growing conditions, harvesting time, geographic origin, soil composition, and extraction techniques significantly influence the concentration of gymnemic acids and other bioactive constituents. This variability complicates the standardisation of extracts, making it difficult to ensure consistent therapeutic outcomes. Without strict phytochemical profiling and quality control, the effectiveness of products derived from *G. sylvestre* may vary considerably (Ribeiro *et al.,* 2023; Zayed *et al.,* 2021).

Another limitation lies in the scarcity of well-controlled clinical trials evaluating the plant's antibiofilm activity specifically in human oral conditions. Although numerous in vitro studies demonstrate strong antimicrobial and antibiofilm effects, translating these findings into clinical success requires tests within the complex environment of the mouth, where factors such as saliva flow, oral pH, diet, and microbiome diversity influence treatment effectiveness. The dynamic nature of oral biofilms also means that the long-term effects of repeated exposure to plant extracts must be assessed to determine whether these treatments influence beneficial microbial communities or promote dysbiosis (Hickl *et al.,* 2024; Rasmi *et al.,* 2024).

Toxicity and safety profiles also need careful examination. While *G. sylvestre* has a long history of traditional use and is generally considered safe, concentrated extracts or purified compounds may produce unexpected effects when applied frequently or in high doses. Assessing cytotoxicity on oral tissues, including gingival fibroblasts and epithelial cells, is essential. Furthermore, because gymnemic acids can alter sweet taste perception, their repeated use in certain formulations may impact eating behaviour, which could be beneficial or undesirable depending on the context (Ghandehari *et al.,* 2025; Hamad, 2024).

Future research must focus on optimising extraction methods, determining ideal dosages, evaluating long-term safety, and conducting randomised clinical trials to validate efficacy in human subjects. Advances in phytochemical standardization, nanotechnology-based delivery systems, and synergistic formulations combining *G. sylvestre* with other natural antimicrobials could enhance its clinical potential. It is equally important to investigate how the plant interacts with multispecies biofilms that more accurately mimic the oral microbiome. Understanding the broader ecological effects of its compounds will help ensure that treatments strengthen oral health without disrupting beneficial bacterial populations. Addressing these limitations will pave the way for the responsible and scientifically supported integration of *G. sylvestre* into modern dentistry (Kumari, 2024; Tiwari *et al.,* 2014).

Conclusion:

Gymnema sylvestre represents a significant and promising botanical resource for the development of innovative oral healthcare strategies aimed at preventing or managing dental caries. Its wide range of phytochemicals, including gymnemic acids, flavonoids, tannins, alkaloids and saponins, confer multiple biological actions capable of disrupting biofilm formation at structural, metabolic, enzymatic, and genetic levels. Through the inhibition of glucosyltransferase enzymes, suppression of EPS matrix formation, interference with quorum sensing, and attenuation of acidogenic pathways, the plant effectively targets the major virulence traits of *Streptococcus mutans*. Experimental and preliminary in vivo studies consistently show that *G. sylvestre* weakens biofilm architecture, reduces microbial viability, and lowers acid production, making it a strong candidate for use in oral care formulations.

Its safety profile, historical medicinal use, and multi-targeted antimicrobial mechanisms offer key advantages over synthetic antimicrobials that often exhibit toxicity or promote resistance. Furthermore, the versatility of *G. sylvestre* allows integration into a wide range of products, from toothpaste and mouthrinses to coating agents, nanocarriers, and biomaterial enhancements.

While limitations exist, particularly regarding phytochemical variability and lack of large-scale clinical studies, ongoing research and technological advancements provide strong potential for overcoming these challenges. In summary, *Gymnema sylvestre* stands out as an effective, natural, and scientifically grounded plant capable of contributing to next-generation caries prevention and oral biofilm control strategies.

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ROLE OF BIOMASS ENERGY IN RENEWABLE AND SUSTAINABLE ENERGY SYSTEMS

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Abstract:

Biomass energy is one of the good and popular energy resources in various renewable energy sources. Biomass energy generates from plants, agricultural crop residues and animal manure. Generation of the biomass energy is based on combustion, chemical and biochemical process. In each process of biomass applications thermal, chemical and biochemical reactions are involved like heating (residential/industrial boilers, stoves), electricity generation (direct combustion, co-firing with coal, gasification), and producing biofuels (ethanol, biodiesel for transport). It also creates sustainable biochemicals, bioproducts, and biofertilizers (biochar), replacing fossil fuels, reducing waste, creating rural jobs, and offering advanced uses in energy storage. It can use for small scale also. Biomass can produce clean energy by different methods but sometimes production of biomass energy contains disadvantages due to mishandling the process.

Keywords: Biomass, Applications, Fuel, Thermal, Gasification, Biochemical, Process.

1. Introduction:

Presently biomass energy is using in various applications in industries and in agriculture sector. It can be generated broadly by three methods as showing in the figure 1. Usually, fuel produces from biomass in form of solid, liquid and gas. Solid fuel is known as briquette. Liquid form is biodiesel and gasification and biogas are main components of biomass energy.

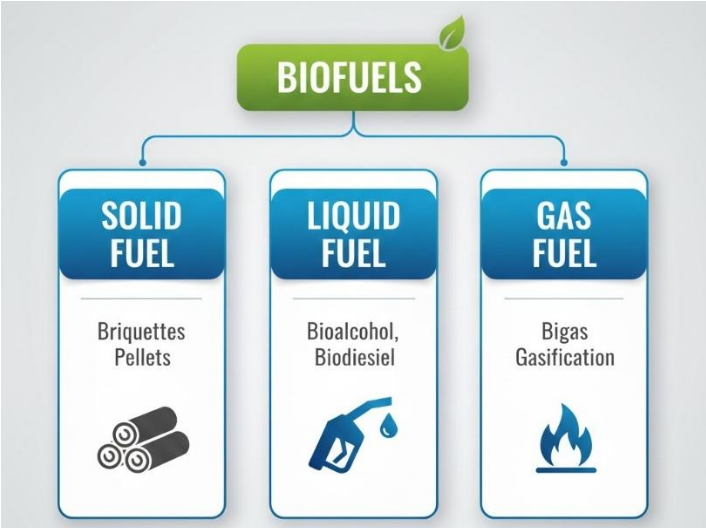

Figure 1: Biofuel

2. Solid Biofuels: In rural areas and village areas where cattle's are existing cattle dung cake (uple) used as a fuel for cooking purposes. But this fuel may generate lots of greenhouse gases so briquettes can be used as a solid biofuels. Briquettes are solid biofuels which are made from biomass. In preparing our basic necessities like food and water, we need fuel. Usually, we rely on electricity and fossil fuel (like LPG and kerosene) for our energy needs. However, there are other resources that have more advantages and benefits than these conventional sources. One such fuel is the briquette and the process of creating briquettes is briquetting. The briquettes are highly preferred in the locations where fuel is hard to find and is costly. Thus at such places, briquetting can become the best option for getting fuel at a cheap price and easy way.

Briquettes are flammable blocks of matter used as fuel. They are made from extruded or compressed shredded combustible materials. A binding agent like starch may be necessary to hold the materials together, though pressure may at times be enough. Some of the common materials used as briquettes are charcoal fines, mineral char, sawdust, chaff from rice, peanut and other crops, peat, and any biomass materials. Here, we will see the advantages and disadvantages of briquette and why it is a better alternative to conventional fuels.

2.1 Types of Briquettes:

In India, different types of briquettes are manufactured through briquetting machines. All types of briquettes are made from agricultural or forestry waste which are used in different industries. There is a collection of various briquettes like biomass briquettes, recycled briquettes, white coal briquettes, saw dust briquettes, agro waste briquettes, wood briquettes, boiler fuel briquettes etc.

2.2 Biomass Briquettes

Biomass and other green waste are gathered and compressed under high pressure and then convert into biomass briquettes. This whole process is known as biomass briquetting process. Biomass briquettes are perfect substitute to coal and lignite. These biomass briquettes are used in industries to heat the boilers and to produce steam as well as at home for cooking. It does not emit sulphur or any other gas which pollute environment.

2.3 Sawdust Briquettes

Sawdust briquettes are quality assured briquettes. These briquettes are comes with low as content and delivers smokeless usage. These briquettes are widely used to provide heat to industrial boilers which in turn produces electricity from steam. Sawdust briquettes are offered by biomass briquettes manufacturer are reliable and economic. They are making these briquettes in saw dust briquette machine which is highly useful machine. These are available in the industrial market with leading price.

2.4 Agro Waste Briquettes

Agro waste briquettes are best alternative to coal and charcoal. These briquettes are made from agriculture or forestry waste and have high specific density compared to lose biomass. These briquettes are easy to handle, transport and store. These are cheaper than coal and offer high boiler efficiency due to low moisture. These have no sulphur content that pollutes environment. Briquette manufacturing unit use biomass briquette press machine to manufacture eco friendly agro waste briquettes.

2.5 Wood Briquettes

Wood briquette has burning efficiency and does not generate any flash. It is the vital source of energy and can be used in the place of coal and fire wood. These briquettes are pollution free and having excellent burning efficiency. The carbon dioxide (CO2) balance is even, because wood briquettes release just as much CO2 to the atmosphere as the tree absorbs through growth by photosynthesis.

Advantages of Briquettes:

- Briquette replaces the usage of the conventional type of fuels
- Briquette is considered as the best renewable source of fuel and energy
- Causes Less pollution as it does not emit sulfur or fly ash
- Has good thermal calorific value
- It requires agro-waste or bio-waste to produce briquette thus it is very cheap
- Easy to store, handle and transport
- Used in domestic, commercial and industrial area for many applications
- Prevents deforestation and helps to conserve natural resources
- Compared to coal briquettes has consistent combustion and ignition temperature
- Best choice for agricultural waste disposal
- Low moisture content results in higher burning efficiency
- No unsafe gas emission
- Briquettes have no smoke, soot or carbon deposits
- Due to compression briquette reduces the waste by 90%

Disadvantages of Briquettes

- In Briquette manufacturing, the process of densification requires more energy
- The initial cost is very high for briquette
- Briquette needs a large space for setting up the plant
- It needs modern machines for shredding, crushing and drying
- Briquettes can be easily affected by atmospheric conditions
- Humidity in weather loosens the combustion characteristic
- Briquettes need large waterproof space for storage

3. Liquid Biofuels:

Biofules can be classified into four types on the basis of generation:

3.1 First-generation biofuels: First-generation" biofuels are made from food crops. Sugar, starch, or vegetable oil obtained from the agricultural crops is converted into biodiesel or ethanol, using transesterification, or yeast fermentation.

3.2 Second-generation biofuels: Second generation biofuels are fuels manufactured from various types of biomass. Second generation biofuels are made from lignocelluloses biomass or woody crops, agricultural residues or waste plant material.

This has both advantages and disadvantages. The advantage is that, unlike with regular food crops, no arable land is used solely for the production of fuel. The disadvantage is that unlike with regular food crops, it may be rather difficult to extract the fuel. For instance, a series of physical and chemical treatments might be required to convert lignocellulosic biomass to liquid fuels suitable for transportation.

3.3 Third-generation biofuels: This type of fuel using algae as a biofuels. The oil-rich algae can then be extracted from the system and processed into biofuels, with the dried remainder further reprocessed to create ethanol. The production of algae to harvest oil for biofuels has not yet been undertaken on a commercial scale, but feasibility studies have been conducted to arrive at the above yield.

3.4 Fourth-generation biofuels: Similarly to third-generation biofuels, fourth-generation biofuels are made using non-arable land. However, unlike third-generation biofuels, they do not require the destruction of biomass. This class of biofuels includes electro fuels and fuels. Some of these fuels are carbon-neutral.

3.5 Liquid biofuels can be classified into two types on the basis of biomass:

Bioethanol: Bioethanol is an alcohol made by fermenting the sugar components of plant material and it is made mostly from sugar and starch crops with advanced technology being developed cellulosic biomass, such as trees and grasses are also used as feed stocks for ethanol production. Ethanol can be used as a fuel for vehicles in its pure form but it is usually used as a gasoline additive to increase octane and improve vehicle emission.

Biodiesel: Biodiesel is made from vegetable oils, animal fats or recycled grasses. Biodiesel can be used as a fuel for vehicles in its pure form.

Ethanol: Biologically produced alcohols, most commonly ethanol, produced by the action of microorganisms and enzymes through the fermentation of sugars or starches. Biobutanol (also called biogasoline) is often claimed to provide a direct replacement for gasoline, because it can be used directly in a gasoline engine. Ethanol fuel is the most common biofuel worldwide, particularly in Brazil. Alcohol fuels are produced by fermentation of sugars derived from wheat, corn, sugar beets, sugar cane, molasses and any sugar or starch from which alcoholic beverages such as whiskey, can be made (such as potato and fruit waste, etc.). The ethanol production methods used are enzyme digestion (to release sugars from stored starches), fermentation of the sugars, distillation and drying. The distillation process requires significant energy input for heat (sometimes unsustainable natural gas fossil fuel, but cellulosic biomass such as bagasse, the waste left after sugar cane is pressed to extract its juice, is the most common fuel in Brazil, while pellets, wood chips and also waste heat are more common in Europe) Waste steam fuels ethanol factory[34] – where waste heat from the factories also is used in the district heating grid.

Ethanol can be used in petrol engines as a replacement for gasoline; it can be mixed with gasoline to any percentage. Most existing car petrol engines can run on blends of up to 15% bioethanol with petroleum/gasoline. Ethanol has a smaller energy density than that of gasoline; this means it takes more fuel (volume and mass) to produce the same amount of work. An advantage of ethanol (CH_3CH_2OH) is that it has a higher octane rating than ethanol-free gasoline available at roadside gas stations, which allows an increase of an engine's compression ratio for increased thermal efficiency. In high-altitude (thin air) locations, some states mandate a mix of gasoline and ethanol as a winter oxidizer to reduce atmospheric pollution emissions.

Ethanol is also used to fuel bioethanol fireplaces. As they do not require a chimney and are "flueless", bioethanol fires are extremely useful for newly built homes and apartments without a flue. The downsides to these fireplaces is that their heat output is slightly less than electric heat or gas fires, and precautions must be taken to avoid carbon monoxide poisoning.

Ethanol has roughly one-third lower energy content per unit of volume compared to gasoline. This is partly counteracted by the better efficiency when using ethanol (in a long-term test of more than 2.1 million km, the BEST project found FFV vehicles to be 1–26% more energy efficient than petrol cars, but the volumetric consumption increases by approximately 30%, so more fuel stops are required).

3.6 Other Bioalcohols

Methanol is currently produced from natural gas, a non-renewable fossil fuel. In the future it is hoped to be produced from biomass as biomethanol. This is technically feasible, but the production is currently being postponed for concerns that the economic viability is still pending.[40] The methanol economy is an alternative to the hydrogen economy, compared to today's hydrogen production from natural gas.

Butanol (C_4H_9OH) is formed by ABE fermentation (acetone, butanol, and ethanol) and experimental modifications of the process show potentially high net energy gains with butanol as the only liquid product. Butanol will produce more energy and allegedly can be burned "straight" in existing gasoline engines (without modification to the engine or car), and is less corrosive and less water-soluble than ethanol, and could be distributed via existing infrastructures. DuPont and BP are working together to help develop butanol. *Escherichia coli* strains have also been successfully engineered to produce butanol by modifying their amino acid metabolism· One drawback to butanol production in E. coli remains the high cost of nutrient rich media; however, recent work has demonstrated E. coli can produce butanol with minimal nutritional supplementation.

3.8 Biodiesel

Biodiesel can be used in any diesel engine when mixed with mineral diesel. It can also be used in its pure form (B100) in diesel engines, but some maintenance and performance problems may then occur during wintertime utilization, since the fuel becomes somewhat more viscous at lower temperatures, depending on the feedstock used.

The process to make biodiesel involves a chemical reaction. This means that the biodiesel industry is a chemical industry. Those involved in making biodiesel must have a good understanding of the underlying chemistry to ensure they are making quality fuel in a safe manner.

Biodiesel is an alternative fuel for diesel engines that is produced by chemically reacting a vegetable oil or animal fat with an alcohol such as methanol or ethanol. In words, the reaction is:

Oil + alcohol → biodiesel + glycerin

Bottle of biodiesel (top layer) and glycerol (bottom layer)

The chemical reaction that converts a vegetable oil or animal fat to biodiesel is called "transesterification." This is a long name for a simple process of combining a chemical compound called an "ester" and an alcohol to make another ester and another alcohol. Oils and fats are included in the ester family. When they react with methanol or ethanol, they make methyl or ethyl esters and a new alcohol called glycerol or, more commonly, glycerin.

The vegetable oils and animal fats used to make biodiesel can come from virtually any source. All of these products consist of chemicals called triglycerides, so biodiesel can be made from soybean oil, canola oil, beef tallow, and pork lard, and even from such exotic oils as walnut oil or avocado oil.

Even used cooking oil or waste oil can be used to make biodiesel. However, these oils present special challenges for biodiesel production because they contain contaminants such as water, meat scraps, and breading that must be filtered out before the oil is converted to biodiesel.

Methanol is the most common alcohol used for making biodiesel. It is sometimes called methyl alcohol or wood alcohol. It is very toxic, and swallowing as little as a spoonful can cause blindness or even death. Dangerous exposure can also occur from breathing methanol vapors or absorbing methanol through skin contact. It is the alcohol that is found in alcoholic drinks, so it is not toxic in small amounts.

The chemical reaction used to make biodiesel requires a catalyst. A catalyst is usually a chemical added to the reaction mixture to speed up the reaction. Since the catalyst is not consumed in the reaction, it will be left over at the end in some form. In biodiesel production, the actual compound that catalyzes the reaction is called methoxide. One common way to make methoxide is to dissolve sodium hydroxide or potassium hydroxide in methanol. Large producers buy a solution of sodium methoxide in methanol that is much safer to work with.

3.9 Green Diesel

Green diesel is produced through hydro cracking biological oil feedstock, such as vegetable oils and animal fats. Hydro cracking is a refinery method that uses elevated temperatures and pressure in the presence of a catalyst to break down larger molecules, such as those found in vegetable oils, into shorter hydrocarbon chains used in diesel engines. It may also be called renewable diesel, hydro treated vegetable oil (HVO fuel) or hydrogen-derived renewable diesel unlike biodiesel, green diesel has exactly the same chemical properties as petroleum-based diesel. It does not require new engines, pipelines or infrastructure to distribute and use, but has not been produced at a cost that is competitive with petroleum. Gasoline versions are also being

4. Gas Fuel: From biomass other type of fuel can be generate in form of gas. This gas fuel may be two types which is known as biogas or gobar gas (local name due to produce from cattle dungs) and other is producer gas. It is used for cooking, heating, to run engine and to generate electricity.

4.1 Biogas: Biogas is produced when bacteria digest organic matter (biomass) in the absence of oxygen. This process is called anaerobic digestion. It occurs naturally anywhere from the within the digestive system to the depth of effluent ponds and can be reproduced artificially in digesters. The ultimate aim of biogas production is to return cattle dung and agricultural residue to the soil for improving fertility and increasing crop production.

4.1.1Principle: Biochemical conversion of biomass into biogas which is a mixture of CH_4, CO_2, H_2, H_2S etc. Biogas produces when anaerobic bacteria digest organic matter in the absence of oxygen. This process occurs naturally into decomposition of solid waste into landfills where CH_4 is collected through pipelines.

All microbes involved in biogas production grow in absence of oxygen. Different group of bacteria acts upon complex organic materials in the absence of air to produce biogas, rich in methane. The process involves the combined action of four groups of bacteria, in four stages in a biogas plant.

The first stage is the degradation of high molecular weight-substances like cellulose, starch, proteins, fats etc. present in organic materials, into small molecular weight compounds like fatty acids, amino acids, carbon dioxide and hydrogen. This is brought about by a hydrolytic group of bacteria.

In the second stage the end product of the first stage converts into acetate and hydrogen by acetogens.

In the third stage to produce more acetate by hemoacetogens convert hydrogen and carbon compounds into acetate produced in the first and second stages.

In the fourth stage acetate converted into other simple compounds like carbon dioxide and hydrogen into methane. This process completed by a group of methanogenic bacteria.

4.2.2 Process of biogas production: There are some stages for production of biogas:

Cattle Dung and other organic matter

↓

Hydrolysis of complex organic compound into fatty and amino acid and CO_2
(by hydrolyzing bacteria)

↓

Production of acetates, hydrogen and simple soluble compound (by acetogen bacteria)

↓

Production of more acetate, CO2 and H2 (by hemoacetogen bacteria)

↓

Conversion of acetates and other compounds into methane (by methanogen bacteria)

↓

Collection of biogas

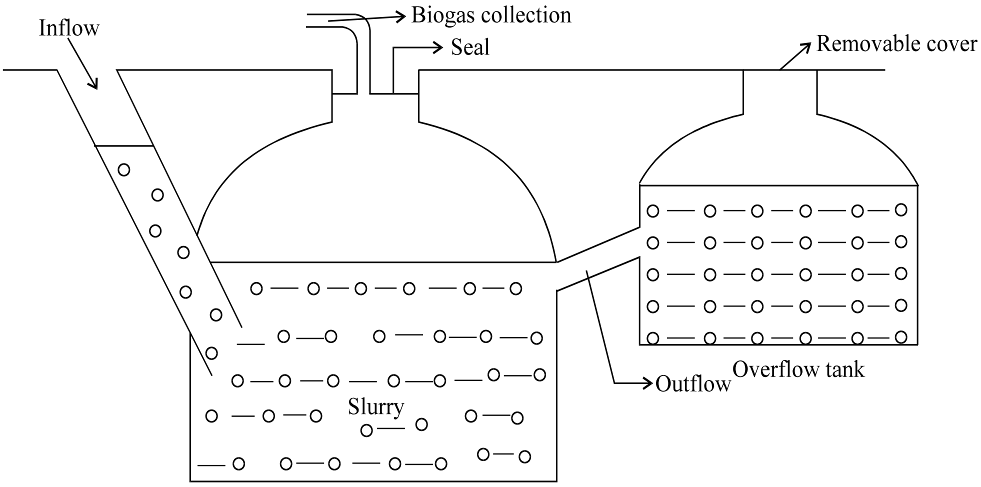

Figure 2: Biogas Plant

Various types of biogas plant are using in rural and urban sectors for the production of biogas. The biogas contains about 60% methane and 40% of other gases. The compositions of gases are following:

CH_4 68% 50 – 60% □ CH_4

CO_2 26% 30 – 40% □CO_2

H_2 1% 5 – 10% □H_2

H_2O 5% 2 – 6% □N_2

Traces of H_2S traces of H_2S

Calorific value □□5871 Kcal/m^3

Heat value of biogas can be improved up to 30% by reducing its CO_2 content

4.2 Biomass Gasification

Biomass gasification means incomplete combustion of biomass resulting in production of combustible gases like CO, H_2, and CH_4. The mixture of CO, H_2, and CH_4 is called producer gas. Producer gas can be used to run internal combustion engine as a fuel.

Producer gas also be known as generator gas or it can be known as gasification. The process of gasification at temp. of about 1000.C and the reactor in which combustion takes place is called gasifier.

The process of gasification may complete in two Steps:

1. Biomass is reduced to charcoal and
2. Charcoal at suitable temperature is converted to produce mixture of carbon monoxide (CO) and hydrogen (H_2)

The main steps involved in the gasification can be categorized as -

(1) **Upstream Processing-**Biomass reduction and drying preparation.

(2) **Gasification-**Heating and chemical reaction and reforming of syngas.

(3) **Downstream Processing**- focuses on cleaning and conditioning the hot, raw syngas.

Based on the working process four types of gasifiers used broadly in the industries.

4.3 Advantages of gasification:

- Cleaner energy production by converting diverse feedstocks (coal, biomass, waste) into valuable synthesis gas (syngas).
- Used for electricity, heat, or fuels, It offers greater energy efficiency.
- Better feedstock flexibility.
- Reduced waste volume.
- Lower carbon emissions and reducing pollutants like SO_2, NO_x.
- Using sustainable biomass, creating a more stable and versatile energy system.

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ARTIFICIAL INTELLIGENCE IN NOVEL AND MAGNETIC COSMETIC FORMULATIONS

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Abstract:

Artificial Intelligence (AI) is increasingly reshaping the cosmetic industry by enabling data-driven decision-making, personalised product development, and advanced formulation design. Unlike conventional cosmetic approaches that rely on generalised formulations, AI allows the integration of individual-specific factors such as skin condition, hair type, lifestyle, and environmental exposure to develop more targeted cosmetic solutions. Recent advancements have demonstrated the effective use of AI in skincare diagnostics, virtual makeup applications, shade matching, haircare analysis, and fragrance customisation.

Beyond consumer-facing applications, AI is gaining attention as a powerful tool in formulation science, particularly for the development of novel and magnetic cosmetic products. Magnetic cosmetics, which employ magnetically responsive particles for improved adhesion and controlled delivery, represent a promising yet underexplored area. When combined with AI-based predictive modelling, these formulations can be optimised for parameters such as particle size, stability, magnetic responsiveness, and compatibility with active ingredients. Furthermore, AI-assisted design of nanocarriers, including liposomes and magnetic nanoemulsions, offers new opportunities for precision delivery and enhanced product performance.

This review critically examines current applications of AI in the cosmetic sector, with a specific focus on personalisation, magnetic formulations, and next-generation delivery systems. It also identifies existing research gaps, including limited integration between AI and magnetic cosmetics, a lack of real-time adaptive formulations, and insufficient clinical validation. The paper highlights future directions, emphasising interdisciplinary collaboration, adaptive cosmetic systems, and clinically validated AI-driven innovations. Overall, the convergence of artificial intelligence with novel and magnetic cosmetic formulations has the potential to redefine the future of intelligent, responsive, and personalised beauty products.

Keywords: Artificial Intelligence, Magnetic Cosmetics, Personalized Formulations, Nanocarriers, Smart Cosmetics.

1. Introduction:

Artificial Intelligence (AI) has emerged as a transformative technology across multiple industries, and the cosmetics sector is no exception (Haykal *et al.,* 2024; Young *et al.,* 2020). The global beauty industry is increasingly integrating AI tools for product development, consumer personalisation, and market analysis (Grech *et al.,* 2024). Unlike conventional "one-size-fits-all" approaches, AI enables individualised solutions by analysing skin type, hair conditions, and lifestyle factors (Xin *et al.,* 2024).

Recent developments highlight applications ranging from AI-driven skincare diagnostics to virtual makeup try-ons and even personalised fragrance design (Lee *et al.,* 2024; Kalicińska *et al.,* 2023). Despite these advances, there is still a significant research gap in the use of AI for novel and magnetic cosmetic formulations, where the combination of smart delivery systems and personalisation remains underexplored (Eppler and Ma, 2025).

This paper aims to review the role of AI in cosmetic innovation, with a special focus on personalisation, magnetic formulations, and next-generation delivery systems (Thacker *et al.,* 2023).

2. Applications of AI in Cosmetics

2.1 AI in Skincare

AI-driven platforms are being widely adopted in skincare diagnostics and personalised recommendations. By employing computer vision and machine learning, these systems can identify pigmentation, acne, wrinkles, and other dermatological concerns with remarkable accuracy (Boukelkal *et al.,* 2024; Ham *et al.,* 2024). Personalised regimens are then generated, often supported by real-time data from wearable devices that track hydration or UV exposure (Hamaguchi *et al.,* 2023).

2.2 AI in Makeup and Shade Matching

AI has transformed the shopping experience in makeup through virtual try-on technologies and augmented reality (AR). These systems reduce uncertainty in purchasing by allowing users to preview products digitally (Yan and Li, 2023). Advanced algorithms also analyse undertones and environmental conditions to ensure accurate foundation and shade matching (Tran *et al.,* 2024). Additionally, AI may support the development of magnetic and adaptive formulations that enhance product personalisation (Zhang *et al.,* 2021).

2.3 AI in Haircare

AI platforms are applied in evaluating scalp health and hair conditions through imaging and diagnostic tools (Rodrigues *et al.,* 2024). Based on machine learning predictions, tailored products such as shampoos, conditioners, and repair treatments are suggested (Santana *et al.,* 2021). Some studies are exploring AI in guiding novel nanotechnology-based serums and treatments for hair restoration (Mahmoud *et al.,* 2021).

2.4 AI in Fragrance Personalisation

Fragrance design has traditionally been standardised, but AI is shifting this towards a consumer-centric approach (Borrego-Ruiz and Borrego, 2024). By analysing emotional responses, preferences, and lifestyle data, AI systems can create unique scent profiles (Habeebuddin *et al.,* 2022). Companies are increasingly offering customised perfumes based on AI recommendations, highlighting the role of technology in experience-driven beauty (Mornet *et al.,* 2004).

3. AI in Novel & Magnetic Cosmetic Formulations

The application of Artificial Intelligence (AI) in cosmetic science is extending beyond diagnostics and personalisation into the realm of novel formulations. One promising area is magnetic cosmetics, which utilise magnetically responsive particles to enable targeted delivery and enhanced adherence of products. These formulations, when combined with AI-driven personalisation, open the possibility of tailoring cosmetic effects according to individual skin conditions and consumer needs Magnetic eyeliners, mascaras, and lipsticks have already been introduced in the market; however, their development remains largely empirical. AI offers the ability to optimise formulation parameters such as particle size, magnetic responsiveness, and stability by simulating product performance before clinical testing. This not only accelerates product innovation but also minimises experimental costs (Santos *et al.,* 2019).

In addition, novel nanocarrier-based formulations, including liposomes, solid lipid nanoparticles, and magnetic nanoemulsions, can be designed using AI algorithms to predict compatibility with active ingredients and user-specific needs (Carrieri *et al.,* 2021). For instance, AI can analyse consumer skin microbiome data and recommend the most effective magnetic or adaptive formulation, thereby merging precision dermatology with cosmetics (Fytianos *et al.,* 2020).

Despite this progress, research in AI-driven magnetic cosmetics remains sparse, with most studies focusing on either AI personalisation or nanotechnology alone (Bonini *et al.,* 2013). There is a clear gap in integrated approaches, where AI not only guides formulation but also enables real-time customisation during product use (e.g., adaptive magnetic masks or smart nail polishes). Such innovations could redefine the cosmetic industry by offering products that are personalised, multifunctional, and responsive (Dhapte-Pawar *et al.,* 2020).

Several studies illustrate the growing role of AI in cosmetic personalisation and formulation optimisation, although integration with magnetic and novel cosmetics remains limited:

These examples demonstrate AI's promise in designing effective, personalised cosmetic products. However, a clear research gap exists in combining AI-driven personalisation with magnetic or adaptive formulations, which represents an important direction for future studies.

Table 1: Case studies highlighting AI applications in cosmetic personalisation and novel formulations

Study / Product	Focus	Key Finding	Reference
AI-Optimized Magnetic Eyeliner	AI algorithms + magnetic formulation	AI predicted optimal particle size and magnetic responsiveness, enhancing adherence and wear time	(Santos *et al.,* 2019)
Personalised Skincare Platform	AI-driven skin analysis	Algorithms analysed skin type, hydration, and UV exposure to recommend tailored regimens, improving user satisfaction	(Boukelkal *et al.,* 2024; Hamaguchi *et al.,* 2023)
Nanocarrier Liposome Cream	AI in formulation design	Machine learning models predicted compatibility of active ingredients and stability, enabling precision delivery to target skin concerns	(Carrieri *et al.,* 2021; Fytianos *et al.,* 2020)

4. Research Gaps and Future Directions

Although AI has shown strong potential in advancing cosmetic science, several critical gaps remain in its application to magnetic and novel formulations.

4.1 Limited Integration of AI with Magnetic Formulations

Most existing research on AI in cosmetics has focused on skincare diagnostics, shade matching, or virtual try-on technologies. Conversely, magnetic formulations (e.g., eyeliners, mascaras, lipsticks) have been studied mainly from a material science perspective without substantial integration of AI for design, optimisation, or personalisation (Colombo *et al.,* 2012).

4.2 Lack of Real-Time Personalisation Models

Current AI-based platforms provide static recommendations based on consumer data (e.g., skin tone, type, microbiome) (Flament *et al.,* 2023). However, there is limited progress toward dynamic, real-time personalisation, where AI algorithms could adjust the cosmetics' performance (e.g., strength of magnetic adherence, colour intensity, or release of actives) based on environmental conditions such as humidity or UV exposure (Jairoun *et al.,* 2023).

4.3 Scarcity of Large-Scale Clinical Validation

While AI-based simulations can accelerate formulation design, very few studies validate these outcomes through clinical or consumer-scale trials (Jairoun *et al.,* 2023). Without such validation, the acceptance of AI-driven magnetic cosmetics in the global regulatory landscape remains uncertain.

4.4 Interdisciplinary Collaboration Gap

There is minimal collaboration between cosmetic chemists, AI engineers, and dermatologists (Gordon *et al.,* 2024). This interdisciplinary gap slows the development of integrated smart formulations, which require both algorithmic precision and biomedical safety assurance.

Future Directions

To address these challenges, future studies should:

1. Develop hybrid AI models that integrate user data with formulation parameters (e.g., magnetic strength, nanocarrier stability).
2. Explore adaptive magnetic cosmetics, capable of changing properties in real time based on AI feedback loops.
3. Establish standardised datasets for training AI models specifically in cosmetic formulation science.
4. Conduct multi-centre clinical validations to ensure product safety, efficacy, and regulatory compliance.
5. Promote interdisciplinary collaborations to accelerate translation of AI-based innovations from lab to market.

Conclusion:

Artificial Intelligence is transforming the cosmetic industry by enabling personalisation, predictive formulation design, and consumer-centric innovations. While significant progress has been achieved in AI-powered diagnostics, shade matching, and digital try-on tools, its integration with novel and magnetic formulations remains in an early stage. Current research has largely focused on either AI-based personalisation or material science approaches to magnetic cosmetics, with limited attempts to combine both.

By identifying these gaps, it becomes evident that the next frontier in cosmetic science lies in the fusion of AI algorithms with advanced formulation strategies such as magnetic nanoparticles, nanocarriers, and adaptive delivery systems. Such integration could allow real-time customisation of product performance, improve stability and efficacy, and offer consumers highly innovative solutions that go beyond conventional cosmetics.

Looking forward, the cosmetic industry will benefit from stronger interdisciplinary collaboration, large-scale clinical validations, and regulatory frameworks that support AI-driven innovations. The convergence of AI and magnetic/novel formulations holds the potential to redefine beauty technology by making cosmetics more intelligent, multifunctional, and personalised than ever before.

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DIGITAL CHARACTER RECOGNITION BY USING DEEP LEARNING MODEL (YOLO V11) FROM 16X2 LCD DISPLAY

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Abstract:

This project presents an innovative approach to digital character recognition using YOLO v11 for extracting and interpreting characters displayed on a 16x2 LCD .The proposed system leverages advanced object detection capabilities of YOLO v11 to precisely detect and recognize characters in real-time from low-resolution digital displays,ensuring high accuracy and efficiency.The integration of the system can significantly enhance automation in various applications such as embedded system monitoring,device diagnostics and industrial automation.The methodology includes pre-processing techniques to handle display noise,optimized training for character sets and deployment on resource-constrained devices.

Keywords: Digital Character Recognition, YOLO v11,16x2 LCD, Object Detection.

Introduction:

Digital Character recognition is a cornerstone technology in the domain of automated systems, enabling the extraction and implementation of textual data from various sources. The advent of deep learning models has significantly enhanced its efficiency and accuracy of character recognition systems, expanding their applicability to various fields. This project focuses on implementing a robust digital character recognition system using YOLO v11, specially tailored to recognize and interpret characters from 16x2 LCD Displays. The 16x2 LCD Displays are widely utilized in embedding systems and industrial devices for presenting alphanumeric information. However, extracting this information programmatically has posed challenges due to the display's limited resolution and potential noise interference. YOLO (You Only Look Once), renowned for its real-time object detection capabilities, offers a promising approach for digital character recognition. YOLO v11 has latest iteration, introduces enhanced accuracy, reduce computational overhead and improved handling of smaller objects, making it as an ideal choice for recognizing characters on low resolution displays. This research contributes to the growing field of automation data extraction, paving the way for its application in embedded systems, industrial automation, and device diagnostics. The following sections provide an in-depth exploration of the methodology, experimental setup, results and potential future enhancements of this project.

Literarture Survey

In recent years several studies have contributed to the advancement of the digital character recognition systems, particularly in environments constrained resources such as low-resolution displays. These studies explore various approaches such as machine learning, deep learning, and hybrid models to improve recognition accuracy and handle challenges such as noise, distortion and various factors. This survey presents a summary of key papers that were influenced recognition systems for digital displays, particularly using YOLO v11 for recognizing characters. in [1], Memorated *et al.* examine a conventional parking system that integrates digital image processing to recognize number plates for parking and billing systems. The author highlights the importance of minimizing human interaction in such systems and the role of character recognition in streaming parking management. The authors propose integrating geodesic paths and non-parametric methods to enhance the accuracy of Chinese character recognition, achieving a 1.5% improvement over traditional methods like ISOMAP and LDA. The study emphasizes the importance of simplifying complex high-dimensional data and maintaining classification precision, which is highly applicable in digital character recognition systems such as YOLO v11 for efficient character segmentation and recognition from low-resolution displays like the 16x2 LCD. In [2], C. Patel *et al.* review various OCR-based vehicular applications, including number plate recognition systems. The paper discusses the challenges posed by lighting conditions and low-quality images, emphasizing the need for enhanced OCR techniques to improve performance in real-world settings, which can be applied to systems with limited image quality, such as the 16x2 LCD. The authors discuss challenges like varying plate designs, poor lighting conditions, and image quality issues, which also impact character recognition from constrained devices. The study reviews various techniques, such as template matching and neural networks, and highlights the necessity of further improvements in OCR systems for real-time applications. These concepts are relevant to developing YOLO v11-based character recognition systems for efficiently processing digital text from constrained environments such as LCD displays. In [3], A. Kumar and S. Godara introduce a Myanmar Optical Character Recognition (MOCR) system that utilizes K-means clustering and Convolutional Neural Networks (CNNs) for character classification. The system's performance is optimized by reducing dimensionality with tensor-based subspace learning. The use of CNNs in the recognition process allows for precise character identification even with high noise levels. This two-stage approach is highly applicable for recognizing digital characters from an LCD screen, where clarity and precision in character recognition are critical. In [4], S. H. Bailmare *et al.* present a vehicle number plate recognition system that uses edge detection and morphological techniques to improve character segmentation. The Sobel operator is employed to detect edges, while morphological operations help fill gaps in the segmented characters. This method provides a robust solution to image segmentation in environments with varied illumination. This approach can be adopted in YOLO v11 systems for detecting and segmenting digital characters from small, low-resolution images such as those displayed on a 16x2 LCD screen. In [5], the authors investigate Urdu character recognition in natural scene images using Convolutional Neural Networks (CNNs). The study highlights challenges in recognizing cursive text, especially for languages like Urdu and Arabic, in complex backgrounds. The authors use data augmentation techniques to improve recognition accuracy and handle variations in font and orientation. This research is valuable for applying YOLO v11 in recognizing characters from an LCD display, as it addresses challenges such as varying text styles and noisy backgrounds in character recognition tasks. In [6], K. R. A. Narayan and A. S. S. S. Reddy focus on handwritten character recognition in resource-constrained devices by proposing a system based on hybrid feature extraction. The authors combine geometric, texture-based, and statistical features to improve the accuracy of recognition systems, particularly in low-resolution environments. Their study suggests that deep learning methods, especially Convolutional Neural Networks (CNNs), work well in improving recognition accuracy for different types of handwritten characters. However, they point out that in devices with limited resources, such as a 16x2 LCD, the need for efficient feature extraction and fast recognition becomes crucial. This work underscores the importance of integrating feature-level fusion into the recognition process, which can significantly enhance the performance of YOLO v11 in the context of constrained systems with minimal resources. The study by S. Y. Lee *et al.* in [7] presents a method for digit recognition on small screens, focusing on the use of hybrid machine learning models that combine Support Vector Machines (SVMs) with CNNs. This method helps improve the generalization of the recognition system, particularly for displays with low pixel density. Lee *et al.* describe how the approach works effectively on devices with limited resolution, providing high accuracy in recognizing digits under varied lighting conditions and noisy backgrounds. Their work is valuable for enhancing the YOLO v11 model's performance in real-time character recognition on 16x2 LCD screens, where clarity and precision in recognition are often impacted by the display's limited resolution.

In [8], M. G. Santhosh and R. B. Kadiyala examine the challenges of recognizing alphanumeric characters from images captured in real-world environments with various lighting, distortion, and font issues. Their paper introduces a multi-step process for character recognition that combines traditional image processing techniques with modern machine learning methods. This hybrid approach includes preprocessing steps such as noise reduction, contrast enhancement, and adaptive thresholding, followed by classification using machine learning models. The paper highlights how integrating preprocessing with learning models can significantly enhance recognition accuracy for small, noisy images, making it applicable to the 16x2 LCD-based character recognition system. It informs the development of YOLO v11 by suggesting enhancements to preprocessing steps that improve image quality before recognition. S. Singh *et al.* in [9] focus on the optimization of character recognition systems for embedded devices with limited processing power. The authors propose a method using a modified Convolutional Neural Network (CNN) to perform efficient feature extraction, followed by the use of lightweight classifiers for character recognition. Their approach is designed for real-time processing, addressing the challenges posed by devices with limited computing power and screen resolution. This work is directly relevant to the development of YOLO v11 for character recognition on a 16x2 LCD, where the system must balance speed and accuracy while operating in a resource-constrained environment. The study's contributions provide insights into optimizing deep learning models for embedded applications with low resource availability. In [10], R. K. Jain and S. Tiwari explore the integration of sliding window techniques with deep learning models for character recognition in digital signage applications. Their work discusses how sliding windows can be used to segment text and extract relevant features for classification, especially in situations where the text is located in different parts of the image. This technique is crucial for devices like 16x2 LCD screens, where text or characters may not be perfectly aligned within the display and may need segmentation before recognition. The paper also highlights how deep learning methods, such as YOLO v11, can be enhanced by incorporating sliding window approaches for improved localization and detection of characters. The study offers practical techniques that can improve YOLO v11's ability to recognize text accurately in dynamic environments, contributing to the overall performance on small displays.

Dataset

In this work, our focus is to recognize the characters of English text the dataset consists of 60 LCD displays, meticulously designed to include a comprehensive collection of characters, operators, and special symbols. These LCD displays, widely utilized in embedded systems and electronic devices, present unique challenges for character recognition due to their constrained resolution and inherent display limitations. Each display operates with a standard configuration, typically a 16x2 layout, capable of rendering 16 characters per line across two lines. The dataset encapsulates a diverse range of content, including uppercase and lowercase letters (A-Z, a-z), numerical digits (0-9), and special characters like **@, #, $,** and **%.** It also incorporates mathematical operators, such as +, -, *, and /, providing a realistic mix of symbols encountered in real-world applications. Each of the 60 display samples contains unique combinations of up to 32 characters, simulating the dynamic nature of LCD-based systems.

In addition to the textual diversity, the dataset accounts for real-world variations, including font thickness, uneven spacing, and common artifacts such as missing pixels, brightness inconsistencies, and partially rendered characters. Images were captured under varying lighting conditions—ranging from bright ambient light to dim environments—to ensure the dataset's robustness for practical applications. The dataset includes ground truth labels, specifying the identity and positional metadata for every character, enabling precise training and evaluation of recognition models.

This dataset poses significant challenges, such as low resolution, display noise, and closely packed characters, making it a valuable benchmark for testing advanced recognition systems. By incorporating real-world scenarios, it mimics the operational conditions of embedded systems like calculators, industrial controllers, and digital signage. The use of this dataset in the proposed model, such as YOLO v11, ensures a comprehensive evaluation and highlights the model's capacity to handle complex character recognition for tasks in the form of resource-constrained environments. Figure 1 shows the sample datasets for the digital character recognition.

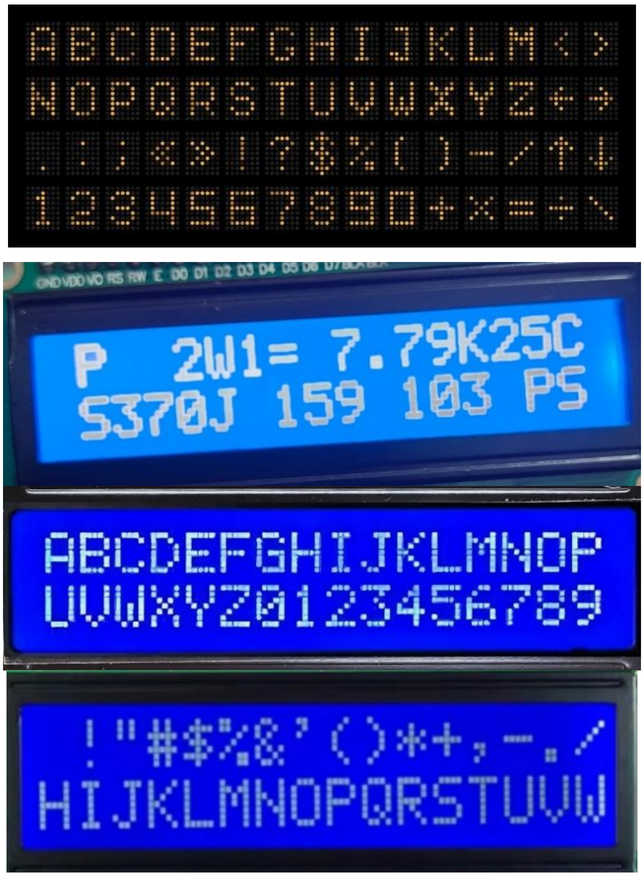

Figure 1: Sample Datasets

Analysis

In the context of digital character recognition using YOLO v1 (You Only Look Once), the objective is to accurately detect and classify characters, operators, and special symbols on LCD displays. YOLO v1 operates on a grid-based detection system and incorporates specific formulas to compute object detection accuracy and loss during training and evaluation. Below is the detailed description of the key formulas:

Object Detection Loss Formula

The total loss in YOLO v11 is calculated as:

$$L_{Total} = L_{coord} + L_{obj} + L_{No\text{-}obj} + L_{class} \quad (1)$$

Where,

L_{coord} - Localization Loss, which Measures the accuracy of the predicted bounding box coordinates relative to the ground truth.

L_{obj} - Confidence loss for object presence.

$L_{No\text{-}obj}$ - Confidence loss for background regions(no object)

L_{class} - Classifications loss.

Labeling Characters

In the dataset comprises alphanumeric characters (A-Z, a-z, 0-9), mathematical and logical operators (+, -, *, /, =, <, >, %), and special characters such as @, #, $ and &. These elements are manually annotated using tools like Labeling or Roboflow, which generate bounding boxes around each character or symbol present in the images. Each label is assigned a unique class ID, and the corresponding annotations are saved in YOLO format. The labeling process must address challenges such as varying resolutions of the LCD displays, overlapping characters that require precise bounding boxes, and diverse font styles like 7-segment and dot-matrix displays, which must be uniformly classified. Additionally, efforts are made to balance the dataset across all classes to prevent bias during training. This comprehensive labeling strategy ensures that the YOLO v11 model can accurately detect and classify characters, operators, and symbols in diverse scenarios, paving the way for robust digital character recognition.

Figure 2: Comprehensive Labeling

Figure 3: Detailed Labeling

Figure 4: Encrypted Labeling

Proposed Work

The proposed project focuses on creating a robust digital character recognition system using the advanced YOLO v11 model. This system is designed to detect and classify characters, operators, and special symbols displayed on digital interfaces such as LCD panels, 7-segment displays, and dot-matrix screens. A key aspect of this project is the meticulous labeling of the dataset, achieved through Label Studio, a powerful annotation tool. Each character, operator, and symbol in the dataset has been individually labeled, with color-coded annotations to enhance clarity and consistency during the training process. The color-coding scheme in Label Studio assigns unique colors to different classes of characters and symbols, such as blue for digits (0-9), green for uppercase alphabets (A-Z), yellow for lowercase alphabets (a-z), and red for operators and special symbols (+, -, *, /, @, #, etc.). This visual distinction not only facilitates easy verification of the labels but also ensures precise and consistent annotations across the dataset. Each annotation is stored in YOLO-compatible format, containing the class ID and normalized bounding box coordinates, which are critical for training the YOLO v11 model. The proposed system aims to achieve high accuracy and efficiency in recognizing characters under varying conditions, including different display resolutions, orientations, and lighting conditions. By leveraging the meticulously labeled and color-coded dataset, the project ensures that the YOLO v11 model can effectively generalize across diverse scenarios, making it a highly reliable solution for digital character recognition tasks in real-world applications.

Architecture

The system begins with an Input Layer, where an LCD display acts as the primary source of text or characters for recognition. The captured images are processed in the Data Acquisition and Preprocessing stage, which includes an Image Acquisition Module for capturing images, a Noise Reduction Module for filtering out artifacts, and a Preprocessing Module for preparing the image (e.g., resizing or normalization) for the YOLO v11 model. The workflow integrates a Dataset Preparation step, which utilizes tools like the Label Studio Annotation Tool for annotating data and a Custom Dataset Module to structure the dataset for training purposes. The core of the system lies in the Character Detection and Recognition phase, where the YOLO v11 model detects and recognizes characters in real time, supported by an Inference Engine to execute these tasks efficiently on the Raspberry Pi. Following detection, the Postprocessing and Analysis stage involves a Text Extraction Module to convert recognized characters into text, alongside a Performance Monitoring Module to evaluate metrics such as accuracy and latency.

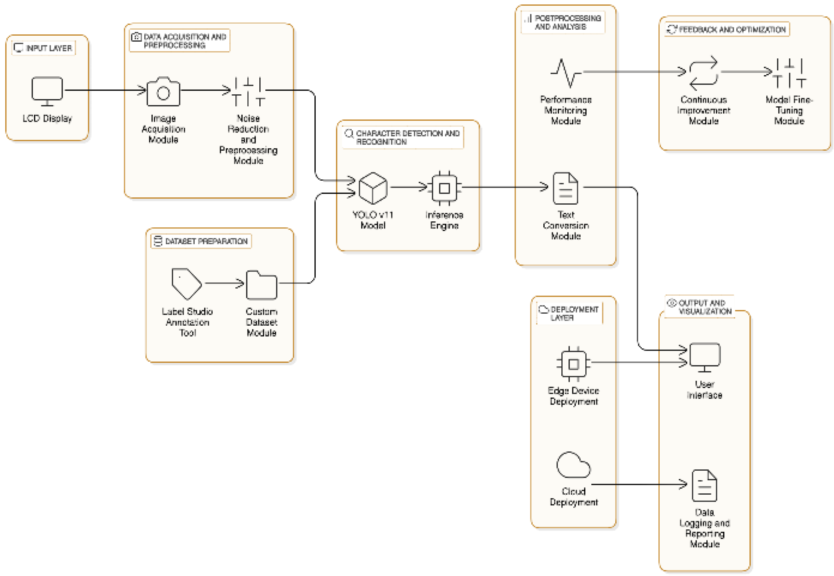

Figure 5: Architecture of Proposed System

The system incorporates a Feedback and Optimization phase, where a Model Fine-Tuning Module refines the YOLO v11 model based on real-world feedback and monitored performance. Deployment is achieved through the Deployment Layer, with Edge Device Deployment for localized processing on the Raspberry Pi and an optional Cloud Deployment for remote data processing or storage. Finally, the results are presented in the Output and Visualization stage, featuring a User Interface for interaction and a Data Logging and Reporting Module for tracking system performance and recognized text. This comprehensive pipeline ensures robust and efficient character recognition, with adaptability for continuous improvement and real-time operation on resource-constrained devices.

Results and Discussion:

The proposed project focuses on object detection, specifically identifying and classifying LCD displays from images. A custom dataset comprising 60 labeled samples of LCD displays was meticulously created for this purpose. The labeling process was performed using Label Studio, ensuring high-quality annotations critical for model training and evaluation. The methodology involved training a robust object detection model to accurately detect and classify the presence of LCD displays in diverse scenarios. The evaluation results highlight the effectiveness of the proposed approach, as evidenced by the comprehensive analysis of the performance metrics. The F1-confidence curve demonstrates a peak F1 score of 0.98 at a confidence threshold of 0.680, signifying the model's exceptional balance between precision and recall. This indicates the ability to correctly identify true positives while minimizing false positives and false negatives, thereby ensuring high overall detection accuracy. The precision-confidence curve further reveals a perfect precision score of 1.00 achieved at a confidence threshold of 0.956. This result underscores the model's capability to make highly confident predictions with no false positives at this threshold, making it particularly suited for application requiring precise detections. The confusion matrix provides additional insights into the classification performance, showing an excellent distribution of true positives and true negatives, with minimal false positives and false negatives. This highlights the model's reliability in detecting LCD displays with high accuracy under various conditions.

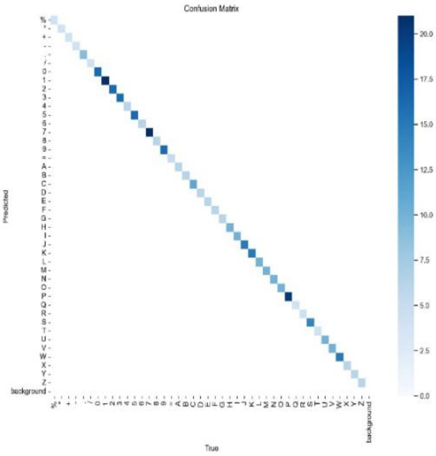

Figure 6: Performance Analysis of Comprehensive Approach

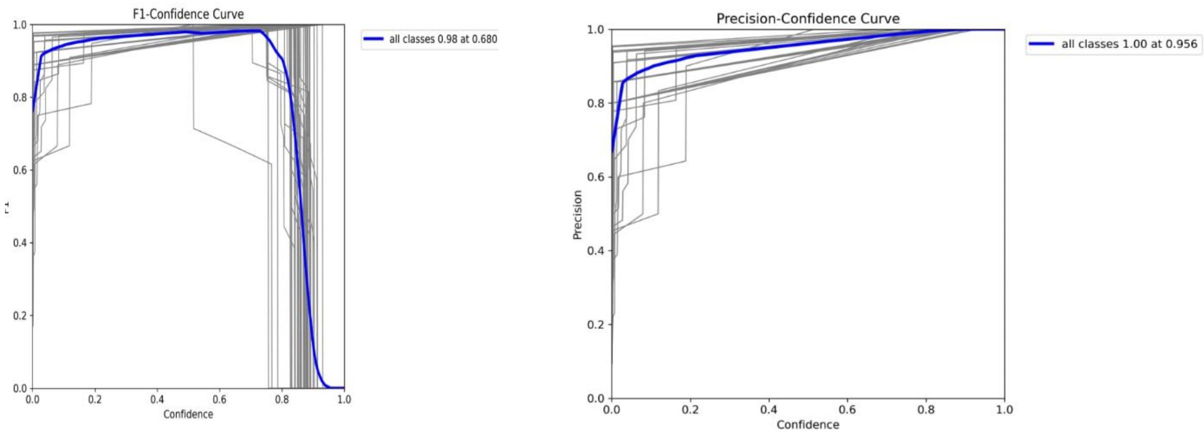

Figure 7: Models Reliability Anlaysis

The graphical representation of these results further solidifies the findings. The F1-confidence curve demonstrates a steep rise to the maximum F1 score, emphasizing the consistency of the model's performance across varying confidence thresholds. The precision-confidence curve shows a gradual increase, culminating in a perfect precision score, reflecting the model's adaptability and reliability. Together, these graphs provide a clear visualization of the trade-off between confidence levels and detection accuracy, offering actionable insights into optimizing the model for different application requirements. Overall, the results validate the effectiveness of the proposed object detection approach. The high F1 score, perfect precision at specific thresholds, and the detailed graphical analysis affirm the model's robustness and suitability for accurately detecting LCD displays. These findings establish a strong foundation for further scaling and real-world deployment of the system, making it a valuable contribution to the field of object detection.

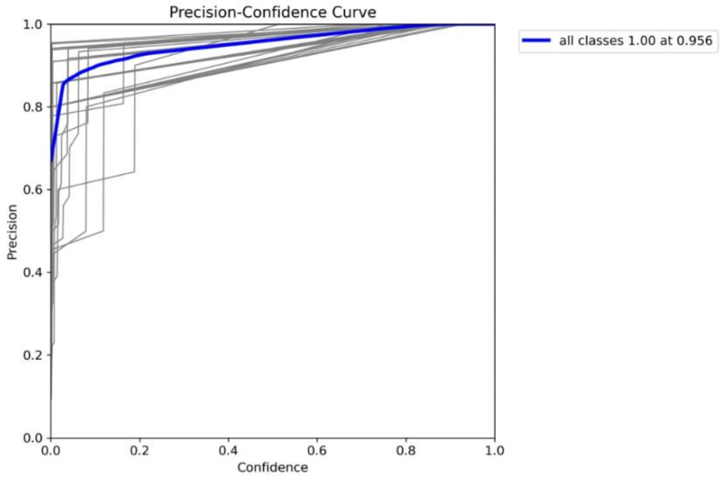

Figure 8: Overall analysis

Table 1: Accuracy Details based on years

Ref Year	Accuracy
2010	85%
2020	91%
2020	94%
2019	94.5%
2018	93.9%
2018	92.3%
2019	95.2%
2011	89.8%
2019	94.2%
2020	91.6%

Conclusion:

In this study, an efficient object detection framework was developed and evaluated for identifying LCD displays in images. The custom dataset, consisting of 60 labeled samples, was created and annotated using Label Studio, ensuring accurate and high-quality data for training the model. The proposed approach demonstrated exceptional performance in detecting LCD displays, with detailed analysis of the results showcasing the robustness and reliability of the model. The evaluation metrics, including F1-confidence and precision-confidence curves, highlighted the model's strong detection capabilities. A peak F1 score of 0.98 was achieved at a confidence threshold of 0.680, indicating an optimal balance between precision and recall. Additionally, the precision-confidence curve revealed a perfect precision score of 1.00 at a confidence threshold of 0.956, reflecting the model's ability to make highly confident and accurate predictions without generating false positives. The confusion matrix further reinforced the reliability of the system, demonstrating a high level of true positive and true negative classifications with minimal misclassifications. The graphical analysis provided valuable insights into the trade-offs between confidence thresholds and model performance, enabling fine-tuning for various application requirements. These findings validate the effectiveness of the proposed object detection approach in achieving high accuracy and precision for LCD display detection. The results demonstrate that the model is well-suited for practical applications where precision and reliability are critical. This work lays the groundwork for scaling the system to larger datasets and more complex real-world scenarios. Future research could focus on expanding the dataset, incorporating more diverse samples, and exploring advanced architectures to further enhance the model's generalizability and efficiency. Overall, the proposed framework represents a significant contribution to the field of object detection, providing a reliable and high-performing solution for detecting LCD displays.

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DESIGN AND DEVELOPMENT OF BIOWASTE MATERIAL BRICK FOR CONSTRUCTION PURPOSES

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Abstract:
This book chapter utilizes biowaste in the construction of bricks, which is often considered waste in our society. For this purpose, a certain percentage of the biowaste is used in the cement and sand to prepare the slurry, which serves as a raw material for brick production. The percentage variation of the biowaste is (5-45%) on which optimization has been performed to calculate the optimum size of the bricks. The output parameters are optimized to be compressive strength, water retention capacity, and thermal conductivity. Finally, it is concluded that the biowaste of 35% concentration sample brick has been selected as per the mechanical testing. it has a 1165 kg/m^3 density, 18 MPa compressive strength, water absorption capacity of 18 %, and thermal conductivity of brick (k_{bric}) 0.44 W/m-K.

Keywords: Biowaste, Bricks, Optimization, Construction.

Introduction:
The construction industry is the 2nd largest industry in India, next only to agriculture. Fast urbanization and exponential population growth in India have created a massive demand for housing and related auxiliary infrastructure, resulting in a scarcity of traditional building-materials. The production of these bricks and construction materials is highly energy-intensive and leads to substantial water pollution, air pollution, and soil pollution. Consequently, to address the continuously growing market demand for construction, the development and adoption of sustainable building materials are imperative [1]. At the same time, the generation of

agricultural solid-waste has emerged as a growing concern, becoming a major source of air-pollution not only in India but also across many developing nations [2]. The main objective of this research-based project is to develop an effective approach for converting agricultural solid-waste into sustainable building materials, thereby simultaneously considering both challenges [3]. The present project investigates the promising use of agricultural waste, such as hay or straw stubble and leftover wood as raw materials ingredients for developing substitute sustainable construction-materials (CM) in the form of bricks [4]. Depending on the availability of agricultural waste-materials, the developed bio-bricks can be adapted to meet the local construction-related market requirements and construction practices. The use of agricultural waste in building materials can significantly reduce the consumption of natural resources utilization and total energy demand [5]. At the same time, it can supplement farmers' income by enabling them to sell leftover stubble instead of burning it, thereby helping to reduce air pollution [6]. To achieve this objective, the process of upcycling, where waste materials are transformed into newly designed products with enhanced environmental importance compared to their original use and can be employed to convert agricultural-waste into usable bio-bricks by blending it with water, stone dust, and lime [7]. This project details the bio-brick manufacturing process, its advantages, potential applications in the construction industry, and its direct environmental benefits [8]. The construction industry in India, along with China, represents one of the rapidly expanding sectors globally, attracting substantial investment. In 2015 alone, India's construction industry recorded a growth of approximately 20 to 30%. The "Smart-City" dream project initiative taken by Government of India is expected to attract a huge amount investment of more than 2-trillion rupees [9]. There are some other Government initiatives like "Housing for All by 2022" which will be a further boost to the construction industries in India [10]. As part of these initiatives, by 2018, the rapid growth in the construction industry is expected to be twice as related to the year 2015. Looking ahead, the industry is projected to attract huge amount investments of nearly USD 650-billion over the next 20 years [11]. Such rapid expansion of the construction sector will require enormous quantities of raw materials for new buildings, thereby intensifying existing challenges related to demand of material and environmental pollution [12]. The consumption of conventional construction materials such as sand, clay bricks, cement, and steel is increasing at an unprecedented rate, making these resources both costly and scarce [13]. Consequently, illegal mining activities have risen, causing significant and uncontrolled degradation of the natural environment. These trends clearly underscore the urgent need to develop sustainable and environmentally friendly alternatives [14]. By the year "2030", nearly 590 million people in India are expected to reside in urban areas, necessitating substantial investments in housing and urban infrastructure [15]. Consequently, demand for raw materials in India is expected to reach approximately 15-billion tonnes by

“2030” and rise further to about 25-billion tonnes by “2050” [15]. A significant share of these resources is located in biodiversity-rich regions, such as river basins including the river Palar and its tributaries, where extraction activities pose serious environmental risks [16].. River-sand, widely favoured in the construction sector due to its high silica content and associated inertness, hardness, and durability, has witnessed excessive extraction. This uncontroled mining has led to severe degradation of riverine ecosystems [17]. The activity is often carried out by unorganized groups, making regulation challenging and allowing the industry to expand rapidly due to low investment requirements and high economic returns. Reports suggest that illegal sand mining in India generated revenues of approximately INR 10 billion (USD 150 million) in 2011. Furthermore, India records the highest extraction intensity globally, at about 1,579 tonnes per square kilometre, compared to a global average of 454 tonnes per square kilometre [18]. As material costs constitute a major portion of total building expenditure, the prevailing scenario underscorse the urgent need for efficient material utilization and the adoption of alternative building solutions [19]. According to the Central Pollution Control Board (CPCB), India operates nearly 140,000 brick kilns, collectively emitting around 66 million tonnes of CO_2 annually [20]. In addition to carbon dioxide (CO_2), these kilns release significant quantities of pollutants such as carbon monoxide (CO), sulphur dioxide (SO_2), nitrogen oxides (NO_x), and particulate matter. The percentage (%) of released pollutions by these construction industries contributing nearly 9% of India’s total greenhouse gas emissions [21]. Brick production also consumes approximately 350 million tonnes of topsoil and clay each year, accelerating soil erosion and increasing the risk of large-scale environmental degradation [22]. Intensified mining activities have further exacerbated ecological damage and social conflicts in resource-rich regions. Continued large-scale extraction is likely to increase carbon emissions further, posing a serious challenge to India’s ability to meet its international climate change commitments [23]. Table 1 represents the comparative analysis of the various research published on the biowaste for replacing sand in bricks.

Table 1: Findings and methodology of previous research on the biowaste

S. No.	Authors Description	Methodology	Findings
1	Sakhare *et al.* (2016)[1]	Biowaste used between the percentage of (5-55%) which replace the sand at constant amount of cement.	Optimum percentage of the biowaste, sand and cement are 35%, 55% and 10%.

2	Barbieri *et al.* (2013)[2]	Sawdust, grapes and cherry seeds have been used as biowaste for production of bricks.	The results showed that 5 % grapes and cherry seeds dust maintain the bricks properties upto 950°C with rupture coefficient 21-23 MPa. Moreover, reduction of the weight noted to be 3-10% by use of the cherry dust.
3	Ramgopal *et al.* (2024)[1], [4]	Biomedical waste has been in different percentages with cement. Then determine the optimum percentage based on mechanical properties.	The variation of biowaste from 15-25% enhanced the mechanical properties greatly but further enhancement reduced the compressive strength.
4	Ajit *et al.* (2025) [5]	Composite plastic and waste rice powder has been used to develop the raw material for bricks and tested for different type of loading.	The analysis indicated that at 150°C heat treatment, the compressive strength of the bricks has been noted to be 140 Kgf/cm^2.
5	Biswas *et al.* (2024) [10]	Used the waste coffee husk in the development of the alkaline bricks. The coffee waste replaced the sand in bricks in the ratio of 0-30% by volume.	At 30% concentration of the waste coffee represents the highest strength and weight loss at the temperature of 575°C.

2. Methodology Adopted

The bricks of varying concentrations have been prepared as per the flow chart shown below:

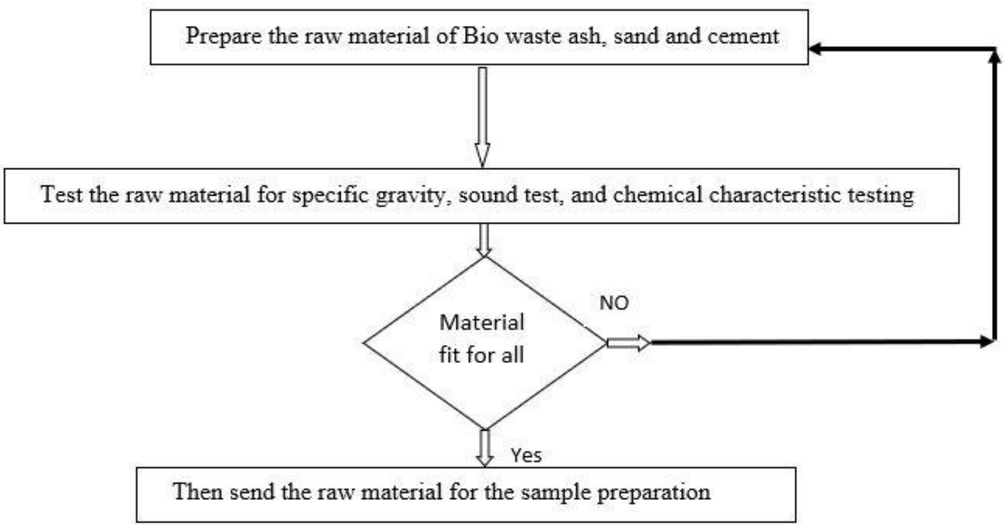

Figure 1: Flow chart for preparation of raw material

The 1st step is to prepare the raw material for producing the samples of the bricks. The biowaste ash content, sand, and cement are three types of raw material required for making the samples of bricks. But the raw materials must pass through all tests so that our material is perfect for sample preparation. The following are the tests performed on the raw material for making them for effective for the construction purposes [24].

a. **Specific Gravity Test (SGT): "**Weigh a clean, dry Le Chatelier flask or specific gravity bottle along with its stopper and record the mass as W_1. Introduce the biowaste, sand, and cement samples individually into the flask up to approximately half its volume (about 50 g), and weigh again with the stopper to obtain W_2. Then add kerosene (a non-polar liquid) to the cement in the flask until it is about half full, and mix thoroughly using a glass rod to eliminate any entrapped air".

b. **Soundness Test: "**The autoclave expansion test (ASTM C 151) was conducted to provide an index of potential delayed expansion caused by the hydration of calcium oxide (CaO) and magnesium oxide (MgO) in hydraulic cements, biowaste and sand". Researchers' questions have arisen over the years regarding the effect of excess crystalline free MgO (periclase) on cement soundness and concrete durability under actual service conditions [25]. It has been suggested that the auto-clave expansion test is overly severe and will exclude cements that perform well in concrete under field service conditions without any reduction in prolonged operational life or long-term durability. Over the years, several additional experimental protocols and soundness tests have been developed and examined, including updated versions of the Le Chatelier soundness test and various modifications involving testing temperatures and durations. Studies have also identified the influence of chemical composition on periclase formation and on the resistance of cement and concrete to expansion. The objective of this literature review is to update and complement earlier reviews on this subject.

c. **Chemical Properties Test:** The X-Ray Fluorescence test spectrometer is used for checking the chemical properties of the raw material so that we check whether our selected raw material is fit for making the brick sample test or not.

If the raw material passes all the tests as explained above, then it is sent to the sample preparation of the bricks in varying concentrations of the raw material. If the raw material did not pass all the tests, then again prepare the raw material and repeat the steps.

3. Preparation of the samples of the Bricks

The 230 x 100 x 80 mm^3 bricks sample has been prepared by varying the biowaste concentration as shown in Table 2.

The biowaste raw material concentration vary from (5 to 55%), the sand concentration varies from (35 to 85%) and the cement concentration in each sample remain constant 10%.

Table 2: Raw material concentration in (%)

Sample No.	Biowaste (%)	Sand (%)	Cement (%)
1	5	85	10
2	15	75	10
3	25	65	10
4	35	55	10
5	45	45	10
6	55	35	10

The following are the steps for preparing the samples. The first step to mixes the raw materials of the ingredient required homogeneously. Now, it is being converted in the form of a slurry by mixing 20% water. Furthermore, this slurry is put in the mould and applied a pressure of 14 MPa then wait for the drying the bricks and removed from the mould.

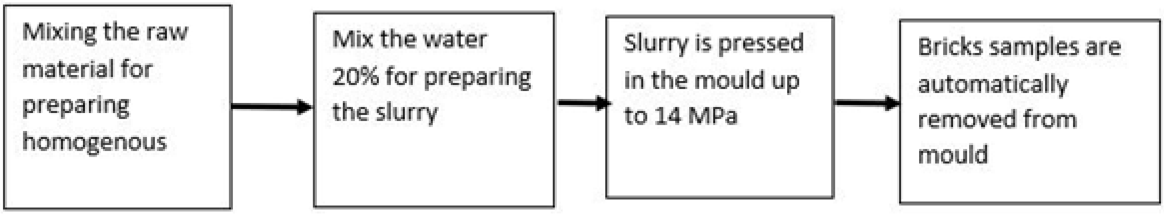

Figure 2: Flow chart of raw material preparation

4. Testing of brick samples and optimizing responses

Figure 3 shows the procedure of the brick sample testing and the optimization procedure of selecting the optimum size of sample. So initially, the brick sample test for the density, compressive strength, water absorption capacity, and thermal conductivity(k_{bric}). In the section below, the explanation is given about the various tests performed to select the bricks of maximum strength.

a. **Density Testing:** The density of the 6-brick samples has been determined by the simple formula.

$$\rho = \frac{m}{V}\ (\frac{Kg}{m3})$$

The mass of each sample of the brick is calculated and divided by the known volume of the brick**.** This is the simplest method for testing the bricks against the density. it is well known that the volume of the brick is fixed, so a higher mass brick has a higher density.

b. Compressive strength Test (CST): The compressive strength (CST) of the brick is determined for its compressive load-bearing capacity. For doing that the brick sample has been tested on the brick compressive testing machine.

In this method, the brick is placed over the flat surface of the machine, and compressive load is applied and measured up to the first failure of the brick. This point is known as the failure load of the brick.

c. **Water absorption Test (WAT):** The water absorption test is conducted to find out the brick's water absorption capacity. For that, all samples of the bricks are fully submerged in the water for 30 minutes, 60 minutes, and 2 hr. The bricks' weight was measured after submerging in water and after submerging in water. Now determine the difference of bricks before dipping in water and after dipping in the water. The difference in the weight of bricks represents the water absorption capacity. This water absorption capacity should not be an optimum level; otherwise, brick sample is rejected.

d. **Lee Disc Apparatus Test:** The Lee disc apparatus test is performed for determining the thermal conductivity of the brick sample(k_{bric}). The results shows that the if the biowaste concentration increases, then the thermal conductivity of the brick sample (k_{bric}) is reduced. The bricks that have lower thermal conductivity will be preferred for the construction but it should be optimum level since trapped heat inside the room must be removed, otherwise the room will always be heated in summer.

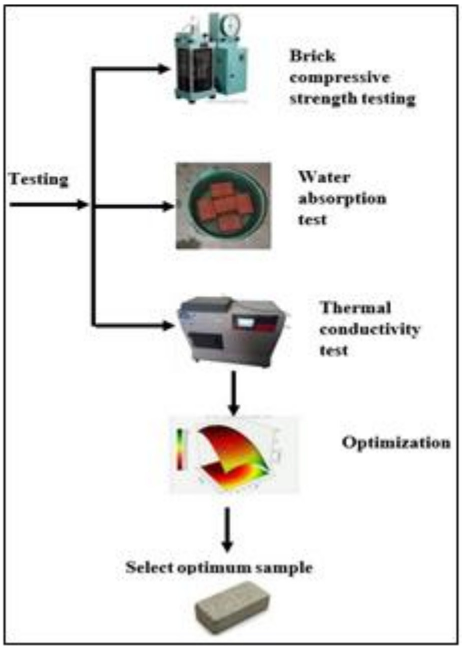

Figure 2: Schematic representation of sample testing and optimization

5. Optimization Method

For optimizing the experimental data Response Surface Methodology (RSM.) is used. The experimental data were optimized using 'MINITAB-17' software through the Design of Experiments (DoE.) approach. In the Design of Experiments framework, the used input variables and response variables were defined using the Response Surface Methodology (RSM.) tool. RSM is a mathematical tool or technique employed to perform regression analysis on the experimental data, as well as to design and optimize the data obtained from experimental setup. The sequence and number of designed experimental runs depend on the number of input variables specified in the RSM. Based on this approach, RSM identifies the optimal combination of input parameters that maximizes or minimizes one or more response variables. The number of experiments conducted on the test rig is therefore governed by the selected input parameters, leading to a significant reduction in experimental time. Overall, this optimization method provides an optimal solution or optimum result with high accuracy.

6. Results and Discussion:

Figure 4 shows that if the biowaste (%) is increasing, then the density of the bricks is reduced. The lower density reduced the weight of the bricks, making it easier to handle. But for maintaining the strength in the bricks, the density must be within a desirable limit. Otherwise, increasing the biowaste material limit can collapse the bricks under loading.

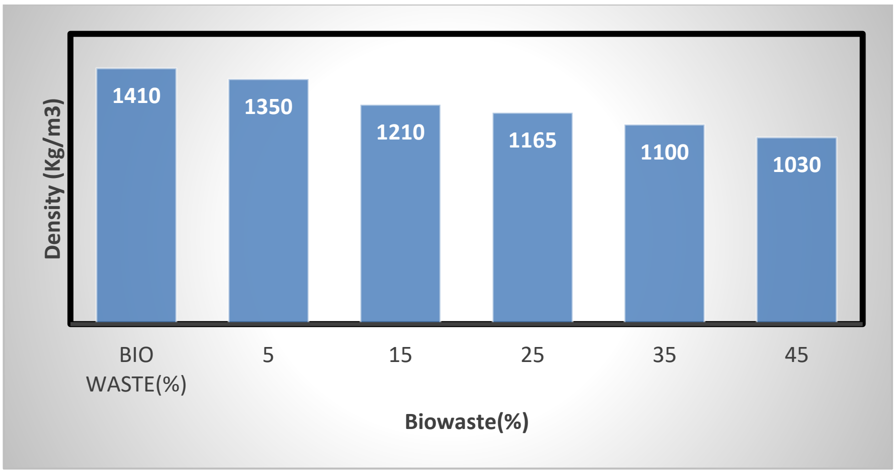

Figure 4: Density variation with Biowaste (%)

It is noticed from Figure 5 that if the biowaste (%) increases from 5 to 35% compressive strength increases, and after 35% if the biowaste (%) increases, then the compressive strength reduces. Initially, the biowaste fibres mixed with sand and cement enhance the strength, but further increasing the biowaste reduces the strength due to the development of the heterogeneous mixture.

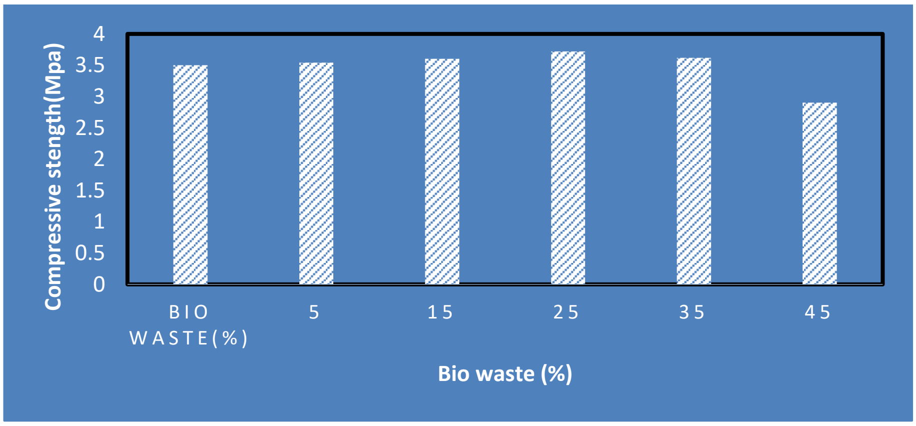

Figure 5: Compressive strength variation with Biowaste (%)

Figure 6 shows that if the biowaste (%) increases, then the water absorption capacity increases. The water absorption capacity has a negative effect on the brick strength and its durability. So, it must be at an optimum level and desirable for the construction material.

Figure 7 shows that if the biowaste concentration increases, then the thermal conductivity is reduced, which will be beneficial for the brick material. it will trap the heat in the winter season, and the room will remain warm, but it will increase the discomfort in the summer season.

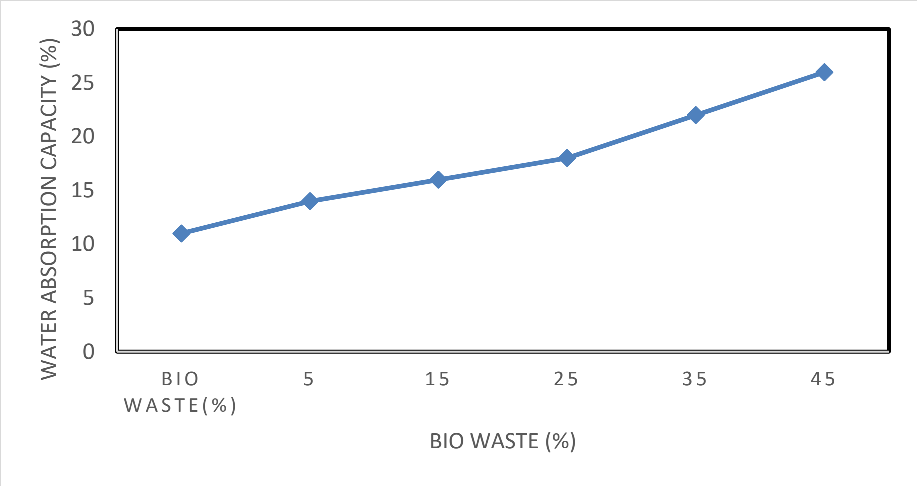

Figure 6: Water Absorption capacity variation with Biowaste (%)

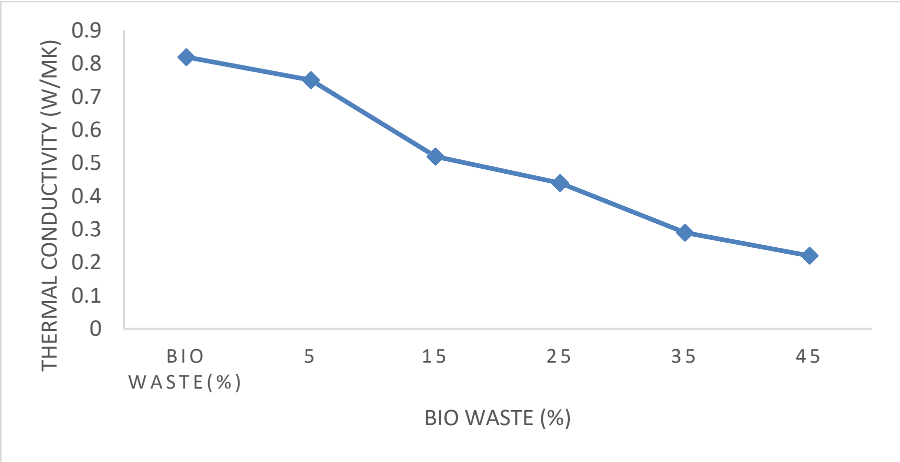

Figure 7: Thermal conductivity variation with biowaste (%)

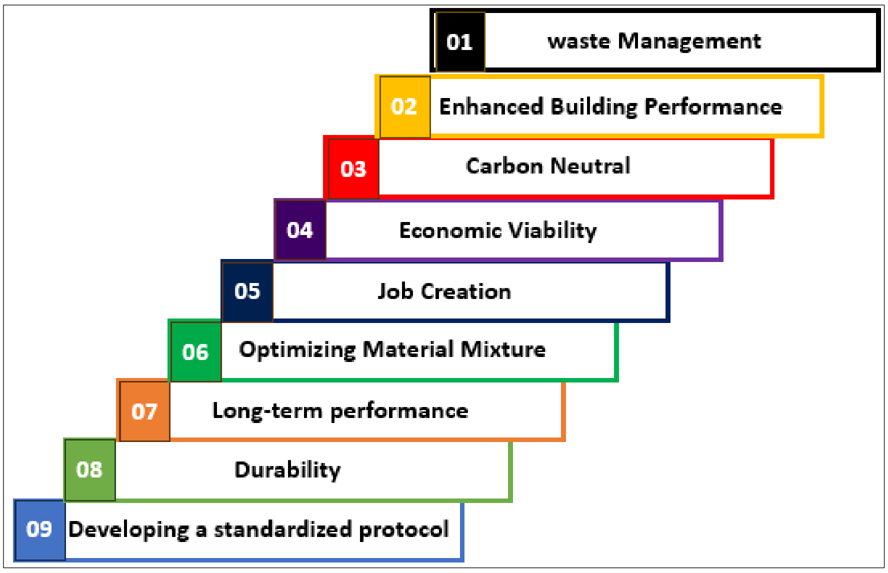

Figure 8: Future scope field of biowaste management

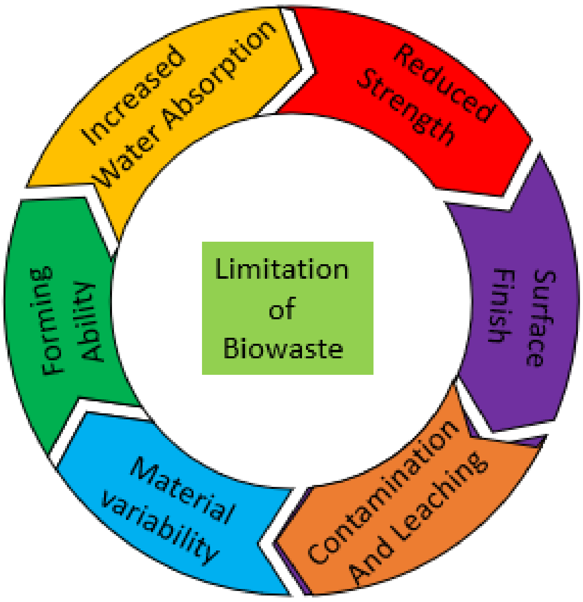

Figure 9: Limitation of use of biowaste in construction of bricks

Conclusion:

Finally, it is concluded that the biowaste of 35% concentration sample brick has been selected as per the mechanical testing. it has a 1165 kg/m^3 density, 18 MPa compressive strength, water absorption capacity of 18 %, and thermal conductivity (k_{bric})of 0.44 W/m-K. if increasing the biowaste content, then the density is reduced, compressive strength increases, water absorption capacity increases, and the thermal conductivity is reduced.

1. Future Scope of Biowaste in Construction: The use of biowaste in the future gain large popularity due to it gives to provide sustainable construction, a solution to waste management, and higher building effectiveness in summer as well as in winter seasons. Figure 8 represents the future scope of biowaste used in the construction.

2. Limitations of the use of the Biowaste: The biowaste material has a lot of benefits but simultaneously has a number of limitations, like enhanced water absorption capacity and reduced material quality**.** Figure 9 shows the limitations of the biowaste used in construction. These limitations put constraints for the use of the biowaste in the construction as bricks.

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RECENT ADVANCES IN NANOMATERIAL SYNTHESIS METHODS

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Abstract:

Nanomaterials and their preparation techniques are discussed extensively within this review chapter. There are two major ways of preparing nanomaterials: top-down and bottom-up techniques. Several nanofabrication techniques, including physical, chemical, and biological methods, are used. Extensive review and discussion of different nanofabrication techniques, based on their mechanisms and advantages and disadvantages, have been presented within this review.

Keywords: Nanomaterial, Techniques, Methods, Top-Down, Bottom-Up

Introduction:

According to the definition provided by the Royal Society and the Royal Academy of Engineering, UK, nanoscience and nanotechnology are described as follows: "Nanoscience is the study of phenomena and the manipulation of materials at atomic, molecular, and macromolecular levels, where properties differ significantly from those of the bulk materials. Nanotechnology involves the characterization, production, and application of structures, devices, and systems by controlling shape and size at the nanometer scale" [1].

A wide variety of synthesis techniques have been developed to fabricate nanomaterials in different forms, such as colloids, clusters, powders, nanotubes, nanorods, nanowires, and thin films. These synthesis techniques broadly include physical, chemical, and biological methods. The selection of an appropriate synthesis method depends on the desired nanomaterial, its size, dimensionality, morphology, and intended application. Nanoscience and nanotechnology, as defined by the Royal Society and the Royal Academy of Engineering, UK, deal with the study and manipulation of materials at the atomic and molecular scale, where their properties differ significantly from bulk materials [1]. Nanomaterials can be synthesized in various forms, including powders, nanowires, nanotubes, and thin films, using physical, chemical, or biological methods. The choice of synthesis technique depends on the required size, shape, and application of the nanomaterial.

Synthesis Method

To create nanomaterial synthesis with specific size, shape, dimensions, and structure, an assortment of methods has been used. The synthesis of nanomaterial may be done in two main methods: top-down and bottom-up. These methods are further separated into many groups according on the operations and reaction circumstances.

There are the two general conditions

(1) Top Down: Begin with a pattern generated on a larger scale, then reduced to nanoscale. This method is slow and not suitable for large scale production.

(2) Bottom –Up: Start with atom or molecules and build up nanostructures, Fabrication is much Less expensive

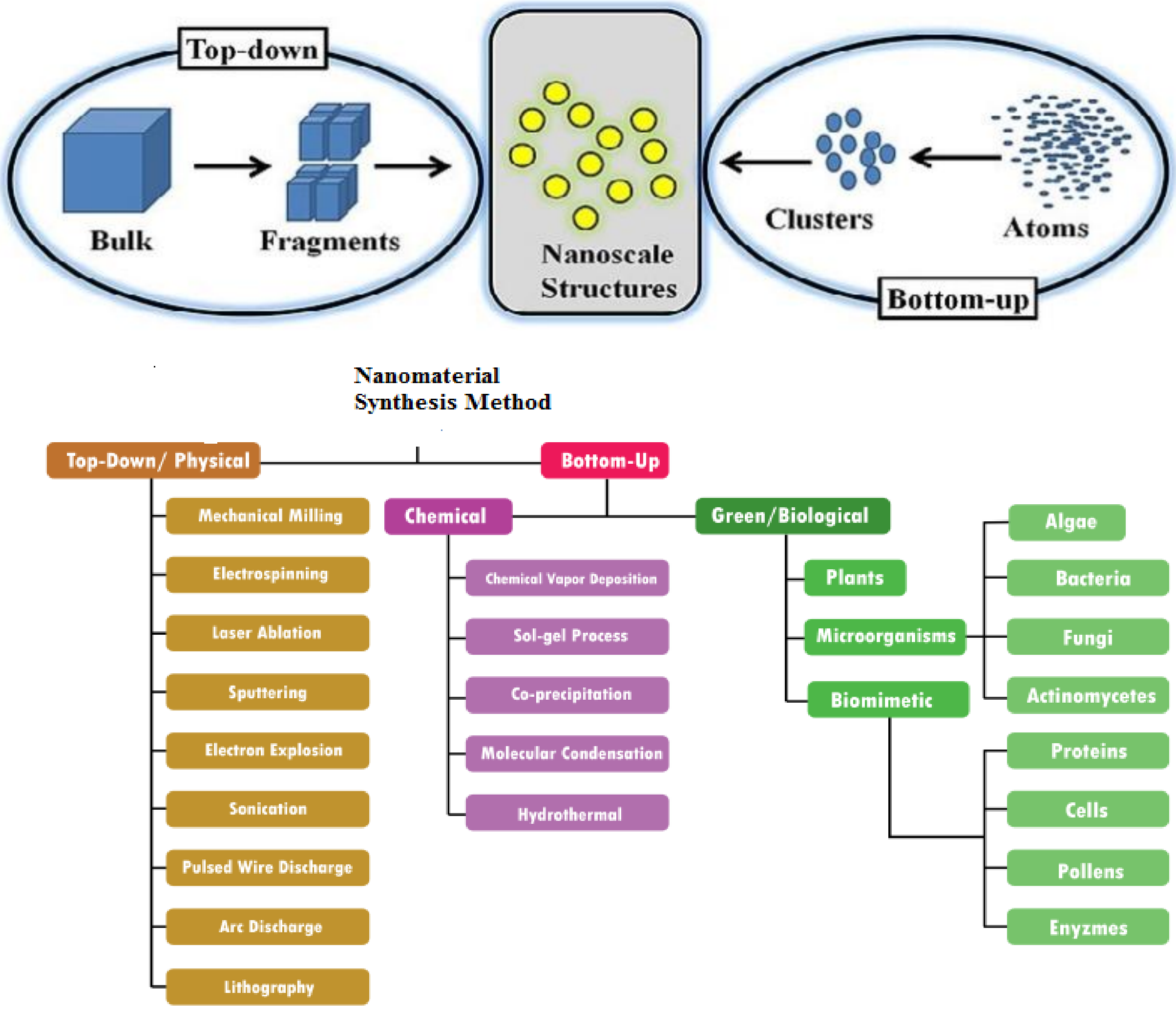

Figure 1: (a) Top-down /Bottom up (b) Different type of method [2,3]

1. Physical Methods

(i) Ball Milling

It is employed to create powdered nanoparticles of certain metals and alloys. To create fine particles, the mill often has one or more containers that are employed simultaneously. The amount of interest determines the container's size. Balls of hardened steel or tungsten carbide are placed in containers with flakes or powder (less than 50 um) of the desired substance. Any size or form can be used for the first material. The container's lids are tight. The containers are rotated at high speed around their own axis. Additionally, they may rotate around some central axis and are therefore called as 'planetary ball mill'. When the containers are rotating around the central axis, the material is forced to the walls and is pressed against the walls. But due to the motion of the containers around their own axis, the material is forced to another region of the container. By controlling the speed of rotation of the central axis and container as well as duration of milling, it is possible to ground the material to fine powder whose size can be quite uniform. Some of the materials like Co, Cr, W, Ni-Ti, Al-Fe, Ag-Fe etc. are made nanocrystalline using ball mill show in fig. 2.

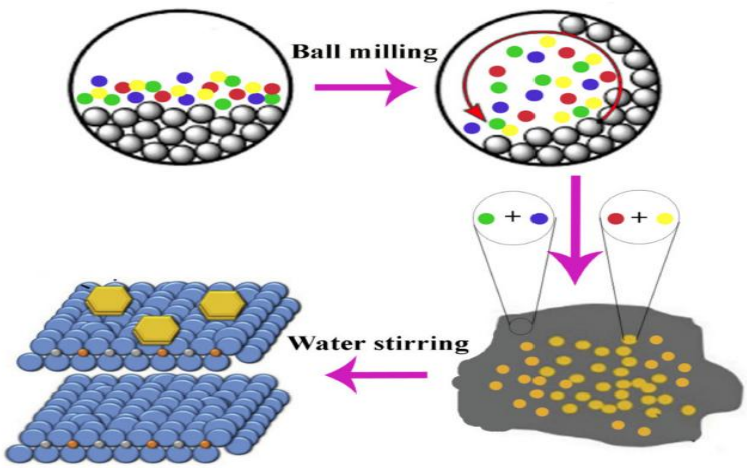

Figure 2: Ball milling synthesis method [4]

(ii) Melt Mixing:

The nanoparticles can be formed or controlled in glass. In terms of structure, glass is an amorphous material that lacks both symmetry and long-range periodic organization of atoms and molecules. A liquid turns into an amorphous or crystalline solid (glass) when it cools below a certain temperature. Both homogenous (in the melt) and inhomogeneous (on the surface of other materials) nuclei can form spontaneously and develop into organized, crystalline solids. Metals typically form crystalline solids, but they may also produce amorphous solids if they are cooled at a very rapid pace. Metallic glasses are the term for such substances. Even in such cases the atoms try to reorganize themselves into crystalline solids. Addition of elements like B, P, Si etc. helps to keep the metallic glasses in amorphous state. Nanocrystals can develop inside metallic glasses. Some nanoparticles can also be created by combining molten metal streams with turbulence at a high speed. After complete mixing, nanoparticles are produced [5].

(iii) Physical Vapor Deposition

The material for evaporation, an inert gas or reactive gas for material vapor collision, a cold finger for condensing clusters or nanoparticles, a scraper for scraping the nanoparticles, and a piston-anvil (a configuration for compacting powdered nanoparticles) are all involved. To ensure that the final product is as pure as possible, every procedure is completed in a vacuum chamber.

Filaments or boats of refractory metals, such as W, Ta, and Mo, in which the materials to be evaporated are stored, are used to evaporate or sublimate metals or high vapor pressure metal oxides. The gas pressure in the deposition chamber can affect the size, shape, and phase of the material that evaporates. Within the vacuum system, clusters or nanoparticles that have condensed on the cold finger (cooled by water or liquid nitrogen) may be scraped off. Until a sufficient amount of material passes through a funnel equipped with a piston-anvil arrangement, the evaporation and condensation process can be repeated several times.

(iv) Laser Vaporization

In this method, vaporization of the material is affected using pulses of laser beam of high power. The set up is a ultra high vacuum or high vacuum system equipped with inert or reactive gas introduction facility, laser beam, solid target and cooled substrate. Clusters of any material of which solid target can be made are possible to synthesize. Usually laser giving UV wavelength such as excimer laser is necessary because other wavelengths like IR or visible are often reflected by some of the metal surface. A powerful beam of laser evaporates the atoms from a solid source; atoms collide with inert gas atoms (or reactive gases) and cool on them forming clusters. They condense on the cooled substrate. The method is often known as laser ablation. Gas pressure is very critical in determining the particle size and distribution. Simultaneous evaporation of another material and mixing the two evaporated materials in inert gas leads to the formation of alloys or compounds.

(v) Chemical Vapour Deposition (CVD)

This hybrid approach makes use of compounds in the vapor phase. In the basic CVD process, reactant gas or vapour is transported to the substrate at a high temperature, where it cracks into various products that diffuse on the surface, go through a chemical reaction at the right place, nucleate, and grow to form the desired material film. It is necessary to return the byproducts produced on the substrate to the gaseous phase in order to remove them from the substrate. It is common practice to use a carrier gas to push desired material vapors into the reaction chamber. In certain instances, the reactions may take place through the gas phase aerosol generation. There are various processes such as reduction of gas, chemical reaction between different source gases, oxidation or some disproportionate reaction by which CVD can proceed. However, it is preferable that the reaction occurs at the substrate rather than in the gas phase. Usually temperature ~ 300 to 1200 C is used at the substrate. There are two ways viz., hot wall and cold wall by which substrates are heated. In hot wall set up the deposition can take place even on reactor walls. This is avoided in cold wall design. Besides this, the reaction can take place in gas phase with hot wall design, which is suppressed in cold wall set up. Furthermore, it is possible to couple a chemical process with plasma in a cold wall setup. Typically, gas pressures between 0.1 and 1.0 Torr are used. The substrate temperature and gas pressure affect growth rate and film quality. The growth is constrained by surface tension kinetics when it occurs at low temperatures.

2. Chemical Method

(i) Co-precipitation

It is a solvent displacement technique and is a wet chemical procedure. Ethanol, acetone, hexane, and non-solvent polymers are examples of solvents. Polymer phases can be either synthetic or natural show in fig. 3.

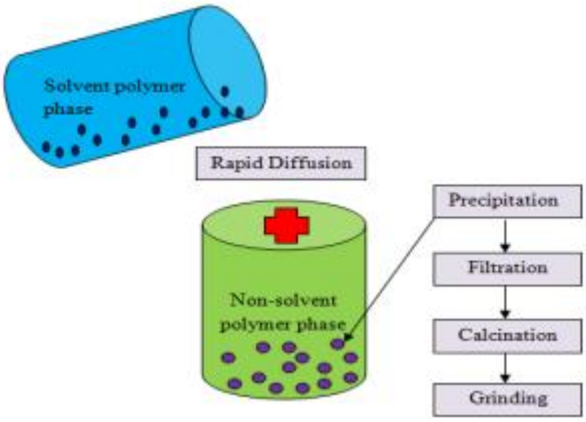

Figure 3: Co-precipitation method [5]

By mixing the polymer solution, fast diffusion of the polymer-solvent into the non-solvent phase of the polymer results. Interfacial stress at two phases results in the formation of nanoparticles.

(ii) Colloids and Colloids in solutions

Colloids are a type of materials that have at least one dimension smaller than a micrometer and consist of two or more phases (solid, liquid, or gas) of the same or distinct materials. Colloids can be fibers, plates, or particles. One of the colloids' dimensions falls between 1 and 100 nm, therefore nanomaterials are a subclass of colloids. The particles suspended in a host matrix are called colloids. Interactions, Colloids are particles with large surface to volume ratio. Therefore atoms on the surface are in a highly reactive state, which easily interact to form bigger particles or tend to coagulate. It is thus necessary to understand the stability of colloids i.e., how the colloids dispersed in a medium can remain suspended particles. In general there are a number of interactions involved. There are two types of interactions: attractive and repulsive. Repulsive interaction involves short distance of Born repulsive interaction and long range attractive interaction van der Waals attraction. Repulsive part arises due to repulsion between electron clouds in each atom and attractive part is due to interaction between fluctuating or permanent dipoles of atoms/molecules. The attractive forces between colloidal particles reduced in colloids in a liquid medium. Colloids in liquid may be positively charged, negatively charged or even neutral. But in most cases, they are charged.

(iii) Sol-Gel Method

Sol-gel uses two different kinds of materials or components, as the name suggests. Sol-gel has a number of benefits. Low temperatures are often used in all sol-gel production processes [6]. As a result, there will be reduced pollution and energy use. Among the advantages are the acquisition of special materials like zeolites, aerogels, and ordered porous solids by organic-inorganic hybridization are unique to sol-gel process [7]. It is also possible to synthesize nanoparticles, nanorods, nanotubes etc., using sol-gel technique show in fig. 4.

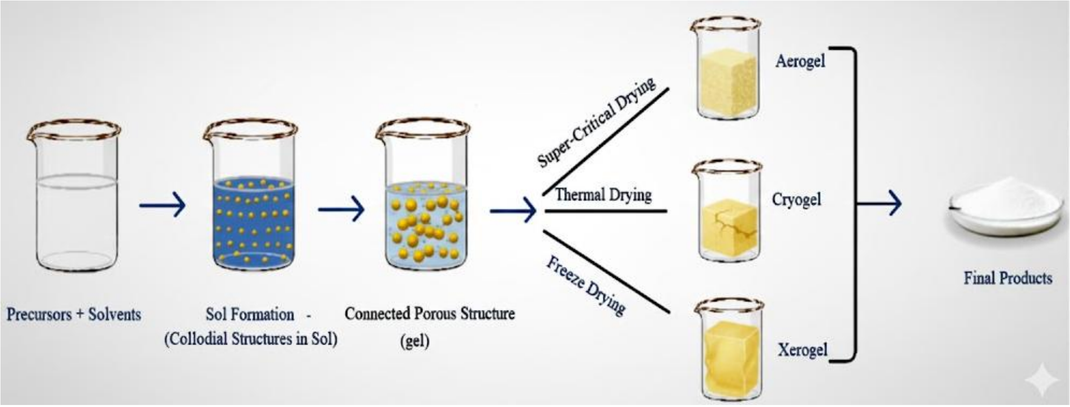

Figure 4: Sol-Gel process for synthesis method

Sols are solid particles in a liquid. They are thus a subclass of colloids. Gels are nothing but a continuous network of particles with pores filled with liquid (or polymers containing liquid). A sol-gel process involves formation of sols in a liquid and then connecting the sol particles (or some subunit capable of forming a porous network) to form a network. By drying the liquid, it is possible to obtain powders, thin films or even monolithic solid[8].

3. Biological Methods

Synthesis of nanomaterials using biological ingredients can be roughly divided into following three types.

(i) Synthesis using Microorganisms

Microorganisms can create nanoparticles by reacting with metals that come into touch with them through their cells. The various ways that metals and microorganisms interact are: (i) Hydrogen sulfide (H_2S) is produced by certain microbes. It has the ability to oxidize organic materials to produce sulphate, which serves as an electron acceptor for metabolism. When metal salt is present, this H_2S has the ability to change metal ions into metal sulfide, which forms extracellular deposits. (ii) Metal ions from a metal salt can occasionally enter the cell. To shield the rest of the cell from the harmful environment, the metal ions are subsequently transformed into a harmless form and coated with proteins. (iii) certain microorganisms are capable of secreting some polymeric materials like polysaccharides. They have some phosphate, hydroxyl and carboxyl anionic groups which complex with metal ions and bind extracellularly (iv) cells are also capable of reacting with metals or ions by processes like oxidation, reduction, methylation, demethylation etc [9].

Semiconductor nanoparticles like CdS, ZnS, PbS etc. can be produced using different microbial routes. Desulfobacteriaceae can form 2-5 nm ZnS nanoparticles. Bacteria Klebsilla pneumoniae can be used to synthesize CdS nanoparticles. When $Cd(NO_3)_2$ is mixed in a solution containing bacteria and solution is shaked for about one day at ~38 C, then the CdS nanoparticles in the size range ~5-200 nm can be formed. CdS nanoparticles with narrow size distribution can be synthesized using the yeasts like Candida glabrata. Similarly it is possible to synthesize PbS by challenging Torulopsis sp. with lead salt like PbNO3.

(ii) Synthesis using Plant Extracts

It has been reported that live alfalfa plants are found to produce gold nanoparticles from solids. Leaves from geranium plant have also been used to synthesize nanoparticles of gold. Nanoparticles obtained using Collectotrichum sp. Fungus related to geranium plant has a wide distribution of sizes and particles are mostly spherical. On the other hand, geranium leaves produce rod- and disk-shaped nanoparticles [10].

Gold nanoparticles form geranium plant extract is as follows: Finely crushed leaves are put in Erlenmeyer flask and boiled in water just for a minute. Leaves get ruptured and cells release intracellular material. Solution is cooled and decanted. This solution is added to HAuCl4 aqueous solution and nanoparticles of gold start forming within a minute [11].

Conclusion:

The synthesis methods presented in this chapter enable the production of a wide variety of nanoparticles with controlled size and morphology. An overview of the fundamental steps involved in top-down and bottom-up nanoparticle synthesis approaches is also discussed.

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DEVELOPMENT AND VALIDATION OF A STABILITY-INDICATING UV SPECTROPHOTOMETRIC METHOD FOR 2-(5-AMINO-3-(4-CHLOROPHENYL)-1H-PYRAZOL-1-YL) ETHANOL

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Abstract:

A simple, sensitive, and stability-indicating UV spectrophotometric method was developed and validated for the quantitative determination of 2-(5-amino-3-(4-chlorophenyl)-1H-pyrazol-1-yl) ethanol, hereafter referred to as 5-ACPE, a synthesized pyrazole derivative of pharmaceutical interest. The UV absorption spectrum of the compound was recorded in the range of 190 nm to 800 nm using Methanol as the solvent, and the maximum absorbance (λ_{max}) was observed at 256 nm. The method exhibited linearity over the concentration range of 10-100 µg/mL, with a correlation coefficient (R^2) of 0.9995. Precision studies demonstrated satisfactory repeatability and intermediate precision, with %RSD values of 0.387% and 1.464 %, respectively. Accuracy was evaluated by recovery studies at 80 %, 100 %, and 120 % levels, yielding recoveries in the range of 97.83 -99.24 %. The method showed adequate robustness against small deliberate variations in analytical parameters. The limits of detection (LOD) and quantification (LOQ) were found to be 0.1341 µg/ml µg/mL and 0.4065 µg/mL, respectively. Forced degradation studies under acidic, alkaline, oxidative, photolytic, and thermal conditions confirmed the stability-indicating capability of the method, as the analyte was well resolved from its degradation products with no interference at the selected wavelength. The proposed method was validated in accordance with ICH Q2(R1) guidelines and can be effectively applied for routine analysis and stability assessment of the synthesized compound.

Keywords: UV Spectrophotometry, Pyrazole Derivatives, Stability-Indicating Method, Forced Degradation Studies, Method Validation, ICH Guidelines

Introduction:

Pyrazole and its derivatives constitute an important class of heterocyclic compounds due to their wide spectrum of biological and pharmacological activities, including anti-inflammatory, antimicrobial, anticancer, and antioxidant properties. Structural modification of the pyrazole nucleus has been shown to significantly influence biological performance, making such compounds attractive candidates for medicinal chemistry research. Among these, 2-(5-amino-3-(4-chlorophenyl)-1H-pyrazol-1-yl) ethanol hereafter referred as 5-ACPE represents a newly synthesized derivative incorporating both an electron-withdrawing chlorophenyl moiety and a polar ethanol side chain, which may enhance its pharmacological potential and solubility characteristics.

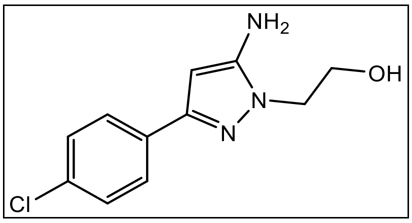


Figure 1: Chemical structure of 5-ACPE

Reliable analytical methods are essential for the evaluation of synthesized compounds during early-stage research, particularly for quantification and stability assessment. UV spectrophotometry remains one of the most widely used analytical techniques owing to its simplicity, cost-effectiveness, rapid analysis, and minimal solvent consumption. When appropriately validated, UV methods can provide accurate and precise quantitative data suitable for routine laboratory analysis.

In addition to quantification, stability studies play a crucial role in understanding the degradation behaviour of compounds under various stress conditions, such as acidic, alkaline, oxidative, thermal, and photolytic environments. A stability-indicating method is capable of distinguishing the intact analyte from its degradation products, thereby ensuring the specificity and reliability of the analytical procedure.

The present chapter focuses on the development and validation of a stability-indicating UV spectrophotometric method for 5-ACPE, following ICH Q1A(R2) and ICH Q2(R1) guidelines. The method aims to provide a simple and robust analytical tool suitable for quantitative determination and stability evaluation of the synthesized compound in bulk form.

Methodology

Chemicals and reagents

All chemicals and reagents used in the present investigation were of Analytical Reagent (AR). Methanol, and distilled water (Milli-Q) were procured from Merck India Pvt. Ltd. The reference standards of synthesized compounds, namely 2-(5-amino-3-(4-chlorophenyl)-1H-pyrazol-1-yl)ethanol (5-ACPE), were prepared and characterized in the laboratory. The test samples were prepared from different batches than those used for the reference standards of the synthesized compounds, which were independently prepared in the laboratory. All other reagents were freshly prepared and used within their stability period. Glassware used throughout the study was thoroughly cleaned, rinsed with distilled water, and dried before use.

Instrumentation

A UV-Visible Spectrophotometer (Analytical Technologies Ltd., Model 2012) was employed, featuring a wavelength resolution of 0.1 nm, a double-beam design, and UV-VIS Analyst Software, with a scanning range of 190–1100 nm. Other instruments used for method development and validation included a cyclo mixer (Remi, India), a sonicator (Wenser Ultra Sonicator WUC-4L), a pH meter (Metrohm), and an analytical balance (Wenser High Precision Balance PGB100) for precise weight measurements. Buffers and triple-distilled water were filtered using 0.45 µm nylon filter membranes (Millipore).

Method Development

Method development involved the selection of a suitable solvent system, preparation of standard solutions, and determination of the maximum absorbance wavelength (λmax) for 5-ACPE compounds.

Selection of solvent Methanol was selected as the solvent for dissolving 5-ACPE.

Preparation of Standard & Sample Solution

To prepared stock solution of standard and sample of 5-ACPE of different batches weighed accurately 10 mg of 5-ACPE in 10 ml volumetric flask and dissolved in 10 ml of methanol solution which gives conc. of 1000 µg/ml or 1000 ppm solutions.

Selection of Analytical Wavelength

5-ACPE solution of 100 ppm was scanned under UV-Vis spectrophotometer in the range 200-400 nm against methanol as blank and λ_{max} was obtained at 256 nm.

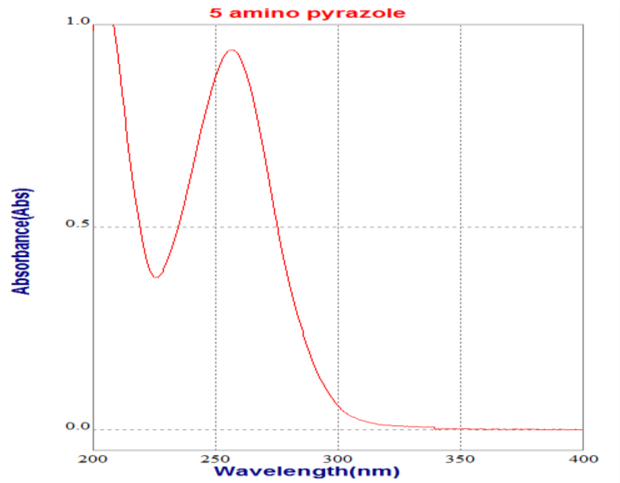


Figure 2: UV spectrum of 5-ACPE

Method Validation

Validation is process of establishing documented evidence, which provides a high degree of assurance that specific activity will always produce desired result or product meeting its predetermined specification and quality characteristics.

1. Linearity

Preparation of Calibration Curve

i. A stock solution with a concentration of 1000 µg/mL was prepared.

ii. Aliquots of 0.1 to 1.0 mL of the stock solution were taken and diluted with methanol to a final volume of 10 mL, resulting in solutions with concentrations ranging from 10 to 100 µg/mL.

iii. The absorbance of each solution was measured at 256 nm using a suitable spectrophotometer.

iv. A standard calibration curve was plotted with absorbance values on the y-axis and concentration (µg/mL) on the x-axis.

v. The calibration curve exhibited linearity within the concentration range of 10–100 µg/mL, with a correlation coefficient (R^2) of 0.9995.

Table 1: Linearity data of 5-ACPE in working standard

Sr. No.	Concentration (ppm)	Absorbance
1	10	0.0953
2	20	0.185
3	30	0.280
4	40	0.359
5	50	0.446
6	60	0.543
7	70	0.644
8	80	0.740
9	90	0.823
10	100	0.912

*Average of ten determination

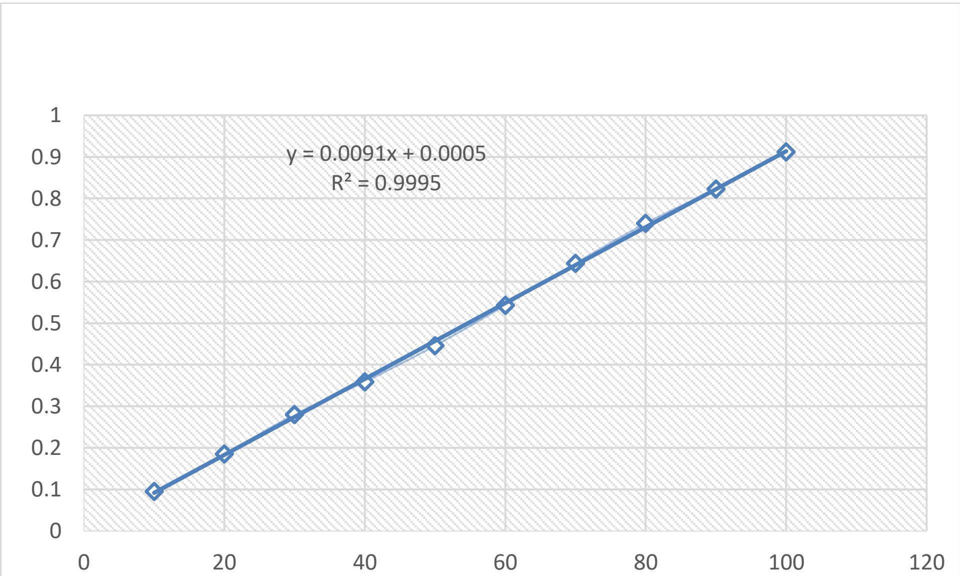


Figure 3: Standard calibration curve of 5-ACPE

Table 2: Optical Characteristics of 5-ACPE

Parameters	Result
Beer's law limit (µg/ml)	10-100 µg/ml
Correlation coefficient	0.9995
Regression equation (Y*)	0.0091x+0.0005
Slope (a)	0.0091
Intercept (b)	0.0005

Accuracy

The accuracy of the developed UV spectrophotometric method was evaluated in accordance with ICH Q2(R1) guidelines. A stock solution of the compound was prepared separately from a well-characterized, synthesized batch (used as the standard) and from an independently synthesized batch (used as the test), both at a concentration of 100 µg/mL. From each stock solution, a working solution of 10 µg/mL was prepared. The working solution prepared from the standard batch was used as the reference (100%) standard solution, while the working solution prepared from the test batch was treated as the unknown test solution.

So; for 80%: for 100%: for 120%:

100% = 10 µg/mL 100% = 10 µg/mL 100% = 10 µg/mL

80% = X 100% = X 120% = X

X = 8 µg/mL X = 10 µg/mL X = 12 µg/mL

Accuracy was assessed at three concentration levels corresponding to 80%, 100%, and 120% of the nominal test concentration. Accordingly, theoretical concentrations of 8 µg/mL, 10 µg/mL, and 12 µg/mL were prepared from the test batch stock solution. Each concentration level was prepared in triplicate, and the absorbance of each solution was measured in triplicate at the selected analytical wavelength.

The concentration found for each preparation was calculated by comparing the absorbance of the test solution with that of the standard solution using the following equation:

$$\text{Concentration found (µg/mL)} = \frac{A_{\text{test}}}{A_{\text{standard}}} \times C_{\text{standard}}$$

where $A_{\text{test}}$is the absorbance of the test solution, $A_{\text{standard}}$is the absorbance of the standard solution (10 µg/mL), and $C_{\text{standard}}$is the concentration of the standard solution (10 µg/mL).

The percentage recovery was calculated by comparing the concentration found with the corresponding theoretical concentration according to the equation:

$$\%\text{Recovery} = \frac{\text{Concentration found}}{\text{Theoretical concentration}} \times 100$$

The recovery results were found to be within the acceptable range of 97.34 % - 99.70 %. for all three concentration levels (80–120%). confirming that the proposed UV spectrophotometric method is accurate, reliable, and suitable for quantitative estimation of the compound over the studied concentration range.

Table 3: Accuracy study of 5-ACPE

No. of Preparation	Concentration (µg/ml)		% Recovery	Mean
	Test	Standard		
S_1:80%	7.94	8	99.25	99.24%
S_2:80%	7.97	8	99.62	
S_3:80%	7.91	8	98.87	
S_1:100%	9.97	10	99.70	99.50%
S_2:100%	9.95	10	99.50	
S_3:100%	9.93	10	99.30	
S_1:120%	11.68	12	97.34	97.83%
S_2:120%	11.75	12	97.91	
S_3:120%	11.78	12	98.25	

3. Precision

Precision of the method was established by intraday and interday variation studies. In intraday variation study three different solutions of three different concentrations were analyzed in a day i.e. from morning, afternoon and evening. In the interday variation studies, solution of three different concentration was analyzed three times for the three consecutive days and the absorbance result mean, standard deviation (S) and % RSD was calculated.

$$s = \sqrt{\frac{\sum_{i=1}^{n}(X_i - \overline{X})^2}{n-1}}$$

Where,

X = individual value

X = arithmetic mean

n = number of samples

Or Coefficient of variation (C.O.V)

% Relative standard deviation (%R.S.D.) = SD/X x 100

Where,

SD= Standard Deviation

X= Mean

Table 4: Intra-day precision studies for 5-ACPE

Conc. (µg/ml)	Absorbance (nm)			Mean	SD	% RSD
	Trial 1	Trial 2	Trial 3			
40	0.361	0.365	0.363	0.363	±0.0020	0.55
80	0.726	0.731	0.729	0.729	±0.0025	0.34
100	0.910	0.913	0.915	0.913	±0.0025	0.27
Average of % RSD = 0.387%						

Table 5: Inter-day precision studies for 5-ACPE

Conc. (µg/ml)	Absorbance (nm)			Mean	SD	% RSD
	Day 1	Day 2	Day 3			
4	0.036	0.037	0.037	0.037	±0.0006	1.62
8	0.071	0.072	0.073	0.072	±0.0010	1.39
12	0.107	0.109	0.110	0109	±0.0015	1.38
Average of % RSD = 1.464%						

4. Robustness

Robustness of the method was determined by carrying out the analysis under different temperature condition i.e. at room temperature and at 18°C. The respective absorbances of 20 µg/ml were noted and the result was indicated as %RSD.

Table 6: Robustness for 5-ACPE

Sr. No.	Concentration (ppm)	Absorbance	
		Room temperature	18^0C
1	20	0.186	0.184
2	20	0.187	0.183
3	20	0.184	0.182
4	20	0.186	0.183
5	20	0.185	0.181
6	20	0.187	0.182
Mean		0.186	0.183
SD		0.00126	0.00110
% RSD		0.68%	0.60%
Average % RSD = 0.64%			

5. Ruggedness

Ruggedness of the method was determined by carrying out the analysis by different analyst and the respective absorbance of 20 µg/ml was noted. The result was indicated as %RSD.

$$s = \sqrt{\frac{\sum_{i=1}^{n}(X_i - \overline{X})^2}{n-1}}$$

Where,

X = individual value

X = arithmetic mean

n = number of samples

% Relative standard deviation (%R.S.D.) = S/X x 100

Where,

S= Standard Deviation

X= Mean

Table 7: Ruggedness for 5-ACPE

Sr. No.	Conc. (ppm)	Absorbance		
		Analyst 1	**Analyst 2**	**Analyst 3**
1	20	0.185	0.183	0.187
2	20	0.186	0.182	0.186
3	20	0.187	0.184	0.185
4	20	0.184	0.183	0.188
5	20	0.186	0.182	0.186
6	20	0.185	0.183	0.187
Mean		0.1855	0.1828	0.1865
SD		0.00112	0.00075	0.00105
% RSD		0.60%	0.41%	0.56%
Average% RSD = 0.524%				

6. Limit of detection (LOD)

The limit of detection (LOD) was separately determined based on the standard deviation of response of the calibration curve. The standard deviation of the y intercept and slope of the calibration curve were used.

LOD is calculated from the formula: -

LOD =3.3 X S.D/ S

Where,

LOD = limit of detection,   3.3 = Standard Factor

S.D = standard deviation of response for the lowest conc. in the range

S = slope of the calibration curve.

LOD = 3.3 X 0.00037 / 0.0091

LOD was found to be 0.1341 µg/ml

7. Limit of quantification (LOQ)

The LOQ is the concentration that can be quantification reliably with a specified level of accuracy and precision. The LOQ was calculated using the formula involving standard deviation of response and slope of calibration curve. The quantitation limit (QL) may be expressed as:

LOQ= 10x S.D/S

Where,

LOQ = Limit of quantification

10 = Standard Factor

S.D = standard deviation of response for the lowest conc. in the range

S = slope of the calibration curve.

LOQ= 10 X0.00037/ 0.0091

LOQ was found to be 0.4065 µg /ml.

Table 7: Summary of validation of 5-ACPE

Sr. No.	Parameter	Result
1	Linearity indicated by correlation coefficient	0.9995
2	Linear regression equation	0.0091x + 0.0005
3	Range	10 µg/ml – 100 µg/ml
4	Intraday Precision (%RSD)	0.387%
5	Interday Precision (%RSD)	1.464 %
6	Limit of Detection	0.1341 µg/ml
7	Limit of Quantification	0.4065 µg/ml
8	Robustness indicated by % RSD	0.64 %
9	Ruggedness indicated by % RSD	0.524 %

(B) Stress Degradation Studies

By UV method

The International Conference on Harmonization (ICH) guidelines entitled stability testing of new drug substance and products requires that stress testing carried out to elucidate the inherent stability characteristics of the synthesized organic compound. The aim of this work was to perform impurity studies on the 5-ACPE using proposed method.

To perform forced degradation studies, ICH Q1A (R2) and ICH Q1B guidelines were followed.

Acid-Induced degradation

5-ACPE (10 mg) was solubilized in 10 mL. 0.1 N methanolic HCl and refluxed at 60°C for 1 h in the dark. From above solution, 0.2 ml was transferred to a volumetric flask and neutralized with 1N NaOH. Volume was made up to 10 mL with methanol and 20 µl. was used for UV analysis.

Base-Induced Degradation

5-ACPE (10 mg) was solubilized in 10 mL. 0.1N methanolic NaOH and refluxed at 60°C for 1 h in the dark. From the above solution, 0.2 mL was transferred to a volumetric flask and neutralized with 1N HCL. The volume was made up to 10 mL with methanol, and the degraded sample was analyzed using UV-Vis spectroscopy to identify and quantify degradation products.

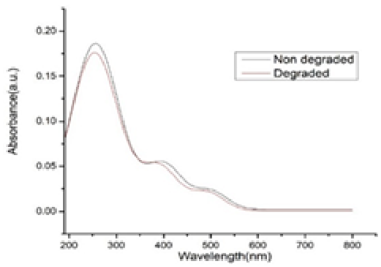
3.Photolytic Degradation

5-ACPE (10 mg) was exposed to direct sunlight for 8 h daily up to six days, corresponding to a total exposure of 48 h. After the exposure, a solution (0.2 mg/ml) of exposed 4-NPTZ was prepared in methanol, and used degraded sample was used for analysis using UV-Vis spectroscopy to identify and quantify degradation products.

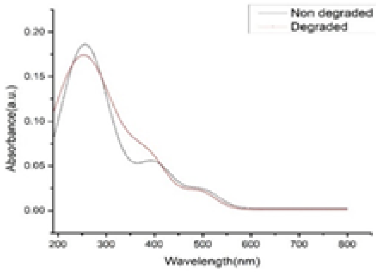
4.Thermal Degradation

5-ACPE (10 mg) in solid powdered form was kept in the oven for 4h at 60°C. and 1mg/ml, a solution was prepared using methanol. From the above solution, 0.2mL. was transferred to a volumetric flask and diluted up to 10 mL with methanol, and used degraded sample was used for analysis using UV-Vis spectroscopy to identify and quantify degradation products.

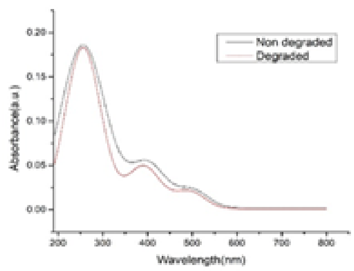
1. **Oxidative Degradation**- Using methanol, a solution of 5-ACPE with 1 mg/ml. was prepared to which 10 ml of 6 % v/v H_2O2, was added and kept at room temperature (28°C) for 1 h in dark. From the above solution, 0.2 ml. was transferred to a volumetric flask and diluted up to 10 ml. with methanol and used degraded sample for analysis using UV-Vis spectroscopy to identify and quantify degradation products.



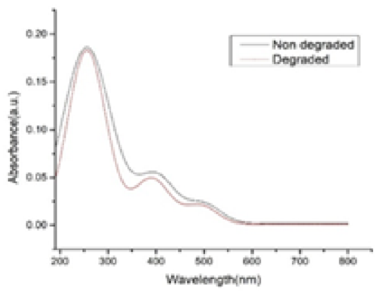
(a)Acidic



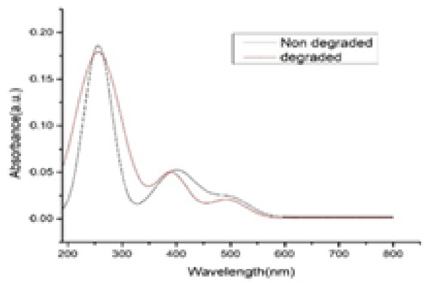
(b)Basic



(c) Photolytic



(d) Thermal



(e) Oxidative

Figure 4: Forced degradation behavior under different stress conditions

Table 9: Summary of result of stress degradation studies

Stress condition	Time	Observation λ max change	Concentration of 5-ACPE degraded (µg/ml)	% Degradation	Absorbance
Without degradation	**-**	**256 nm**	**-**	**-**	**0.186**
Acidic Degradation	Reflux 1 hours	(254 nm)λ max shifted	1.1	5.5	0.176
Alkali Degradation	Reflux 1 hours	(253 nm) λ max shifted	1.32	6.60	0.174
Photo Degradation	24 hours	No λ max shifted	0.33	1.65	0.183
Thermal degradation	48 hours	No λ max shifted	0.44	2.2	0.182
Oxidative degradation	RT 1 hours	No λ max shifted	0.66	3.85	0.179

*RT- Room Temperature

Conclusion:

A stability-indicating UV spectrophotometric method was successfully developed and validated for the quantitative determination of 5-ACPE. The method demonstrated acceptable linearity, precision, accuracy, robustness, and sensitivity in accordance with ICH Q2(R1) guidelines. Forced degradation studies confirmed that the method is capable of effectively monitoring the stability of the compound under various stress conditions without interference from degradation products. The compound demonstrates moderate instability under acidic and alkaline conditions, with noticeable chemical changes indicated by shifts in λ_{max}. In contrast, it appears quite stable under photo, thermal, and oxidative stress, with minimal degradation observed in these conditions.

Owing to its simplicity, reliability, and cost-effectiveness, the proposed UV method is suitable for routine quantitative analysis and stability studies of the synthesized pyrazole derivative in research and quality control laboratories.

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EXPLORING THE STRATEGIC AND FUNCTIONAL IMPACT OF ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING ON THE EVOLUTION OF LIBRARY SYSTEMS AND SERVICES

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Abstract:
In the role of this plan and execution of reducing aspect automations like artificial intelligence and machine learning includes turn out to be relevant, lecturers, researchers and statistics experts include research within place. The aim of this efficient literature evaluation be able supply a combining of practical studies scrutinizing benefit of Artificial intelligence and machine learning in libraries. To obtain the objectives of the examiner, a scientific literature evaluate became performed based totally on the unique recommendations proposed indirect "Kitchenham" and others. (2009). Information become composed from reap of technology, "Scopus", "LISA" and "LISTA" databases. Succeeding the severe/ settled selection form, a complete of thirty two items were subsequently s elected, inspected and resolved. Thirty documents have been labeled, resolved and epitomized at the request of AI and ML area and approaches that are often used. Findings display that the current country of the AI and ML studies namely appropriate accompanying the LIS area particularly form a concentration of hypothetical works. However, any scientists further emphasized on implement at ion tasks or case studies. For accumulation administration in libraries, numerous ML procedures like logistic reversion, KNN, Ada Boost had happened widely used for Metadata production, aid finding; and book procurement. Whereas for circulate (e book recommendation, services score, bibliographic enumerations etc.) recommender gadget, SVM, connection rule have happened used. Library in apartment activities like; arrange, class, indexing, document reasoning, textual content opinion etc., had been financed accompanying the aid of two together AI and ML technology.

Any superior AI and ML actions like pattern opinion and MAS are more getting used to confirm library protection; person correspondence; book recognize acknowledgment; RFID control, as well as additional presidency ventures. Deep promote information of, neural network algorithms, spiral affecting animate nerve organs networks have likewise been confirmed as active supplies for scholarship, accumulations finding, search and reasoning. Except, an by artificial means shrewd talkative power or chatbot everything as a virtual remark curator. It complements head to head human interplay for library net site journey information, computerized in essence remark

helpers, lectors' advisory librarians, and in essence account tellers. This scrutinize at may be going to help in the bettering of current ideas and models or supplies to guide and embellish the householder ecologies of libraries. This obey will offer an awesome view of AI and ML in libraries for researchers, experts and educators for advancing the extra electronics oriented methods, and looking forward future change pathways. Keywords: Artificial Intelligence, Library and Information Science, Library services, Information Technology, ML, AI, machine intelligence, libraries, orderly review.

Keywords: Artificial Intelligence, Library And Information Science, Library Services, Information Technology, ML (Machine Learning), Libraries, Systematic Review.

Introduction:

The synthesis of artificial Intelligence (AI) within Library and information science (LIS) holds received large consideration in current age, imparting encouraging possibilities until bedeck library administration and person reviews. This chapter bounties a complete review of the literature on AI in LIS, harmonizing key issues, judgments, and associations from existent research.

This assessment recognizes numerous conveniences granted by AI technologies, which includes stepped forward information retrieval, customized recommendation plans, in essence cooperation, records analysis, and virtual preservation. Pupils focus the capacity from AI to recast library services, intelligible operations, and encourage approachability and inclusivity.

But this overview still examines various demanding situations moreover drawbacks related to AI implementations modern LIS, in addition to concerning manipulation of numbers bias, isolation concerns, virtual distribute, value and capital necessities, in addition moral concerns, Researchers highlight the need for painstaking consideration of those disputes to ensure obliged and impartial AI consumer in libraries.

Consumer outlooks and stories accompanying AI-urged library contributions are tested, disclosing visions into approval elements, person alternatives, as well as issues approximately solitude, information pleasant, including agree with in AI technology. The evolving functions and abilities of librarians and records expert inside the AI age also are mentioned, highlighting the importance of indirect proficiency, certainties control, and moral choice-making.

Case research as well as refined practices exhibit a success model of AI principle in libraries, imparting precious training found out and insights for library practitioners. finally, future directions and studies occasion table for AI in LIS are classified, incorporating the bettering of AI-pressured gear abide duties, survey of moral and community associations, and integrative cooperation to encourage talent and novelty on this rapidly developing subject. General, the overview underscores the transformative capability of AI in LIS while emphasizing the importance of addressing demanding situations and moral considerations to make sure responsible AI implantation and maximize its advantages for libraries and their buyers.

Artificial Intelligence (AI) is a department of computer technology that focuses on building structures able to operating responsibilities that usually call for human intelligence. These responsibilities encompass getting to know, reasoning, problem-fixing, notion, and language understanding.AI ambitions to duplicate or simulate human cognitive abilities in machines, enabling them to research information, make selections, and adapt to new situations.

The sphere of AI encompasses numerous techniques and procedures, along with:

1. **Machine Learning (ML):** Machine learning is a subspace of AI that includes training algorithms to learn from data and make predictions or decisions without being explicitly programmed to perform specific tasks. ML algorithms improve their performance over time Period as they are exposed to more and more data.
2. **Deep Learning:** Deep learning is a type of machine intelligence that uses unreal affecting animate nerve organs networks with many layers (hence the term "deep") to learn representations of data. Deep learning has shown remarkable success in areas such as image recognition, natural language processing, and speech recognition.
3. **Natural Language Processing (NLP):** focuses on permissive computers to accept, define, and generate human expression. NLP methods are pre-owned in uses such as emotion analysis, automobile interpretation, text account in speech, and chatbots.
4. **Computer Vision:** it associates contributing machines the strength to interpret and comprehend optical information from the natural world. Computer vision algorithms can evaluate figures and video to act tasks such as object acceptance, representation allocation, and illustration separation.
5. **Robotics:** Robotics integrates AI accompanying architecture to design and build cyborgs capable of interactive with the physical world. AI algorithms are acclimated authorize cyborgs to recognize their atmosphere, make decisions, and act tasks individually.

AI packages are ubiquitous and retain to evolve hastily. They may be determined in various industries and domain names, inclusive of healthcare, finance, transportation, entertainment, agriculture, and training. Examples of AI packages encompass virtual private assistants (e.g. Siri, Alexa), recommendations machine, and smart home gadgets. even as AI gives several blessings, such as automation, efficiency, and innovation, it additionally raises ethical, social, and monetary considerations. These include issues about task displacement, algorithmic bias, privacy, security, and the ethical use of AI technology. As AI keeps to improve, it's miles vital to make sure that it is developed and deployed responsibly, with cautious attention of its capacity effect on society and the environment. Furthermore, ongoing studies and collaboration are important to cope with challenges and harness the full ability of AI for the advantage of humanity.

History of AI (Artificial Intelligence)

These records of AI dates returned to relic, with early philosophical and mythological concepts of unreal beings and mechanical automata. But, the current generation of AI started out within the mid-20th century with the emergence of computational concept and the improvement of virtual computers. Here's a short overview of key milestones in the records of AI:

1. Early concepts (Antiquity- 20th Century): at some stage in records, there have been diverse depictions of artificial beings and intelligent machines in mythology, folklore, and literature. for example, historical Greek myths function tales of automatons created through Hephaestus, the god of blacksmiths, even as the Chinese language mythological discern of Yan Shi is said to have built mechanical men.

2. Computational theory (20th Century): the foundations of modern AI were laid inside the mid-twentieth century with the development of computational idea. Mathematicians together with Alan Turning and John Von Neumann made big contributions to the principle of computation, laying the foundation for the development of digital computer systems.

3. Dartmouth conference (1956): The term "artificial Intelligence" became coined on the Dartmouth conference in 1956, in which main scientists and researchers accrued to talk about the capability for growing intelligent machines. This conference is considered a landmark even within the history of AI, marking the formal status quo of the sphere.

4. Early AI packages (1950s-1960s): in the course of the 1950s and 1960s, researchers evolved a number of the earliest AI packages, which include programs for gambling video games inclusive of chess and checkers, first rate examples include Arthur Samuel's checkers software and Herbert Simon and Allen Newell's good judgment Theorist.

5. Symbolic AI and expert systems (1960s – 1980s): Symbolic AI, additionally known as "proper AI" (GOFAI), dominated AI studies at some point of the 1960s to Eighties. Researchers advanced expert systems, which were rule-based totally systems designed to emulate the hassle-solving skills of human specialists in unique domains.

6. AI wintry weather (1970s-1980s): regardless of preliminary optimism and substantial development in AI studies, the sphere experiences a series of setbacks at some stage in the 1970s and 1980s, called "AI winters." funding cuts, unrealistic expectations, and boundaries of current technologies let to a decline in interest and investment in AI studies.

7. Resurgence of AI (1990s-present): The overdue 20th century saw a resurgence of hobby in AI, fueled via advances in computing electricity, algorithmic strategies, and the provision of huge datasets. gadget getting to know, neural networks, and different subfields of AI experienced rapid growth, leading to breakthroughs in regions consisting of computer imaginative and prescient, herbal language processing, and robotics.

8. modern-day improvement (21st Century): inside the twenty first century, AI has grown to be more and more incorporated into everyday lifestyles, with applications starting from virtual assistants and recommendation systems to autonomous automobiles and healthcare diagnostics. Deep studying, fueled through advances in neural network architectures and hardware accelerators, has performed a important function in lots of recent AI breakthroughs.

Ordinary, the records of AI is characterized by means of intervals of optimism, followed by setbacks and demanding situations. in spite of these united states of American downs, AI continues to advance swiftly, with profound implications for technology, society, and the destiny of humanity.

The idea of attributing the name "Father of AI" to unmarried person is complex and debated within the discipline, because the improvement of Artificial intelligence has concerned the contributions of several researchers and pioneers over many years. But numerous individuals are frequently referred to for his or her foundational contributions and sizable have an effect on on the sector. A number of those first-rate figures consist of:

1. Alan Turning: broadly seemed as one in every of founding fathers of pc science, Turning made pioneering contributions to the theory of computation and artificial intelligence. His well-known Turning test, proposed in 1950, stays a fundamental concept in AI studies for assessing a machine's capability to exhibit sensible behavior indistinguishable from that of a human.

2. John McCarthy: McCarthy is credited with coining the time period "artificial Intelligence" and organizing the Dartmouth convention in 1956, that is taken into consideration the delivery of AI as a discipline of observe. He also advanced the Lisp programming language, which ahs been widely used in AI research.

3. Marvin Minsky: Minsky changed into a key determine inside the early improvement of AI and Co-founding father of the MIT Artificial Intelligence Laboratory. His paintings on neural networks, robotics, and theories of human cognition laid essential foundation for destiny AI research.

4. Herbert Simon and Allen Newell: Simon and Newell were pioneers within the field of AI and made good sized contributions to the improvement of early AI packages, which includes the good judgment Theorist and the general hassle Solver. They introduced the idea of "Symbolic AI" and advanced influential theories of hassle-solving and human cognition.

5. Arthur Samuel: Samuel is thought for developing a number of the earliest self-getting to know applications, specifically in the place of sport gambling AI. His checkers-playing program, developed within the Fifties, verified the feasibility of gadget getting to know and laid the inspiration for future research on this place.

6. Geoffrey Hinton, Yann LeCun, and Yoshua Bengio: frequently called the "Godfathers of Deep mastering," Hinton, LeCun, and Bengio are credited with pioneering breakthroughs in deep neural networks and revitalizing interest in neural network studies. Their paintings has permit to sizeable improvements in regions including laptop vision, herbal language processing, and speech recognition.

Whilst these individuals have made big contributions to the field of Artificial Intelligence, its vital to understand that AI is a multidisciplinary area with contributions from researchers in laptop technological know-how, mathematics, cognitive psychology neuroscience, and other disciplines. The development of AI has been a collaborative attempt involving many minds over a few years.

Objective

The objective of this review is to provide a comprehensive overview to the integration of Artificial Intelligence (AI) into Library and Information Science (LIS). Specifically, the review aims to:

1. Identify the opportunities afforded by AI technologies for enhancing library administration, containing information retrieval, embodied recommendation methods, virtual help, data science of logical analysis, and digital protection.
2. Examine the challenges and drawbacks accompanying AI implementation in LIS, in the way that concerning manipulation of numbers bias, isolation responsibilities, digital classify, cost and resource wants, and moral developments.
3. Explore user perspectives and experiences with AI driven library services, including approval components, end user options, and responsibilities around privations, conclusions status, as well as count on AI Technics.
4. Discuss that progressing duties and expertise's of librarians and advice experts in this AI age, emphasizing the significance of automated articulateness, data administration, and moral conclusion preparing.
5. Highlight event studies and most excellently undertakes reveal profitable models of AI exercise in libraries, giving insights and communication well-informed for library experts.
6. Identify future guidance's and research program for AI in LIS containing the growth of AI possessed forms and aids, survey of virtuous and public associations, evaluation of the impact of AI on library operations and user experiences, and interdisciplinary collaborations to drive innovation in this rapidly evolving field.
7. By accomplishing the goals, which review ambitions to influence a deeper belief of these excuse, challenges, and suggestions of AI in LIS and inform future research, practice, and policy initiatives in this area.

Review of Literature

The impact of artificial intelligence on libraries is essential vicinity for investigation. Its miles crucial to don't forget insights from a selection of research. Presently, AI is broadly mentioned, and its outcomes at the education region are widespread. It is vital to recognize how libraries had been adapting to those changing dynamics. This segment presents a comprehensive review of recent research analyzing the software of synthetic intelligence and device studying and their good sized affect on modern library science and control systems.

To discover if there had been any discussions approximately artificial intelligence (AI) in libraries, Wheatley and Hervieux (2019) completed a take a look at on outstanding studies universities in Canada and America. The reason changed into to discover how libraries could react to this shift and what the librarian's process might be in an AI-dominated destiny. They discovered that even though numerous institutions had been taking element in or beginning their own AI centers, there has been a lack of responsiveness or know-how of the modern-day AI movement. They maintained that the library verified a resistance to change, often delaying the adoption of a new fashion.

Consistent with Osagie & Oladokun's (2024) report, synthetic intelligence (AI) has substantially stepped forward the automation of metadata management and cataloguing, reducing human errors and boosting the performance of operation in libraries. It has also aided inside the maintenance of records, each digital and analogue. This has been made possible by using automated restore methods and real-time tracking, which assure that information are protected from every kind of attacks. additionally, with the aid of leveraging natural language processing and semantic seek abilities, the development of AI-powered search engines like google and yahoo has advanced the relevancy and accuracy of search results, making it simpler for customers to discover the data they require. The record also mentioned several limitations to integrating AI into library systems, together with troubles with information fine, privateers, biases in AI algorithms, and worker reluctance.

Suneetha *et al.* (2024) highlighted the transformative impact of arithmetic and AI on library technology, mainly in facts control. They emphasized the mixing of established mathematical frameworks, just like the vector area version, with advanced natural language processing (NLP) techniques. A key finding was the symbiotic courting among mathematics and AI, suggesting that their convergence can reshape aid management and information retrieval. The look at proposed that those improvements have empowered library buyers to navigate large quantities of knowledge more effectively and efficiently.

Huang *et al.* (2023) examined AI applications in educational libraries inside the United Kingdom and China. They observed that AI was hardly ever stated in UK university strategies; then again, maximum Chinese universities blanketed it suggesting that libraries in China are extra proactive in enforcing AI technology in comparison to the UK. They diagnosed numerous demanding situations along with lack of investment, technical expertise, and ethical worries. They argued that increased strategic engagement with AI by using libraries is needed to beautify offerings while addressing ethical implications.

To explore the perspectives of library specialists on AI in libraries, a observe changed into carried out through Subaveerapandiyan and Gozali (2024) the use of a quantitative survey of 386 professionals throughout educational institutions. They observed that there may be a high consciousness of AI's benefits (e.g., enhancing accessibility, and decision making) among those professionals, however, they had been also worried about AI changing human roles and ethical issues (e.g., bias, privacy). yet, it becomes determined that there may be an increase inside the adoption of AI tools like clever shelving and OCR displaying that specialists recognize AI's capability but emphasize the want for ethical issues and adequate training. The combination of AI in library operations allows for real-time monitoring and automated answers for file upkeep, improving each digital and bodily file control. the following phase presents a detailed dialogue of the findings of this literature overview focusing on how AI and ML are being applied on this area of library science.

Methodology

Literature Search Strategy:

- **Key-word selection:** A comprehensive set of keywords associated with AI in library technological know-how became recognized, along with phrases such as "artificial Intelligence in Libraries," "AI programs in Libraries," "device gaining knowledge of for Library services," and "AI-driven Library systems."
- **Database and search engines:** The literature search changed into performed the use of multiple databases and search Engines to make certain a large coverage of applicable research. Databases covered Google student, IEEE Xplore, Scopus, and library-precise databases consisting of Library and facts technological know-how Abstracts (LISA) and Library Literature & facts technology complete text (LLISFT).

Search process:

- Initial search: using the recognized keywords, searches had been achieved in every database. Boolean operators (AND, OR, not) have been used to refine and narrow down effects.
- Inclusion standards: Articles were protected if they centered on AI packages in library science, have been posted in peer-reviewed journals or reliable conferences, and were written in English and whose full-textual content changed into available.
- Exclusion standards: Articles were excluded if they had been now not immediately associated with AI in library technology, lacked peer evaluate, or have been not available in complete textual content.

Selection and Screening: Titles and abstracts of the search outcomes were reviewed to assess relevance. Articles that met the inclusion criteria had been decided on for complete-textual content evaluate. Decided on articles had been read in detail to make certain they met the standards for inclusion. Key factors along with AI applications, benefits, challenges, and future directions were mentioned.

Secondary search: by the usage of the reference lists of finally decided on papers more relevant studies or assessment papers were decided on and people fulfilling the exclusion and inclusion standards have been covered inside the very last analysis.

Data Extraction and evaluation

Key records turned into extracted from every decided-on article, which include:

- AI technology and strategies mentioned
- Applications and case research in library science
- reported blessings and demanding situations
- Recommendations and future trends

Data Synthesis: Extracted facts had been prepared thematically. The synthesis concerned grouping findings into classes consisting of AI applications (e.g., automation, statistics control) and challenges (e.g., implementation troubles, ethical concerns).

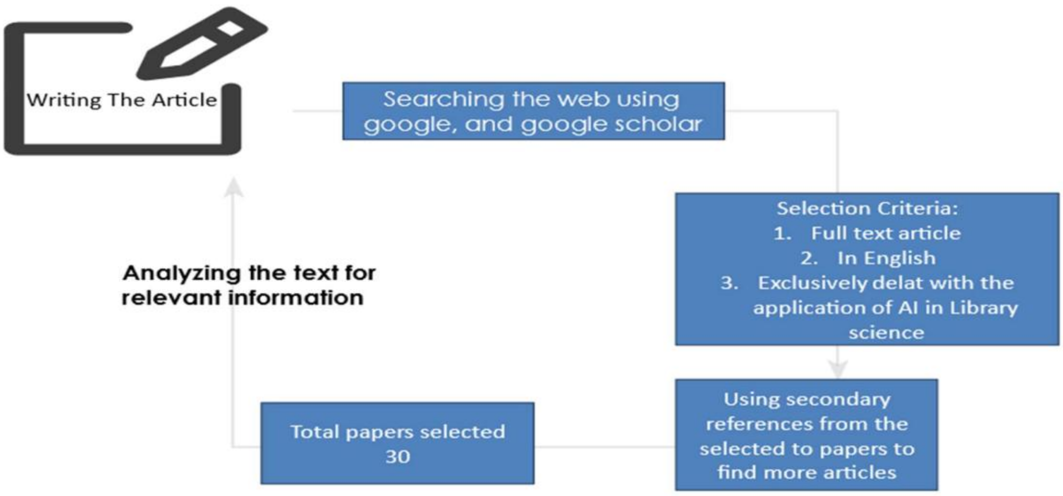

Figure 1: The process of searching research or review papers on the topic of the Application of Artificial Intelligence (AI) in Library Science

Discussion:

The implementation of AI in libraries has extensively impacted the entire library control system. Before delving into the info of ways AI has been included into libraries and its outcomes, it's far critical to understand the workflow of libraries. figure 1 affords a detailed workflow diagram illustrating the operational tactics of a normal library machine. The diagram includes various tiers along with cataloging, move, acquisitions, user offerings, and digital resource management. Each step is interconnected to make certain efficient management and provider transport inside the library. These components are described in short:

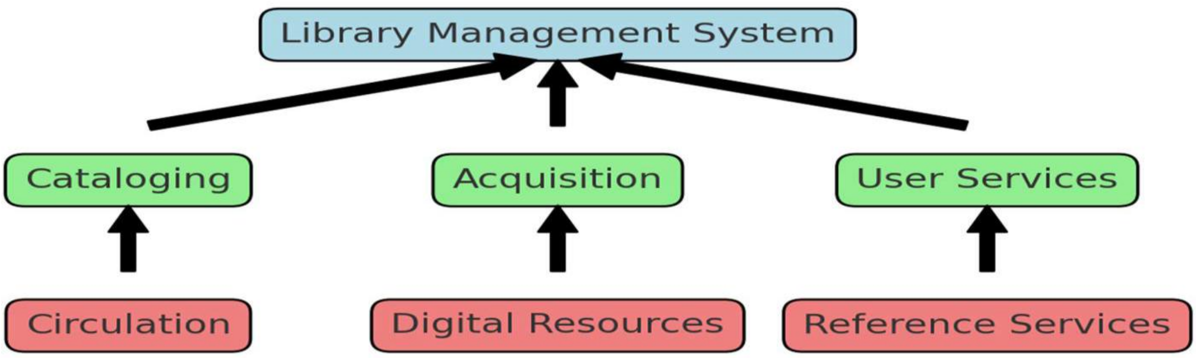

Figure 2: Workflow Diagram of a Library System

1. Cataloging: Involves the classification and indexing of all new library materials. This step is essential for organizing resources and ensuring they are easily retrievable by users.

2. Acquisition: Refers to the process of selecting and purchasing new materials for the library's collection. This includes both physical and digital resources.

3. User Services: Encompasses a range of services provided to library patrons, including assistance with finding resources, using the library's catalogue, and accessing online databases.

4. Circulation: Deals with the borrowing and returning of library materials. It includes managing user accounts, due dates, and fines.

5. Digital Resources: Focuses on managing and providing access to electronic resources such as e-books, online journals, and databases.

6. Reference Services: Offers specialized assistance to patrons in finding and using information, often requiring expert knowledge of the library's resources.

Figure 2 presents an organizational chart of a library. It shows several key sections, each responsible for different aspects of library management and services:

1. Administration and Finance: This section handles the records and files, diary and alacrity, distribution and payment, fund registers, and nurturing of library possessions.

2. Acquisitioning: Associates the draft, commanding, gathering, and provide of new materials. It also includes accessioning and processing bills related to new acquisitions.

3. Technical Processing: Responsible for the classification, cataloging, card filing, and shelving of library materials.

4. Circulation: Manages membership work, the issuing (charging) and returning (discharging) of library materials to patrons.

5. Reference: Deals with the formation of collections and answering queries from library users, providing reference services.

6. Periodicals: Involves the recording of receipts, display, and preparation of volumes for binding, specifically for periodical publications.

7. Maintenance: This section is responsible for the formation of collections, shelving, re-shelving, dusting, cleaning, mending, binding, weeding, and stock verification.

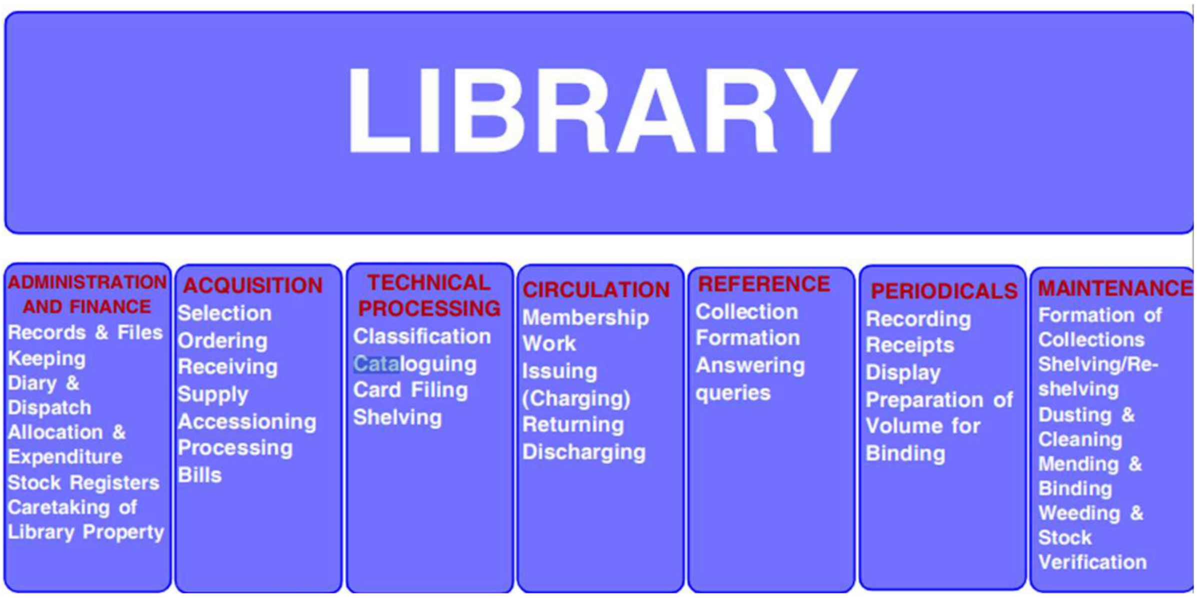

Figure 3: Library organizational chart showing various sections required to carry out whole Library management (National Institute of Open Schooling)

Challenges

Integrating AI with legacy library structures may be complicated. Libraries often have a long time-vintage infrastructure, and retrofitting AI calls for thoughtful making plans. Moreover, library professionals need new talent sets to paintings successfully with AI tools. It's not pretty much understanding Dewey Decimal; it's about knowledge algorithms and data systems. The advent of AI disrupts traditional librarian responsibilities. Librarians are now not simply human engines like google; they turn out to be curators of algorithms. Metadata introduction, as soon as a manual venture, now includes collaboration with AI fashions. Librarians must significantly compare AI-generated metadata and make sure it aligns with library values. Workflow modifications are vital to deal with AI-pushed processes. Librarians become orchestrators, ensuring that AI augments their paintings instead of changing it.

Data privacy and protection: AI structures regularly require get right of entry to large quantities of facts, which includes the personal data of library customers. Making sure that this fact is stored cozy and private is a sizeable undertaking, mainly with policies like GDPR that govern records managing (Forcier *et al.,* 2019).

Bias and fairness: AI algorithms can inherit biases gift in the information they're educated on, leading to unfair or biased outcomes. Inside the context of library technological know-how, this will have an effect on search effects, recommendations, and other AI-driven services, potentially disadvantaging certain user companies (Saeidnia, H2023).

Technical Complexity and Implementation expenses: imposing AI structures calls for vast technical understanding and assets. Libraries, particularly smaller ones with restrained budgets, can also conflict with the price of integrating AI technology, which include the want for ongoing protection and updates (Wójcik, 2021).

Resistance to trade: Library team of workers and users may face up to adopting new AI technologies, especially if they are unfamiliar or uncomfortable with that gear. Overcoming this resistance calls for powerful training and verbal exchange to illustrate the blessings of AI (Li, *et al.,* 2023).

Ethical issues: the use of AI raises moral questions, inclusive of the transparency of AI choice-making procedures, the ability for surveillance, and the impact on employment in libraries. Addressing those concerns is vital to ensuring Accountable AI use. Hodonu-Wusu (2024) recommended that libraries must prioritize privateers, transparency, fairness, and inclusivity of their AI tasks. They must regularly examine AI algorithms for bias and non-stop effort need to be made for user empowerment where AI can beautify personalized suggestions, virtual assistants, and records analytics to enhance consumer stories.

Integration with existing structures: Many libraries nevertheless rely upon outdated legacy systems for cataloging, category, and person control. The combination of AI with these current systems poses technical challenges and might require substantial modifications. Research carried out with the aid of Ajani (2022) revealed that though librarians believed that the mixing of AI has the capacity to decorate library functions by means of reducing human errors, there have been apprehensions regarding the opportunity of AI finally replacing their roles. The examiner brings to light various boundaries faced via educational libraries in Nigeria, such as investment problems, a loss of experts, unreliable electricity supply, restricted budgets for technology acquisition, and the need for educated employees to control these structures. It recommends that libraries secure good enough funding for making an investment in AI and different records and communiqué technology, as well as recruiting librarians prepared with the vital talents to successfully oversee these technologies.

Schooling and skill development: Library group of workers want to gain knowledge of to efficiently use and control AI tools. This requires ongoing schooling and expert improvement, which may be resource-intensive. Inside the look at by means of Andersdotter (2023), many librarian participants expressed demanding situations in incorporating AI into their coaching of information literacy to customers, which shows that there may be a need to expand a program imparting AI talents as a part of their facts literacy (IL) training.

Future Directions

- **Personalized discovery:** AI can recommend books based on individual preferences, reading history, and context.
- **Adaptive classification schemes:** Imagine a dynamic system that adjusts classification rules based on emerging topics or societal shifts.
- **Predictive collection development:** AI can forecast which books will be in demand, optimizing library budgets and acquisitions.

Conclusion:

The integration of artificial Intelligence (AI) into Library and statistics technology (LIS) gives substantial ability to revolutionize library offerings, enhance person experiences, and enhance information access and control. Trough this evaluate of the literature, several key conclusions may be drawn:

1. Opportunities for Innovation: AI technologies gift opportunities for innovation in numerous aspects of library services, such as information retrieval, personalized recommendation structures, digital assistance, facts analytics, and digital maintenance. Libraries can leverage AI to streamline operations, increase efficiency, and higher meet the needs of their customers.

2. Challenges and ethical considerations: in spite of the ability advantages of AI, there are massive challenges and ethical considerations that need to be addressed. Those consist of algorithmic bias, privacy issues, digital divide, price and resource necessities, and moral dilemmas surrounding AI use in libraries. Its miles vital for libraries to carefully recollect those challenges and undertake accountable AI practices to mitigate capability risks.

3. Consumer Centric approach: expertise consumer perspectives and stories with AI-driven library services are crucial for successful implementation. Libraries have to prioritize person desires and alternatives, ensuring that AI technologies beautify in preference to detract from the user revel in. Transparency, consumer accepts as true with, and records privacy ought to be prioritized to construct self assurance in AI pushed library services.

4. Expert development and Collaboration: the integration of AI into LIS necessitates the development of new talents and capabilities among librarians and records specialists. digital literacy, facts management, and moral decision-making are vital competencies for navigating the AI panorama. Collaboration with AI specialists, researchers, and stakeholders is also vital for leveraging AI technology efficiently in libraries.

5. Future directions: looking in advance, there are various possibilities for similarly research and innovation in AI and LIS. Future studies should awareness on addressing the identified challenges, exploring ethical and social implications, comparing the impact of AI on library operations and user experiences, and advancing interdisciplinary collaborations to force innovation in this hastily evolving discipline.

6. Summary of Findings: Recap the primary findings from the substances and techniques sections, emphasizing the effect of AI on library services.

7. Implications for practice: discuss sensible implications for librarians, policymakers, and different stakeholders based totally on the study's findings.

8. Future directions: endorse areas for future studies and development inside the discipline of AI-enabled library services.

In conclusion, AI preserves extraordinary promise for transforming libraries into more efficient, responsive, and inclusive establishments. Via embracing responsible AI practices, libraries can harness the power of AI to higher serve their customers and fulfill their mission of supplying get entry to information and expertise for all. It's far important for libraries to remain vigilant, proactive, and ethically mindful as they navigate the evolving panorama of AI in LIS.

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A CONCEPTUAL FRAMEWORK FOR DISEASE PROGRESSION MODELING USING MARKOV CHAINS

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Abstract:

Disease progression is characterized by inherent uncertainty, variability, and complex transitions between health states over time. Traditional deterministic models often fall short in capturing the stochastic nature of disease evolution, particularly in chronic and long-term conditions. Probabilistic modeling approaches offer a more flexible and realistic framework for understanding disease dynamics, with Markov chain models gaining significant attention due to their ability to represent state-based transitions governed by probability structures. This paper presents a conceptual framework for modeling disease progression using discrete-time Markov chains. The proposed framework systematically defines health states, transition mechanisms, and time-dependent evolution of disease conditions under the Markovian assumption. Rather than relying on specific datasets, the study focuses on developing a generalized methodological structure adaptable to various diseases and healthcare scenarios. The framework demonstrates how disease stages can be represented as stochastic states and how transition probabilities can describe the likelihood of progression, stability, or improvement over time. Its strength lies in its simplicity, interpretability, and adaptability, providing a foundation for researchers to integrate real-world clinical data, risk factors, or covariates in future extensions. This conceptual approach serves as a valuable methodological reference for researchers in healthcare analytics, disease modeling, and applied stochastic processes. Additionally, the framework offers potential support for decision-making and policy planning by enabling systematic analysis of disease progression patterns. By providing a flexible and robust structure for modeling disease dynamics, this work contributes to the advancement of probabilistic approaches in healthcare research and planning.

Keywords: Markov Chains, Disease Progression, Stochastic Modeling, Healthcare Analytics, Conceptual Framework

1. Introduction:

Disease progression modeling plays a crucial role in understanding the temporal evolution of health conditions and supporting clinical and policy-related decision-making. Many diseases, particularly chronic and long-term conditions, progress through multiple stages over time and are influenced by uncertainty, patient heterogeneity, and varying treatment responses. Traditional deterministic models often fail to capture such complexity, motivating the use of probabilistic and stochastic modeling approaches in healthcare research (Sonnenberg and Beck, 1993; Briggs *et al.,* 2006). Among stochastic approaches, Markov and multi-state models have been widely adopted to represent disease evolution as transitions between discrete health states over time. In these models, each state corresponds to a clinically meaningful stage of disease, and transitions between states are governed by probabilities. The Markovian assumption, which states that future disease status depends only on the current state, provides a mathematically tractable and interpretable framework for analyzing disease progression processes (Norris, 1997; Puterman, 1994). Multi-state modeling frameworks have been extensively studied in epidemiology and medical statistics as effective tools for analyzing event history data and disease progression pathways. Early foundational work established the theoretical basis for multi-state and competing-risk models and demonstrated their applicability in medical and epidemiological studies (Commenges, 1999; Hougaard, 1999; Putter *et al.,* 2006). These models enable systematic analysis of transitions between disease states and allow researchers to study long-term outcomes such as progression, recovery, or survival.

In recent years, methodological advancements have further expanded the applicability of disease progression models. Joint modeling and latent class approaches have been introduced to simultaneously analyze longitudinal measurements and time-to-event outcomes, providing deeper insight into unobserved disease heterogeneity and progression dynamics (Proust-Lima *et al.,* 2012; Proust-Lima *et al.,* 2017). Such extensions enhance the flexibility of traditional state-transition models while maintaining their interpretability. In parallel, modern healthcare analytics has increasingly emphasized precision, risk stratification, and individualized outcome prediction. Recent studies have demonstrated that advanced statistical and machine learning–based methods can complement traditional probabilistic frameworks by improving prognostic accuracy and supporting risk-based decision-making in clinical settings (Alaa and van der Schaar, 2018; Benkeser *et al.,* 2020). However, despite these advancements, there remains a strong need for generalized conceptual frameworks that clearly define model structure and assumptions before incorporating complex data-driven techniques.

Motivated by these developments, the present study focuses on a conceptual framework for disease progression modeling using Markov chains and multi-state modeling principles. Rather than relying on disease-specific datasets, this work emphasizes methodological clarity by outlining the key components of disease progression models, including state definition, transition mechanisms, and temporal structure. Such a conceptual approach provides a flexible foundation for future empirical studies, simulation-based analysis, and methodological extensions in healthcare analytics (Andersen and Keiding, 2002; van Houwelingen and Putter, 2011).

2. Literature Review

Mathematical and statistical models have long been employed to study disease progression and health-related outcomes. Early research emphasized probabilistic modeling as an effective approach for capturing uncertainty and variability in disease evolution. Among these approaches, Markov and multi-state models emerged as foundational tools for representing disease processes as transitions between discrete health states over time. One of the earliest applications of Markov models in healthcare demonstrated their usefulness in medical decision-making by providing a structured framework for evaluating long-term disease outcomes and treatment strategies (Sonnenberg and Beck, 1993). The theoretical foundations of Markov chains and stochastic processes have been well established in the literature. Norris (1997) provided a comprehensive treatment of Markov chains, highlighting their mathematical properties and long-term behavior. Building on these principles, Puterman (1994) introduced Markov decision processes, which extended classical Markov models to decision-making contexts. These foundational works laid-out the groundwork for applying state-transition models in healthcare, where disease progression is naturally represented through sequential health states.

Multi-state models have been extensively studied in epidemiology and survival analysis as a generalization of traditional Markov frameworks. Commenges (1999) and Hougaard (1999) presented early reviews of multi-state models, emphasizing their relevance for analyzing disease progression and event history data. These studies highlighted how individuals may move through multiple intermediate disease states rather than following a single progression pathway. Such models enable the analysis of complex disease trajectories, including progression, recovery, and competing risks.

Further methodological advancements were introduced through competing-risk and multi-state modeling frameworks. Putter *et al.* (2006) provided a detailed tutorial on competing risks and multi-state models, demonstrating their applicability in medical research and survival analysis. These approaches allow for more realistic representation of disease progression by accounting for multiple possible events and transitions, which is particularly important in chronic and long-term diseases.

Recent developments in disease progression modeling have focused on joint modeling and latent class approaches. Proust-Lima *et al.* (2012) reviewed joint latent class models that simultaneously analyze longitudinal measurements and time-to-event data, offering deeper insight into unobserved heterogeneity in disease progression. Extensions of these ideas were further developed through latent process and mixed modeling frameworks, enabling flexible modeling of complex disease dynamics (Proust-Lima *et al.,* 2017). These methodologies enhance traditional state-transition models by incorporating individual-level variability while preserving interpretability.

In addition to methodological advances, modern healthcare analytics has increasingly emphasized precision and risk-based modeling. Alaa and van der Schaar (2018) demonstrated how automated machine learning techniques can be used for prognostication and risk factor identification in clinical settings, illustrating the growing role of advanced analytics in healthcare research. Similarly, Benkeser *et al.* (2020) highlighted the importance of covariate adjustment and precision improvement in clinical trials, reinforcing the need for robust statistical frameworks in disease outcome analysis. Dynamic prediction has also gained attention as an important component of disease progression analysis. van Houwelingen and Putter (2011) discussed dynamic prediction methods in clinical survival analysis, showing how patient risk profiles can be updated over time as new information becomes available. Such approaches complement traditional Markov and multi-state models by enabling time-updated predictions of disease outcomes.

Overall, the existing literature demonstrates a clear evolution from classical Markov chain models to advanced multi-state, joint, and dynamic modeling frameworks for disease progression analysis. While early studies established the theoretical and practical foundations, recent research has focused on improving flexibility, precision, and interpretability. This progression highlights the importance of developing clear conceptual frameworks that integrate established stochastic modeling principles with modern healthcare analytics, forming the basis for the present study.

3. Basics of Markov Chain Model

Markov chain models belong to a class of stochastic processes that describe systems evolving randomly over time through a set of discrete states. These models are particularly suitable for situations where the system dynamics are governed by probabilistic transitions rather than deterministic rules. In healthcare and disease modeling, Markov chains provide a natural framework for representing disease progression, where patients may move between different health states over time under uncertainty (Sonnenberg and Beck, 1993).

3.1 Markov Property

The defining characteristic of a Markov chain is the Markov property, which states that the future state of a system depends only on its current state and not on the sequence of states that preceded it. This memoryless assumption simplifies the modeling of complex temporal processes and allows for tractable mathematical analysis. Despite its simplicity, the Markov property has been shown to be effective in many medical and epidemiological applications, where the current disease status often captures the most relevant information for predicting future outcomes (Norris, 1997).

3.2 States and State Space

In a Markov chain model, the system occupies one state at each time point. The collection of all possible states is known as state space. In disease progression modeling, states typically represent clinically meaningful stages of disease, such as early, intermediate, or advanced conditions, recovery, or death. Careful definition of state space is essential, as it directly influences model interpretability and analytical validity. Multi-state representations allow disease progression to be described more realistically by accounting for intermediate stages rather than assuming a single transition (Commenges, 1999; Hougaard, 1999).

3.3 Transition Mechanism

Transitions describe the movement of the system from one state to another over a specified time interval. In discrete-time Markov chains, transitions occur at fixed and equally spaced time points, such as months or years. Each transition is governed by a probability that reflects the likelihood of moving between states during one-time step. These transition probabilities capture the inherent uncertainty in disease progression and form the basis for long-term analysis of disease dynamics (Norris, 1997).

3.4 Transition Probability Matrix

The transition probabilities of a Markov chain are summarized in a transition probability matrix, where each element represents the probability of moving from one state to another within a single time interval. The rows of this matrix correspond to the current state, while the columns represent the next state. The probabilities in each row sum to one. This matrix-based representation provides a compact and interpretable description of disease dynamics and enables simulation and long-term projection of disease progression patterns (Puterman, 1994).

3.5 Long-Term Behavior and Interpretation

An important advantage of Markov chain models is their ability to analyze long-term system behavior through repeated transitions over time. By iteratively applying the transition probability matrix, researchers can study expected time spent in each disease state, progression pathways, and eventual outcomes. Such analyses are particularly valuable in chronic disease research and health planning, where long-term disease evolution is of primary interest (Sonnenberg and Beck, 1993).

Overall, Markov chain models provide a simple yet powerful foundation for modeling disease progression under uncertainty. Their conceptual clarity, combined with strong theoretical support from stochastic process theory and multi-state modeling, makes them an essential tool in healthcare analytics. These properties form the basis for extending Markov chains to more advanced multi-state, joint, and dynamic modeling frameworks discussed in subsequent sections (Puterman, 1994; Commenges, 1999).

4. Disease Progression Modeling Using Markov Chains

Disease progression modeling aims to describe how an individual's health status evolves over time through different stages of a disease. Many diseases, particularly chronic and degenerative conditions, exhibit complex progression patterns characterized by uncertainty, heterogeneity, and multiple possible outcomes. As a result, probabilistic modeling approaches have been widely adopted to capture the stochastic nature of disease evolution. Markov chain models provide a natural and effective framework for representing disease progression as transitions between discrete health states over time (Sonnenberg and Beck, 1993).

In a Markov-based disease progression model, the course of a disease is represented by a finite set of health states, each corresponding to a clinically or conceptually meaningful stage of disease. At each time point, an individual is assumed to occupy exactly one state, and transitions between states occur probabilistically at discrete time intervals. This state-transition structure allows disease dynamics to be analyzed systematically and provides a clear interpretation of progression, stability, recovery, or adverse outcomes (Norris, 1997). The state-based representation of disease progression is visually summarized in Figure 1.

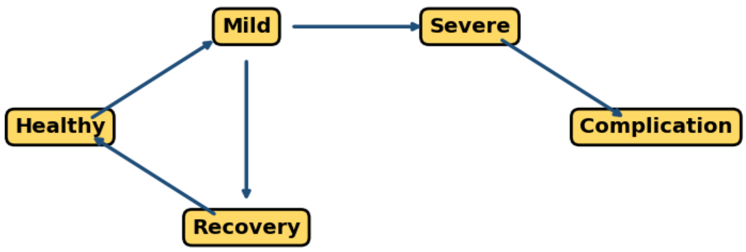

Figure 1: Disease progression state-transition diagram using a Markov model

Figure 1 illustrates a conceptual state-transition diagram for disease progression modeled using a Markov framework. The diagram represents discrete health states, namely Healthy, Mild, Severe, Recovery, and Complication, with directed arrows indicating possible transitions over time. Such state-based representations are commonly used to describe disease evolution as probabilistic transitions between health states occurring at discrete time intervals (Sonnenberg and Beck, 1993; Norris, 1997). The inclusion of both progression and recovery pathways reflects the stochastic and dynamic nature of disease processes within a Markov modeling framework (Puterman, 1994).

Multi-state modeling frameworks extend classical Markov chains by allowing individuals to move through multiple intermediate disease states rather than following a single irreversible pathway. Such models are particularly useful for capturing realistic disease trajectories involving relapse, recovery, or competing outcomes. Early methodological studies demonstrated the relevance of multi-state models for analyzing disease progression and event history data in medical research (Commenges, 1999; Hougaard, 1999). These approaches enable detailed investigation of disease pathways while maintaining mathematical tractability.

The transition probabilities governing movement between disease states play a central role in Markov-based progression models. These probabilities quantify the likelihood of disease progression or improvement over a given time interval and summarize the uncertainty inherent in disease evolution. By organizing these probabilities into a transition probability matrix, researchers can simulate disease trajectories and study long-term behavior such as expected time spent in each state or the probability of reaching severe disease stages (Puterman, 1994).

Disease progression models based on Markov chains have been widely applied in medical decision-making and health economics. Such models allow researchers to evaluate long-term disease outcomes and compare alternative intervention strategies in a structured manner. Sonnenberg and Beck (1993) demonstrated how Markov models can support medical decision analysis by providing a transparent framework for evaluating disease outcomes under uncertainty. These applications highlight the practical relevance of Markov-based disease progression models in healthcare research.

Recent methodological developments have further expanded the scope of disease progression modeling. Joint modeling and latent class approaches have been introduced to capture unobserved heterogeneity and complex longitudinal disease dynamics. These methods allow simultaneous analysis of longitudinal disease measurements and time-to-event outcomes, offering a more comprehensive representation of disease progression processes (Proust-Lima *et al.,* 2012; Proust-Lima *et al.,* 2017). Such extensions complement traditional Markov frameworks while preserving their interpretability.

Overall, disease progression modeling using Markov chains and multi-state frameworks provides a flexible and conceptually clear approach for analyzing complex disease dynamics. By representing disease evolution as probabilistic transitions between discrete states, these models enable systematic analysis of progression patterns and long-term outcomes. This methodological foundation supports the development of generalized conceptual frameworks for disease progression modeling, as discussed in the subsequent section.

5. Proposed Conceptual Framework

Conceptual frameworks play a vital role in methodological research by providing a structured and transparent approach for model development. In the context of disease progression analysis, a well-defined framework helps clarify model assumptions, define system components, and guide future extensions. Rather than focusing on disease-specific data, conceptual frameworks emphasize general modeling principles that can be adapted across different healthcare contexts (Sonnenberg and Beck, 1993; Briggs *et al.,* 2006).

The proposed framework in this study models disease progression as a stochastic state-transition process using Markov chains and multi-state modeling principles. This choice is motivated by the ability of Markov-based approaches to represent uncertainty and temporal dynamics through probabilistic transitions between discrete health states. The framework is designed to remain flexible and interpretable while providing a systematic structure for disease progression analysis (Norris, 1997; Puterman, 1994).

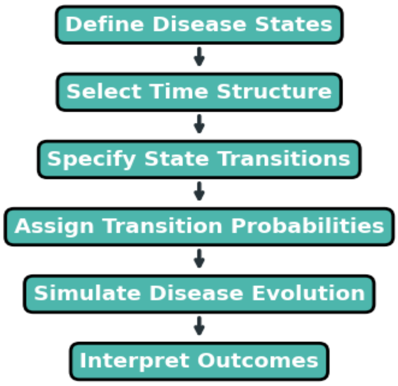

Figure 2: Conceptual framework for disease progression modeling using Markov chains

Figure 2 presents the proposed conceptual framework for disease progression modeling using Markov chains. The framework outlines a systematic sequence beginning with the definition of disease states and the selection of an appropriate time structure, followed by the specification of state transitions and assignment of transition probabilities. This structured approach aligns with established principles of multi-state and Markov-based disease modeling, where disease evolution is represented through a sequence of probabilistic transitions over time (Commenges, 1999; Hougaard, 1999). The final steps involving simulation and interpretation of outcomes support qualitative assessment of long-term disease dynamics within a state-transition framework (Briggs *et al.,* 2006).

5.1 Definition of Disease States

The first component of the framework involves identifying a finite set of disease states that represent meaningful stages of disease progression. These states may correspond to clinical severity levels, functional conditions, or health outcomes such as recovery or complication. Proper state definition is essential for ensuring interpretability and analytical validity. Multi-state representations allow intermediate disease stages to be incorporated, providing a more realistic description of disease evolution (Commenges, 1999; Hougaard, 1999).

5.2 Temporal Structure

The second component specifies the temporal structure of the model. Disease progression is assumed to occur over discrete and equally spaced time intervals, such as months or years. This discrete-time formulation simplifies analysis and enables the use of transition probability matrices to study disease evolution over extended periods. Discrete-time Markov models are widely used in healthcare research due to their conceptual clarity and practical applicability (Puterman, 1994).

5.3 Specification of State Transitions

Once the disease states and time structure are defined, the framework specifies the allowable transitions between states. These transitions represent possible changes in disease status over one time interval, including progression, stability, or improvement. Logical or clinical constraints may be imposed to restrict unrealistic transitions. Such structured transition specification enhances model realism and supports meaningful interpretation of disease pathways (Commenges, 1999).

5.4 Transition Probabilities

Transition probabilities quantify the likelihood of moving from one disease state to another within a single time step. In the proposed framework, these probabilities are treated as conceptual parameters rather than empirically estimated values. This abstraction allows the framework to remain independent of specific datasets while providing a foundation for future data-driven estimation or simulation studies. The transition probability matrix serves as a central component for analyzing long-term disease behavior (Sonnenberg and Beck, 1993; Puterman, 1994).

5.5 Disease Evolution and Interpretation

By repeatedly applying the transition probability matrix, the framework describes disease evolution over multiple time intervals. This iterative process enables qualitative assessment of progression patterns, such as persistence in certain states or movement toward advanced disease stages. Such analysis is particularly useful for understanding long-term disease dynamics and evaluating potential intervention strategies within a conceptual modeling setting (Briggs *et al.,* 2006).

5.6 Extensions and Adaptability

A key strength of the proposed conceptual framework is its adaptability. The framework can be extended to incorporate additional modeling components, such as longitudinal measurements, latent disease states, or joint modeling approaches, when more detailed data become available. Joint and latent class modeling frameworks have been shown to enhance disease progression analysis by capturing unobserved heterogeneity and complex temporal dynamics (Proust-Lima *et al.,* 2012; Proust-Lima *et al.,* 2017). These extensions can be integrated while preserving the core Markov-based structure of the framework.

Overall, the proposed conceptual framework provides a clear and systematic approach for disease progression modeling using Markov chains and multi-state principles. By emphasizing methodological structure and flexibility, the framework serves as a foundation for future empirical studies, simulation-based analyses, and advanced methodological developments in healthcare analytics.

6. Advantages and Applications

The proposed conceptual framework for disease progression modeling using Markov chains offers several methodological advantages. One of the primary strengths of the framework is its simplicity and interpretability. By representing disease evolution through discrete health states and probabilistic transitions, the framework provides a transparent structure that is easy to understand and communicate. This clarity is particularly valuable in healthcare research, where models are often used to support decision-making and policy analysis. Another important advantage of the framework is its flexibility. Since the framework is conceptual and not restricted to a specific disease or dataset, it can be adapted to a wide range of healthcare contexts. The number of disease states, transition pathways, and time intervals can be modified based on the characteristics of the disease under study. This adaptability allows the framework to be applied across different clinical and epidemiological settings.

The framework also supports long-term disease analysis. By iteratively applying state transitions over multiple time periods, it enables qualitative assessment of disease trajectories, such as persistence in certain states or progression toward severe outcomes. This feature is particularly useful for studying chronic diseases, where understanding long-term progression patterns is essential.

In terms of applications, the proposed framework can serve as a foundation for simulation studies, methodological research, and educational purposes. It can also be extended to empirical studies when suitable data becomes available, supporting applications in epidemiology, health economics, and clinical outcome analysis. Furthermore, the framework provides a structured basis for incorporating advanced modeling extensions, such as latent state or joint modeling approaches, while maintaining conceptual clarity.

7. Limitations

Despite its advantages, the proposed conceptual framework has certain limitations. First, the framework is based on the Markov assumption, which implies that future disease states depend only on the current state and not on the full history of disease progression. In real-world healthcare settings, disease evolution may be influenced by long-term history, treatment effects, or cumulative risk factors that are not explicitly captured under this assumption. Second, the framework is conceptual in nature and does not involve empirical estimation of transition probabilities. As a result, it does not provide quantitative predictions or direct validation against real-world data. While this abstraction is appropriate for methodological development, practical implementation would require reliable data and rigorous model calibration.

Another limitation is the assumption of discrete and fixed time intervals. Disease progression in clinical practice may occur continuously or at irregular time points, which may not be fully represented within a discrete-time modeling framework. Although discrete-time models offer simplicity and interpretability, certain applications may require more advanced modeling structures to capture continuous disease dynamics. These limitations indicate that the proposed framework should be viewed as a foundational methodological structure rather than a complete predictive model.

Conclusion and Future Scope:

This study presented a conceptual framework for disease progression modeling using Markov chains and multi-state principles. By modeling disease evolution as a stochastic state-transition process, the framework provides a clear and flexible approach for analyzing disease dynamics under uncertainty. The emphasis on methodological structure rather than disease-specific data enhances the generality and adaptability of the framework.

The proposed framework highlights key components of disease progression modeling, including state definition, transition mechanisms, and temporal structure. Its conceptual nature makes it suitable for early-stage research, simulation-based analysis, and methodological exploration. At the same time, the framework provides a strong foundation for future empirical applications when appropriate data become available.

Future research may extend the framework by incorporating real-world clinical or observational data to estimate transition probabilities and validate model assumptions. Additional enhancements may include the integration of longitudinal measurements, latent disease states, or joint modeling approaches to capture unobserved heterogeneity and complex disease dynamics. Such extensions have the potential to improve the applicability of disease progression models in healthcare analytics, clinical decision support, and policy planning. Overall, the proposed conceptual framework contributes to the methodological understanding of disease progression modeling and offers a structured pathway for future research in stochastic modeling and healthcare analytics.

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A BAYESIAN COMPUTATIONAL FRAMEWORK FOR INTERPRETING DISCORDANT SEROLOGICAL AND HEMATOLOGICAL MARKERS IN SUSPECTED TYPHOID FEVER: A SINGLE-SUBJECT DIAGNOSTIC ANALYSIS

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Abstract:

Background: The diagnosis of enteric fever in endemic regions is often confounded by the poor specificity of serological tests and the non-specific nature of clinical symptoms, leading to the overuse of antibiotics and the rise of antimicrobial resistance. This is particularly problematic when serological results are positive, but hematological markers of inflammation are absent.

Objective: To develop and apply a computational Bayesian framework, to a single subject case to quantitatively interpret the discordant diagnostic data and also model the posterior probability of an active infection.

Methods: A 25-year-old male presented with positive Typhidot IgM and IgG serology but displayed a hematologically silent profile with a normal Total Leukocyte Count (TLC) of 5.5 x $10^3/\mu L$ and a normal Erythrocyte Sedimentation Rate (ESR) of 10 mm/hr. A sequential Bayesian update algorithm was implemented in Python to calculate the post-test probability of active typhoid fever. The model integrated the subject's serology with the computationally derived Neutrophil-to-Lymphocyte Ratio (NLR) and standard inflammatory markers (TLC, ESR), using parameters derived from existing literature on test sensitivity and specificity.

Results: The initial clinical suspicion (prior probability) of 30% increased to 49% following the positive Typhidot result. The subject's NLR of 1.4, a signature consistent with intracellular pathogens, provided the strongest evidence, elevating the probability to 77%. However, the normal ESR, indicating a lack of systemic inflammation, significantly reduced this probability to a final posterior probability of 55%.

Conclusion: The Bayesian framework successfully quantified the diagnostic uncertainty, placing the patient in a "diagnostic grey zone." The model demonstrates that despite a positive serological test, the integration of computational biomarkers like NLR and traditional inflammatory markers can temper diagnostic conclusions. This framework provides a mathematical basis for clinical decision-making, potentially improving antibiotic stewardship by identifying patients for whom a "watchful waiting" approach may be justified.

Keywords: Typhoid Fever, Computational Diagnostics, Bayesian Belief Network, Neutrophil-to-Lymphocyte Ratio (NLR), Diagnostic Uncertainty, Antimicrobial Stewardship.

Introduction:

Enteric fever, caused by *Salmonella enterica* serovar Typhi, remains a significant public health burden in South Asia, particularly in Pakistan, which has faced a severe outbreak of extensively drug-resistant (XDR) strains [1]. The cornerstone of managing this disease is a prompt and accurate diagnosis to guide appropriate antimicrobial therapy [2]. However, the diagnostic landscape is fraught with challenges. The gold standard, blood culture, suffers from low sensitivity (40-60%) and is slow and expensive, making it impractical in many primary care settings [3].

This has led to a heavy reliance on serological assays like the Widal test and the Typhidot rapid immunoassay [4]. While sensitive, these tests, particularly in endemic regions, are plagued by low specificity [5]. Persistent IgG antibodies from previous infections and cross-reactivity with other pathogens frequently lead to false-positive results, contributing to diagnostic ambiguity. This ambiguity often results in the presumptive and excessive use of antibiotics, which is a primary driver of the very antimicrobial resistance that complicates treatment [6].

A critical diagnostic dilemma arises when a patient, like the subject of this study, presents with positive serology but lacks the classic hematological signs of a bacterial infection, such as leukopenia or an elevated Erythrocyte Sedimentation Rate (ESR) [7]. This paper proposes a computational approach to resolve such ambiguity. We introduce a Bayesian computational framework to interpret these discordant markers in a single-subject case, moving beyond a binary "positive/negative" interpretation to a more nuanced, probabilistic understanding of the diagnosis.

Materials and Methods

1. Case Presentation

The subject is a 25-year-old male from the Gujrat district of Pakistan. A routine laboratory workup for suspected fever yielded the following key results:

- Serology: Typhidot IgM - Positive; Typhidot IgG - Positive.
- Hematology: Total Leukocyte Count (TLC) - 5.5 x $10^3/\mu L$ (Normal: 4.0-11.0); Erythrocyte Sedimentation Rate (ESR) - 10 mm/1st hr (Normal: <15).
- Differential Count: Neutrophils - 56%; Lymphocytes - 40%.

2. The Bayesian Framework

We modeled the post-test probability of disease using Bayes' theorem, which updates the probability of a hypothesis as more evidence becomes available. The probability is updated sequentially using the likelihood ratio (LR) of each test result. The prior odds of disease are multiplied by the LR of a test to calculate the posterior odds:

Posterior Odds = Prior Odds × Likelihood Ratio

3. Parameter Estimation and Computational Implementation

The model was implemented using the Python programming language with the Pandas library for data management. Parameters were estimated from peer-reviewed literature relevant to the South Asian population.

- **Prior Probability:** A pre-test probability of 30% was assigned, representing a standard level of clinical suspicion for a febrile patient in a typhoid-endemic region.
- **Typhidot (IgM Positive):** Based on regional studies, the model used a sensitivity of 90% and a low specificity of 60% to account for high false-positive rates. This yields a Likelihood Ratio Positive (LR+) of 2.25.
- **Neutrophil-to-Lymphocyte Ratio (NLR):** The subject's NLR was calculated as 1.4 (56/40). An NLR < 2.0 is characteristic of intracellular infections like typhoid, distinguishing it from pyogenic bacterial infections where NLR is often > 6. A Likelihood Ratio of 3.8 was assigned to this finding based on established cutoff values in similar studies.
- **Inflammatory Markers:** A normal TLC and a normal ESR are inconsistent with severe acute inflammation. A conservative negative Likelihood Ratio (LR-) of 0.9 and 0.4, respectively, were assigned to these findings, indicating they reduce the probability of an active, severe inflammatory state

Results:

The sequential application of the Bayesian framework yielded a clear diagnostic trajectory, visualized in Figure 1.

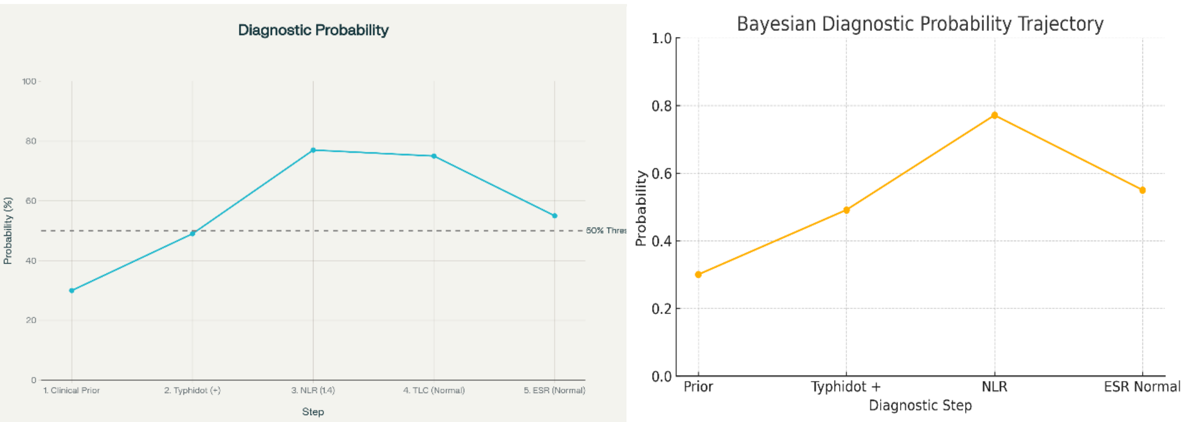

Figure 1: Bayesian Diagnostic Probability Trajectory for the Subject

Bayesian Diagnostic Probability Trajectory for Patient Faheem

The model began with a prior probability of 30%. The positive Typhidot result increased the probability to 49.1%. The NLR of 1.4 provided the most significant evidence in favor of the diagnosis, elevating the probability to 77.1%. Finally, the hematologically silent profile (Normal TLC and ESR) acted as contrary evidence, reducing the final posterior probability to 55.0%.

Table 1: Hematological Profile and Computational Interpretation

Marker	Patient Value	Normal Reference Range	Status	Computational Interpretation (Likelihood)
TLC (Total Leukocyte Count)	5.5x 10^3/µL	4.0 - 11.0 x 10^3/µL	Normal	Negative Predictor: Absence of leukopenia (low white cell count) slightly reduces probability of severe/classic Typhoid.
Neutrophils	56.0%	40.0 - 70.0%	Normal	Neutral: Within normal limits; does not indicate acute bacterial sepsis (which typically shows >70%).
Lymphocytes	40.0%	20.0 - 40.0%	High-Normal	Positive Signal: Relatively high lymphocyte count is consistent with viral or intracellular bacterial infections (likeS. Typhi).
NLR (Neutrophil-to-Lymphocyte Ratio)	1.4	1.5 - 3.0 (Healthy) >6.0 (Sepsis)	Low	Strong Positive Predictor: An NLR < 2.0 strongly favors intracellular pathogens (Salmonellaor Viral) over pyogenic bacteria.
Hemoglobin (Hb)	14.0g/dL	12.0 - 16.0 g/dL	Normal	Negative Predictor: No anemia detected. Chronic or severe Typhoid often causes anemia due to bone marrow suppression.
ESR (Erythrocyte Sedimentation Rate)	10mm/1st hr	05 - 10 mm/1st hr	Normal	Strong Negative Predictor: Normal ESR argues against active, acute systemic inflammation, suggesting mild infection or recovery.

Discussion:

This study demonstrates the power of a computational Bayesian framework to navigate diagnostic uncertainty in real-world clinical scenarios [8-10]. The final probability of 55% places the patient in a "diagnostic grey zone," a finding with profound clinical implications.

The most significant contribution of the model is its formal integration of the Neutrophil-to-Lymphocyte Ratio (NLR). While individual neutrophil and lymphocyte counts were within normal limits, the computationally derived ratio of 1.4 provided a powerful bio-signature [11-12]. This low NLR is characteristic of the immune response to intracellular pathogens, which aligns with *S. Typhi*'s biology, thereby correctly increasing the model's confidence.

Conversely, the normal ESR, a strong negative predictor for systemic inflammation, correctly tempered the conclusion. A clinician might dismiss this, but the algorithm mathematically demonstrates its importance, preventing a premature conclusion. The final 55% probability does not rule out typhoid; rather, it suggests a clinical state that is not one of acute, severe infection. This could represent:

1. An early, uncomplicated infection before the peak inflammatory response.
2. A post-convalescent state, with waning inflammation but persistent antibodies.
3. A serological false positive, where the NLR value coincidentally mimics a typhoid-like state.

This work highlights a path toward enhanced antibiotic stewardship. By providing a quantitative risk score rather than a simple positive/negative result, clinicians are better equipped to justify a "watchful waiting" approach for patients in this grey zone, potentially avoiding unnecessary antibiotic use.

The primary limitation of this study is its nature as a single-subject analysis (N=1), which means its findings are illustrative, not generalizable. The accuracy of the model is also contingent on the quality of the literature-derived parameters, which can vary between populations.

Future work should involve validating this framework on a large, prospective cohort of febrile patients with blood culture results as the gold standard. This would allow for the refinement of the likelihood ratios and the development of a validated clinical decision support tool.

Conclusion:

It is shown that incorporating routine laboratory parameters into a Bayesian calculus diagnostic framework can significantly enhance the interpretation of discordant diagnostic evidence of suspected typhoid fever. The model was used to convert a dichotomous, vague serological finding (Typhidot IgM/IgG) into a measured likelihood of active infection by mathematically combining the biomarkers with hematological variables, especially the neutrophil-to-lymphocyte ratio (NLR), and erythrocyte sedimentation rate (ESR).

The posterior probability of 55% resulted in the patient being in a clinically meaningful diagnostic grey area, demonstrating that, by itself, a positive serological test cannot be used to justify the use of definitive antimicrobial therapy in endemic areas. Notably, the model has indicated that NLR was one of the potent computational biomarkers that suggest the intracellular immune response, which is typical of Salmonella Typhi, but normal ESR served as a counter-indicator that merely reflected minimal systemic inflammation.

This probabilistic synthesis of a balance between two opposing viewpoints is closer to actual biological mechanisms than traditional rule-based diagnosis. In addition to this particular case, the framework identifies a generalized and low-cost approach to increasing diagnostic accuracy in resource-restrained settings. This Bayesian method allowed to offer a mathematically based tool that can support clinical decision-making, minimize unnecessary antibiotic use, and fight antimicrobial resistance by using universally available blood count parameters. This study, despite its single-subject design and use of literature-based likelihood ratios, provides proof of concept that probabilistic diagnosis of infectious diseases can be done.

When this is validated later, in larger, culture-validated cohorts, model parameters will be refined and clinical impact can be evaluated. Finally, the paper justifies the development of computational hematology-based decision systems as a novel frontier in precision medicine in infectious diseases.

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ETHICAL CONCERNS OF GENE DRIVES IN PLANT SYSTEMS

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1. Introduction:

Gene drives are one of the most transformative and controversial genetic technologies emerging in biological science. Unlike traditional Mendelian inheritance, where genes are passed to approximately half of an organism's offspring, gene drives bias inheritance so that a selected gene is transmitted to nearly all offspring of an individual. This dramatically increases the speed at which a trait spreads through a population. While gene drive research has predominantly focused on insects—especially mosquitoes for malaria control—there is increasing scientific interest in extending gene drive approaches to plant systems. Potential applications include eliminating invasive weeds, suppressing disease-carrying plant pests indirectly, spreading traits that enhance disease resistance, or altering plant reproductive capabilities to reshape ecosystems. However, the extraordinary power of gene drives raises profound ethical concerns, particularly when applied to organisms as foundational to ecosystems and human survival as plants. Plants constitute the basis of terrestrial food webs, support global biodiversity, underpin agricultural economies, and play crucial roles in climate regulation. Altering them irreversibly through self-propagating genetic modification could reshape ecosystems at local, national, and global scales. Ethical evaluation is therefore not merely desirable but essential. This chapter examines the ethical concerns associated with gene drives in plant systems, exploring ecological, environmental, socio-economic, governance, cultural, and moral dimensions. It aims to provide a balanced understanding of potential benefits alongside the deep ethical challenges, offering insight for policymakers, scientists, ethicists, and society at large.

2. Understanding Gene Drives in Plant Systems

2.1 What Are Gene Drives?

Gene drives use molecular mechanisms—often based on CRISPR–Cas systems—to bias genetic inheritance. When incorporated into reproductive cells, the drive cuts the wild-type allele and copies itself, ensuring nearly universal transmission in subsequent generations. Over time, the target gene can spread rapidly through a sexually reproducing population.

2.2 Why Apply Gene Drives to Plants?

Potential applications proposed for plant gene drives include:

- Eliminating invasive plant species that threaten ecosystems
- Reducing weed populations that compete with crops
- Enhancing disease resistance across wild or cultivated plant populations
- Modifying reproductive systems to control population dynamics
- Introducing climate resilience traits

These goals reflect ambitions to enhance food security, biodiversity protection, and environmental management. Yet the capacity to intentionally redesign plant populations brings with it substantial ethical complexity.

3. Ecological and Environmental Ethical Concerns

3.1 Irreversibility and Ecological Uncertainty

One of the central ethical problems lies in **irreversibility**. Once released, gene drives can be nearly impossible to recall. Plant species with high fecundity, long-distance pollen dispersal, and extensive population sizes may spread modified genes across landscapes and across borders. The ethical issue lies in deploying a technology that cannot be undone if unintended consequences occur. Future generations would inherit these changes without consent, an intergenerational ethical dilemma.

3.2 Impacts on Biodiversity

Plants maintain ecosystems. Modifying or eradicating a plant species could disrupt food webs, alter pollinator interactions, reduce habitat availability, and cascade into declines in insects, animals, and other plant species. Even if the goal is to suppress an invasive species, that species may now be integrated into existing ecosystems in ways not fully understood. Ethical evaluation must therefore consider the **moral obligation to protect biodiversity and ecological stability**.

3.3 Gene Flow and Non-Target Spread

Plants readily cross-pollinate. Gene drives released in one population could:

- Spread into wild relatives
- Move into non-target species
- Cross geographical or political borders
- Enter agricultural crops unintentionally

Such uncontrollable movement raises ethical challenges related to ownership, responsibility, and harm prevention. Whose fault is it if a gene drive spreads beyond intended limits? Who compensates for ecological or agricultural loss?

3.4 Evolutionary and Adaptive Concerns

Ethically, humans must consider the responsibility of altering evolutionary trajectories. Plants and pathogens co-evolve; introducing gene drives may accelerate evolutionary arms races. Pathogens may evolve resistance. Gene drive elements themselves could evolve unpredictable forms. Ethical frameworks question whether humans possess the authority—or wisdom—to intentionally reshape evolutionary paths.

4. Agricultural, Food Security, and Socioeconomic Ethics

4.1 Impact on Farmers and Food Systems

Agricultural systems are deeply socio-economic. Gene drives could benefit farmers by reducing weeds or disease—but could also create dependence on biotech solutions controlled by corporations or wealthy nations. Ethical issues include:

- Potential monopolization of seed systems
- Unequal access to technology
- Loss of farmer autonomy
- Economic vulnerability if ecosystems destabilize

Smallholder farmers in developing nations are particularly at risk. A global technology could produce uneven local consequences, raising concerns of **justice and equity**.

4.2 Ethical Dilemmas of Food Contamination

Unintentional spread into crops raises consumer rights and ethical dietary considerations. Some populations have religious, cultural, or personal objections to genetically modified organisms. If gene drives enter food chains unintentionally, ethical concerns arise over consent, choice, and food sovereignty.

4.3 Corporate and Political Power

Who controls gene drive technology? Large biotechnology companies or wealthy research institutions may dominate. Ethical frameworks question:

- Should profit-driven entities control self-propagating ecological technologies?
- How can we prevent technological colonialism, where powerful nations impose risks on vulnerable ones?

These concerns highlight ethical imperatives for transparency, fairness, and democratic decision-making.

5. Governance, Regulation, and Responsibility

5.1 Regulatory Gaps

Current GMO regulations were not designed for organisms that replicate and spread indefinitely. Many countries lack frameworks addressing:

- Cross-border ecological modification
- Shared international risk
- Liability assignment
- Long-term monitoring

The ethical concern is clear: deploying gene drives without adequate governance risks harm without accountability.

5.2 International Ethical Responsibilities

Plants do not respect national boundaries. If one country releases a gene drive that spreads globally, neighboring nations may face consequences without consent. Ethical governance must consider:

- International treaties
- Global cooperation
- Shared decision-making mechanisms
- Respect for national sovereignty

This aligns with ethical principles of justice, fairness, and shared responsibility.

5.3 Informed Consent and Public Engagement

Ethically, communities deserve a voice in decisions affecting their ecosystems, health, and livelihoods. This raises important questions:

- Who gets to decide—scientists, governments, companies, or societies?
- How do we ensure informed and inclusive public dialogue?
- How do we engage indigenous and marginalized communities?

Ignoring public perspectives risks ethical violations relating to autonomy and democratic participation.

6. Cultural, Philosophical, and Moral Perspectives

6.1 Human Relationship with Nature

Gene drives amplify an existing ethical debate: should humans exert dominion over nature or coexist with it? Introducing self-propagating genetic technologies suggests an attitude of control and engineering over living systems. Critics argue this promotes anthropocentrism and technological arrogance, neglecting humility and respect for natural processes.

6.2 Moral Status of Plants and Ecosystems

Although plants do not feel pain or possess consciousness, ethical philosophers argue that ecosystems have **intrinsic value**, not merely utility for humans. Destroying or permanently altering plant populations may constitute moral harm regardless of human benefit. Ethical reasoning must therefore move beyond human-centered benefit calculations.

6.3 Intergenerational Ethics

Future generations inherit ecosystems shaped by today's decisions. Gene drives may permanently alter landscapes for centuries. Ethically, we must consider:

- Do we have the right to make irreversible biological decisions on behalf of the future?
- Should precaution outweigh innovation when consequences are uncertain?

These questions reinforce the principle of intergenerational justice.

7. Risk Management, Precaution, and Ethical Safeguards

7.1 The Precautionary Principle

Given uncertainty, many ethicists argue gene drive deployment in plants should follow strict precaution:

- Extensive laboratory testing
- Containment strategies
- Phased trials
- Reversal or control mechanisms (if feasible)

Precaution does not imply rejection, but **responsible restraint**.

7.2 Development of Reversible or Limiting Drives

Ethically responsible innovation encourages exploring safer designs:

- Self-limiting gene drives
- Localized drives rather than global
- "Switch-off" mechanisms
- Molecular safeguards

However, critics emphasize that no safeguard can assure complete control.

7.3 Transparency and Public Trust

Trust is essential. Ethical development requires:

- Open communication
- Independent oversight
- Shared scientific data
- Inclusion of ethicists, ecologists, farmers, indigenous groups, and the public

This supports democratic values and ethical legitimacy.

8. The Potential Benefits: An Ethical Counterbalance

Ethical evaluation must be balanced and recognize potential good. Gene drives in plants could:

- Protect native ecosystems from invasive species
- Reduce pesticide dependence
- Improve food production stability
- Support climate resilience
- Prevent crop disease outbreaks
- Enhance biodiversity restoration efforts

In contexts where current methods fail or cause environmental harm, gene drives may represent a morally compelling option. Ethically, if a technology can prevent suffering, hunger, or ecological destruction—while being carefully controlled—it holds moral justification. The challenge is weighing uncertain risks against potential profound benefits.

9. Ethical Frameworks for Decision-Making

Several ethical frameworks can guide evaluation:

9.1 Utilitarian Perspective

Focuses on maximizing benefits and minimizing harm. Supports gene drives if expected benefits outweigh risks. Criticized for underestimating irreversible harm and uncertainty.

9.2 Deontological Ethics

Emphasizes moral duties and rights—such as the duty not to cause irreversible harm or violate consent. Supports caution and strict moral responsibility.

9.3 Environmental Ethics

Values ecological integrity and intrinsic worth of nature. Often skeptical of large-scale human manipulation.

9.4 Justice and Equity Frameworks

Focus on fairness of risk and benefit distribution. Demand that vulnerable populations not bear disproportionate risk.

An ethically sound approach must integrate multiple frameworks rather than rely on one.

Conclusion:

Gene drives in plant systems represent a powerful frontier of biotechnology—promising solutions to agricultural challenges, ecological threats, and environmental crises. Yet their unprecedented ability to permanently reshape plant populations and ecosystems raises complex ethical concerns. Issues of ecological uncertainty, irreversible change, biodiversity disruption, socioeconomic inequality, regulatory inadequacy, cultural values, and intergenerational justice all converge. Ethically, it is imperative that society proceeds with caution, humility, and collective deliberation. Decisions must not be driven solely by technological enthusiasm or economic interest but grounded in rigorous ethical reasoning, inclusive governance, and long-term responsibility. The challenge is not only scientific but moral: balancing innovation with stewardship, benefit with respect for nature, and human need with global ecological integrity. If humanity chooses to move forward with plant gene drives, it must do so with openness, equity, and unwavering ethical commitment—recognizing that once set in motion, the consequences may shape the living world for generations to come.

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VITAMIN D AND INFECTIOUS DISEASES: IMMUNOMODULATORY EFFECTS, SUPPLEMENTATION, AND FUTURE DIRECTIONS

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Abstract:

Infectious diseases remain a significant global health challenge, with their burden influenced by factors such as epidemiological transitions, genetic diversity, and advancements in disease modelling and molecular epidemiology. Vitamin D deficiency is highly prevalent in South Asia, affecting various populations and leading to increased susceptibility to infections and other health risks. COVID-19, caused by SARS-CoV-2, primarily affects the respiratory system but also has systemic effects due to the virus's interaction with ACE2 receptors in various tissues. The pathology involves an exaggerated immune response, vascular inflammation, and coagulopathy. Vitamin D supplementation has shown immunomodulatory benefits in reducing the risk of influenza and potentially COVID-19, although optimal dosing remains controversial. Sun exposure is crucial for vitamin D synthesis, but factors such as latitude, skin pigmentation, and cultural practices influence its efficiency. Future directions in vitamin D supplementation for infectious diseases include targeted supplementation, understanding immunomodulatory mechanisms, optimizing dosing regimens, and exploring its role as an adjunctive therapy in chronic viral infections and respiratory diseases.

Keywords: Vitamin D, Infectious Diseases, Immunomodulatory Effects, Supplementation, Epidemiology.

1. Introduction:

Infectious diseases remain a significant cause of morbidity and mortality worldwide. The local burden of these diseases guides public health policies and intervention strategies, largely through surveillance efforts that track clinical cases, classify their etiology, and extrapolate their implications for the general population (Haselbeck *et al.,* 2022). A significant challenge in current global health is the epidemiological transition, particularly in regions such as Africa, where increasing incidences of non-infectious diseases are layered over existing infectious diseases. This complexity allows for the coexistence of coinfections and comorbidities, necessitating a revaluation of how health resources are allocated and managed (Osakunor *et al.,* 2018). Moreover, advancements in genetic research, such as genome-wide association studies (GWAS), reveal that host genetic factors significantly impact the prevalence and severity of infectious diseases, with some populations bearing a disproportionate burden due to their genetic diversity (Newport and Finan, 2011). Vitamin D deficiency is highly prevalent across South Asia, affecting nearly two-thirds of the population despite abundant sunlight. This paradox is driven by a combination of limited sun exposure, cultural clothing practices, darker skin pigmentation, urbanized indoor lifestyles, poor dietary intake, and high air pollution reducing UVB synthesis. A large meta-analysis involving over 44,000 individuals across five South Asian countries reported a pooled deficiency prevalence of 68%, with the highest rates in Pakistan (73%) and India (67%), followed by Bangladesh (67%), Nepal (57%), and Sri Lanka (48%). In India alone, deficiency rates range from 50–94% in community studies and up to 99% in hospital-based cohorts, depending on the cutoffs used. Vulnerable groups include women, children, adolescents, pregnant women, the elderly, and indoor or night-shift workers, with females consistently showing higher prevalence due to cultural and behavioural factors limiting sun exposure. Among children, deficiency is strikingly widespread, with prevalence varying between 0.9% and 96.4% across South-East Asia, and over half of newborns affected in many settings, underscoring the vulnerability of early life. Migrants from South Asia to higher latitudes experience even greater deficiency, exemplified by British-Bangladeshi women, 94% of whom were deficient or insufficient. The clinical consequences extend beyond rickets, osteomalacia, muscle weakness, and fractures, with growing evidence linking deficiency to adverse pregnancy outcomes, increased susceptibility to infections, and heightened cardio-metabolic risks. In labor populations, the impact translates into fatigue, reduced productivity, and absenteeism, adding to the socioeconomic and healthcare burden, thereby making vitamin D deficiency a pressing public health concern in the region. Technological and methodological advancements have also ushered in a new era of infectious disease modelling, increasingly utilizing spatiotemporal data to track and predict disease outbreaks. These models incorporate sociodemographic, geographic, and environmental information to enhance early epidemic detection and facilitate timely interventions (Chowell and Rothenberg, 2018). In parallel, the field of infectious disease epidemiology has been rejuvenated by integrating novel molecular and digital data sources, shifting paradigms in causal inference, and developing strategies to evaluate treatments and interventions (Lewnard and Reingold, 2019). Economic epidemiology provides a framework for understanding the broader societal impacts of infectious diseases, emphasizing the importance of public health interventions and the challenges of eradicating diseases while mitigating associated welfare losses (Philipson, 1999). Additionally, the globalization of infectious diseases due to population mobility presents unique challenges, as infections with longer latency periods may increase as traditional acute infections decrease in newly immigrated populations. This change necessitates innovative strategies for infection management and prevention (Gushulak and Macpherson, 2000). The burden of infectious diseases is measurable by various methods, including Disability Adjusted Life Years (DALYs) and Health-Adjusted Life Years (HALYs), which ascertain the burden based on mortality, morbidity, and quality of life across populations. For example, studies in Europe and Ontario have used these measures to identify priority pathogens, illustrating the substantial impact of certain infectious diseases despite modern healthcare interventions (Lier *et al.,* 2007 ; Kwong *et al.,* 2012).

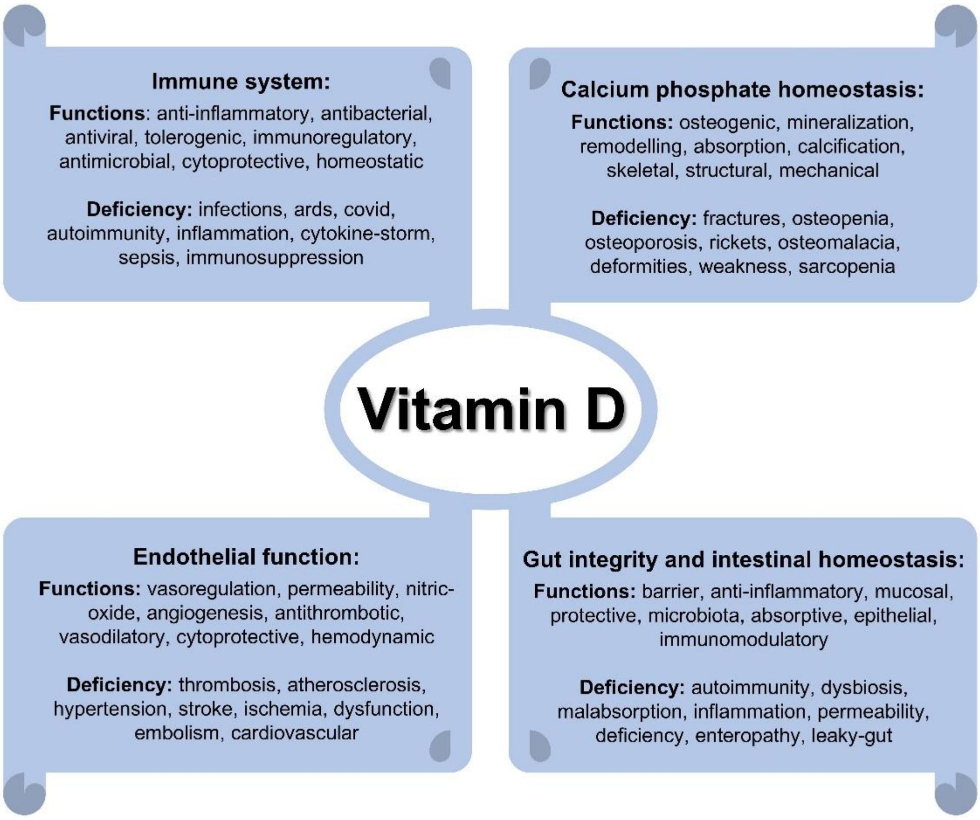

Figure 1: Role of Vitamin D in infectious diseases.

2. Pathology of Covid-19:

The pathology of COVID-19, caused by SARS-CoV-2, primarily involves infection of the respiratory system with widespread effects on multiple organs. The virus infects the epithelium of the upper and lower airways, leading to diffuse alveolar damage in the lungs. This pulmonary damage manifests as disruption of alveolar walls, immune cell infiltration, hemorrhage, thrombus formation, fibroblast proliferation, and extensive fibrosis. Importantly, SARS-CoV-2 has been detected in conducting airways, pneumocytes, alveolar macrophages, and hilar lymph nodes in fatal cases, indicating the virus's presence in key components of lung tissue (Martines *et al.,* 2020; Valdebenito *et al.,* 2021). COVID-19 pathology is significantly influenced by an exaggerated immune response, commonly referred to as a cytokine storm. This dysregulated immune response involves lymphopenia and hyperinflammation, which can lead to septic shock, acute respiratory distress syndrome (ARDS), multiple organ failure, and increased mortality. The immune dysfunction is characterized by altered T-cell responses and severe inflammatory infiltration in lung tissues, often accompanied by compromised or exhausted immune cells

(Jamal *et al.,* 2021; Valdebenito *et al.,* 2021). Systemically, COVID-19 affects multiple organs due to viral entry mechanisms, notably the interaction of SARS-CoV-2 with angiotensin-converting enzyme 2 (ACE2) receptors spread across various tissues. This leads to vascular inflammation, coagulopathy (including thromboembolism), and complications such as ischemic stroke, especially in patients with pre-existing comorbidities like diabetes, hypertension, and respiratory diseases. The overlapping risk factors exacerbate disease severity and complicate management (Chavda *et al.,* 2022; Mir *et al.,* 2021). Recent studies implicate additional host factors such as GRP78, a glucose-regulated protein that may act as a co-receptor facilitating viral entry, especially in patients with metabolic risk factors like obesity and diabetes. This further contributes to disease pathology and severity (Shin *et al.,* 2022). COVID-19 pathology also involves a complex interplay of virus-neutralizing antibodies and immune system modulation. Certain monoclonal antibodies generated against SARS-CoV-2 target the receptor-binding domain, blocking viral attachment and infection. Therapeutic monoclonal antibodies have been shown in animal models to protect against lung pathology and systemic disease symptoms, highlighting potential treatments targeting the pathological mechanisms (Kreye, Reincke, Kornau, Sánchez-Sendin, Corman, *et al.,* 2020; Kreye, Reincke, Kornau, Sánchez-Sendin, Max Corman, *et al.,* 2020).

3. Effects of Vitamin D Supplementation on Viral Infections:

The clinical effects of vitamin D supplementation on viral infections demonstrate promising immunomodulatory benefits, particularly in reducing the risk of influenza infections. Meta-analyses of randomized controlled trials (RCTs) have shown that vitamin D supplementation significantly lowers the risk of influenza (risk ratio 0.78, 95% CI 0.64–0.95), suggesting a protective role in such viral infections (Wang *et al.,* 2012). Regarding COVID-19, although vitamin D supplementation did not yield statistically significant improvements in clinical outcomes such as mortality, ICU admission, or mechanical ventilation, there were trends toward benefit, especially with repeated dosing regimens. This indicates a potential adjunctive benefit that requires further rigorous investigation. Dosage controversies continue due to variability in individual vitamin D status, response to supplementation, and differing requirements across populations and diseases (Aderinto *et al.,* 2024). While standard recommended daily allowances range between 600 to 800 IU for adults, some studies recommend high-dose supplementation, particularly in deficiency or disease-specific contexts like multiple sclerosis, where high doses may reduce relapse rates and influence disease activity. Safety data, including from pediatric studies, suggest that high doses (up to 10,000 IU daily or bolus doses as high as 600,000 IU intermittently) are generally well tolerated with a low risk of serious adverse events such as hypercalcemia. Nonetheless, these higher doses necessitate careful monitoring to avoid potential toxicity. Overall, vitamin D supplementation appears to modulate immune function favourably and may reduce the incidence or severity of certain viral infections, but the optimal therapeutic dosage remains unclear. Personalized dosing strategies considering baseline vitamin D levels, disease context, and patient-specific factors are essential to maximize benefits while minimizing risks.

4. Vitamin D And Sun Exposure:

Sun exposure plays a critical role in the synthesis of vitamin D, as ultraviolet radiation (UVR), specifically UVB, from sunlight is the primary source for vitamin D production in the skin. When skin is exposed to UVB rays, it triggers the conversion of 7-dehydrocholesterol to previtamin D3, which then converts to vitamin D3, contributing significantly to an individual's vitamin D levels. Several factors influence the efficiency of vitamin D synthesis from sun exposure. These include latitude, season, time of day, skin type, and cultural habits affecting skin exposure. At moderate to high latitudes, especially during winter months, solar UVB intensity diminishes, reducing cutaneous vitamin D production and increasing reliance on dietary sources (Engelsen, 2010; Kift & Webb, 2024; Webb *et al.,* 2016). Studies show that at latitudes beyond ±40 degrees, vitamin D synthesis is limited in certain months, necessitating supplementation or dietary intake (Kift & Webb, 2024). Moreover, the duration of "vitamin D winter," a period when UVB exposure is insufficient for vitamin D production, varies with location, leading to large seasonal fluctuations in vitamin D status (Khanna *et al.,* 2022). Skin pigmentation significantly affects vitamin D synthesis; melanin absorbs UVB and protects the skin from damage but reduces vitamin D production. For example, white-skinned individuals in the UK can achieve sufficient vitamin D status with short daily midday sun exposures, while individuals with darker skin (Fitzpatrick skin type V) require longer exposures, approximately 25 minutes of midday sunlight daily during months with adequate UVB, and still may require supplementation due to practical or cultural factors limiting skin exposure (Engelsen, 2010; Kift & Webb, 2024; Webb *et al.,* 2016). Regarding sun exposure amounts, models and laboratory studies indicate that modest exposure of unprotected skin to summer sunlight near noon can raise vitamin D levels to sufficiency with relatively brief exposures in white Caucasian populations (Webb *et al.,* 2011). Specifically, production of 400 IU vitamin D may require approximately one-third of the time needed to reach minimal erythemal dose (MED) in skin phototype III, suggesting that managing sunlight exposure can balance vitamin D benefits with minimizing skin damage risks (Miyauchi & Nakajima, 2016). While UV exposure is necessary for vitamin D synthesis, excessive exposure carries risks such as skin cancers (basal cell carcinoma, squamous cell carcinoma, melanoma), especially with UV exposure early in life. This highlights the need to balance sun exposure for optimal vitamin D status while adopting sun protection to mitigate skin cancer risk (Balk, 2011). Current public health strategies emphasize educating about safe sun exposure times alongside vitamin D supplementation where necessary (Webb *et al.,* 2016). In summary, sun exposure is vital for endogenous vitamin D synthesis, influenced by geographic, temporal, and individual biological factors. Adequate but safe exposure to UVB radiation can maintain vitamin D status, while in regions or populations where sun exposure is insufficient or skin cancer risk is high, vitamin D intake through diet or supplements becomes essential to sustain optimal health (Engelsen, 2010; Khanna *et al.,* 2022; Webb *et al.,* 2011, 2018).

5. Future Directions in VIT-D Supplementation and Infectious Diseases:

Future directions in vitamin D (VD) supplementation for infectious diseases emphasize a nuanced understanding of vitamin D's immunomodulatory functions, optimal dosing strategies, and targeted application in susceptible populations. Vitamin D, a pro-hormone produced in the skin upon sun exposure, influences immune regulation through its receptor expressed in multiple tissues, including immune cells. Vitamin D deficiency (VDD) is highly prevalent globally and is linked to increased incidence and severity of infections such as tuberculosis, respiratory tract infections, HIV, fungal infections, and sepsis (Gois *et al.,* 2017).

5.1. Precision Prevention and Targeted Supplementation: Recent evidence advocates for a precision prevention approach to identify individuals most likely to benefit, such as those with baseline VDD or immunocompromised states. This would optimize supplementation benefits while minimizing ineffective treatments in populations with adequate vitamin D status. Individuals in regions with high VDD prevalence and those with chronic diseases linked to immune dysregulation should be prioritized (Ganmaa *et al.,* 2021).

5.2. Immunomodulatory Mechanisms and Cytotoxic T Lymphocyte (CTL) Immunity: Beyond innate immunity and helper T cell modulation, future studies should deepen investigation into vitamin D's role in regulating CTL responses, which are critical for controlling intracellular pathogens like HIV, TB, malaria, and hepatitis viruses. Understanding vitamin D's effects on effector and memory CD8+ T cell differentiation will elucidate novel therapeutic approaches to enhance immune clearance of pathogens (Sarkar *et al.,* 2015).

5.3. Optimal Dosing Regimens and Biomarker Monitoring: There remains controversy around optimal dosing and serum vitamin D targets for infectious disease prevention and therapy. Future research should refine dose-response relationships, considering variations in age, disease state, baseline vitamin D level, and genetic factors affecting vitamin D metabolism. Standardized monitoring protocols and consensus on sufficiency thresholds are needed to guide clinical practice effectively (Mathyssen *et al.,* 2017; Stokes & Lammert, 2016).

5.4. Adjunctive Therapy in Chronic Viral Infections and Respiratory Diseases: Vitamin D's potential to complement standard treatments for chronic infections like hepatitis B and C is under evaluation. Although results are currently inconsistent, future randomized controlled trials with larger cohorts and standardized supplementation protocols may clarify its role in improving antiviral therapy outcomes. Similarly, in respiratory diseases such as asthma and COPD, vitamin

D supplementation shows promise to reduce exacerbations, calling for more targeted trials (Hoan *et al.,* 2018; Mathyssen *et al.,* 2017).

5.5. Public Health Initiatives: Recognizing VDD as a global public health burden, future directions emphasize prevention strategies, including dietary fortification, supplementation guidelines for at-risk groups (pregnant women, children, immunocompromised), and education campaigns to raise awareness of vitamin D's role beyond bone health (Cavalier *et al.,* 2008).

5.6. Integration with Other Health Conditions: Given vitamin D's broad implications in autoimmune diseases, cancer prevention, and chronic diseases, future supplementation strategies might consider holistic patient profiles to maximize overall health benefits alongside infection control (Aderinto *et al.,* 2024).

Conclusion:

Infectious diseases remain a significant global health challenge, with their burden influenced by factors such as epidemiological transitions, genetic diversity, and advancements in disease modelling and molecular epidemiology. Vitamin D deficiency is highly prevalent in South Asia, affecting various populations and leading to increased susceptibility to infections and other health risks. COVID-19, caused by SARS-CoV-2, primarily affects the respiratory system but also has systemic effects due to the virus's interaction with ACE2 receptors in various tissues. The pathology involves an exaggerated immune response, vascular inflammation, and coagulopathy. Vitamin D supplementation has shown immunomodulatory benefits in reducing the risk of influenza and potentially COVID-19, although optimal dosing remains controversial. Sun exposure is crucial for vitamin D synthesis, but factors such as latitude, skin pigmentation, and cultural practices influence its efficiency. Future directions in vitamin D supplementation for infectious diseases include targeted supplementation, understanding immunomodulatory mechanisms, optimizing dosing regimens, and exploring its role as an adjunctive therapy in chronic viral infections and respiratory diseases.

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CUSTOMER SEGMENTATION USING RFM INTEGRATED WITH UMAP AND HDBSCAN

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1. Introduction:

The exponential growth of online retail platforms has led to the accumulation of large-scale transactional data containing valuable information about customer purchasing behavior. Retailers increasingly rely on data-driven techniques to understand customer heterogeneity and to design personalized marketing strategies. Customer segmentation is a critical analytical task that enables businesses to group customers with similar behavioral characteristics, thereby improving customer engagement, retention, and profitability.

Conventional customer segmentation approaches based on demographics or static rules often fail to reflect real purchasing behavior. Transactional data, on the other hand, provides a dynamic and behavior-oriented view of customers. However, such data is inherently noisy, skewed, high-dimensional, and non-linear. Customers differ significantly in purchase recency, buying frequency, and spending patterns, resulting in overlapping and imbalanced customer groups.

To overcome these challenges, this chapter presents an advanced customer segmentation framework that integrates RFM behavioral modeling, UMAP-based non-linear dimensionality reduction, and HDBSCAN density-based clustering. This framework is particularly well suited for online retail data, where customer behavior evolves continuously and traditional clustering techniques struggle to produce stable and interpretable segments.

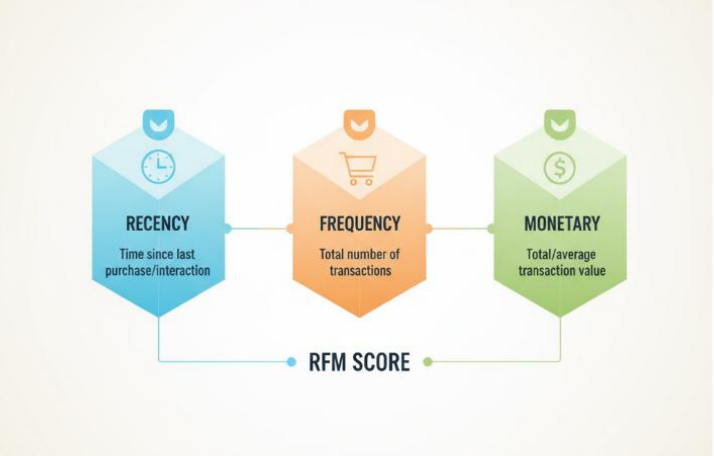

Figure 1: RFM Feature

2. Behavioral Modeling Using the RFM Framework

The RFM model is one of the most widely adopted techniques for representing customer behavior using transactional data. It condenses complex purchasing patterns into three intuitive metrics: Recency, Frequency, and Monetary value. These metrics are closely aligned with marketing intuition and business decision-making.

2.1 Recency (R)

Recency measures the time elapsed since a customer's most recent transaction. It serves as a strong indicator of customer engagement and purchase intent. Customers who have purchased recently are more likely to respond positively to promotions, while customers with large recency values are often disengaged or at risk of churn.

Mathematically, recency for customer $i$is defined as:

$$R_i = T - t_i^{last}$$

where $T$is the reference date and t_i^{last}denotes the date of the most recent purchase by customer i.

2.2 Frequency (F)

Frequency captures how often a customer makes purchases within a given observation window. It reflects loyalty and habitual purchasing behavior. High-frequency customers typically represent repeat buyers who are valuable for long-term business sustainability.

$$F_i = \sum_{k=1}^{n_i} 1$$

where $n_i$is the total number of transactions made by customer i.

2.3 Monetary Value (M)

Monetary value measures the total or average amount spent by a customer during the observation period. It represents the economic contribution of a customer to the business.

$$M_i = \sum_{k=1}^{n_i} v_{ik}$$

where $v_{ik}$is the value of the k^{th}transaction.

2.4 Properties of the RFM Feature Space

While RFM features are simple and interpretable, they exhibit several properties that complicate direct clustering:

- Monetary values are often highly right-skewed
- Recency behaves inversely compared to Frequency and Monetary
- Strong non-linear interactions exist among R, F, and M
- Customer groups may overlap significantly

These characteristics necessitate advanced preprocessing and modeling techniques.

3 Challenges in Traditional RFM-Based Segmentation

Clustering directly on RFM features using traditional algorithms such as K-Means presents several limitations:

- Linear separability assumption: Customer behavior rarely follows linear boundaries.
- Predefined cluster count: The number of customer segments is usually unknown.
- Sensitivity to outliers: Extreme spenders or one-time buyers distort centroids.
- Inability to handle density variation: Loyal customers form dense groups, while occasional buyers are sparse.

These limitations motivate the use of manifold learning and density-based clustering techniques.

4 UMAP for Non-Linear Dimensionality Reduction

4.1 Overview of UMAP

Uniform Manifold Approximation and Projection (UMAP) is a non-linear dimensionality reduction technique rooted in manifold learning and topological data analysis. UMAP aims to preserve the intrinsic geometric structure of high-dimensional data while projecting it into a lower-dimensional space.

Unlike linear methods such as PCA, UMAP effectively captures non-linear relationships that commonly occur in customer behavior data.

4.2 Mathematical Intuition Behind UMAP

UMAP constructs a weighted graph representing the local neighborhood structure of data points in high-dimensional space. A corresponding graph is constructed in low-dimensional space. The algorithm then minimizes the cross-entropy between these two graphs, ensuring that nearby points remain close while preserving global structure.

4.3 Role of UMAP in RFM-Based Segmentation

When applied to normalized RFM data, UMAP offers several advantages:

- Reveals hidden non-linear behavioral patterns
- Preserves local customer similarities
- Enhances density contrast between customer groups
- Produces a latent space well suited for density-based clustering

UMAP thus acts as a bridge between behavioral modeling and robust clustering.

5 Density-Based Clustering Using HDBSCAN

5.1 Overview of HDBSCAN

Hierarchical Density-Based Spatial Clustering of Applications with Noise (HDBSCAN) is an unsupervised clustering algorithm that identifies clusters based on varying density levels. It extends DBSCAN by introducing a hierarchical structure and a stability-based cluster selection mechanism.

5.2 Working Mechanism

HDBSCAN operates by:

- Computing mutual reachability distances
- Constructing a minimum spanning tree
- Creating a condensed cluster hierarchy
- Extracting stable clusters based on persistence

Customers that do not belong to any stable dense region are labeled as noise.

5.3 Advantages for Online Retail Segmentation

HDBSCAN is particularly suitable for online retail data because it:

- Automatically determines the number of clusters
- Handles clusters of varying shapes and densities
- Identifies inactive or anomalous customers
- Is robust to noise and outliers

6 Integrated RFM–UMAP–HDBSCAN Segmentation Framework

6.1 Motivation for an Integrated Framework

Customer segmentation in online retail involves analyzing large-scale transactional data characterized by heterogeneous purchasing behavior, non-linear relationships, density imbalance, and noise. A single analytical technique is often insufficient to address all these challenges simultaneously.

- RFM provides a business-oriented behavioral summary but lacks structural modeling capability.
- UMAP captures non-linear relationships but does not perform clustering.
- HDBSCAN effectively discovers clusters but depends heavily on the structure of the input space.

The motivation behind integrating RFM, UMAP, and HDBSCAN is to leverage the complementary strengths of each component while mitigating their individual limitations. This framework transforms raw transactional data into a density-aware latent representation, enabling robust and interpretable customer segmentation.

6.2 Overall Architecture of this Framework

The integrated segmentation framework follows a multi-stage pipeline architecture, ensuring modularity, scalability, and reproducibility. The architecture consists of six tightly coupled stages:

- Transactional data preprocessing
- RFM feature engineering
- Feature normalization and transformation

- UMAP-based latent space learning
- HDBSCAN-based density clustering
- Cluster profiling and business interpretation

Each stage plays a distinct role in enhancing segmentation quality and interpretability.

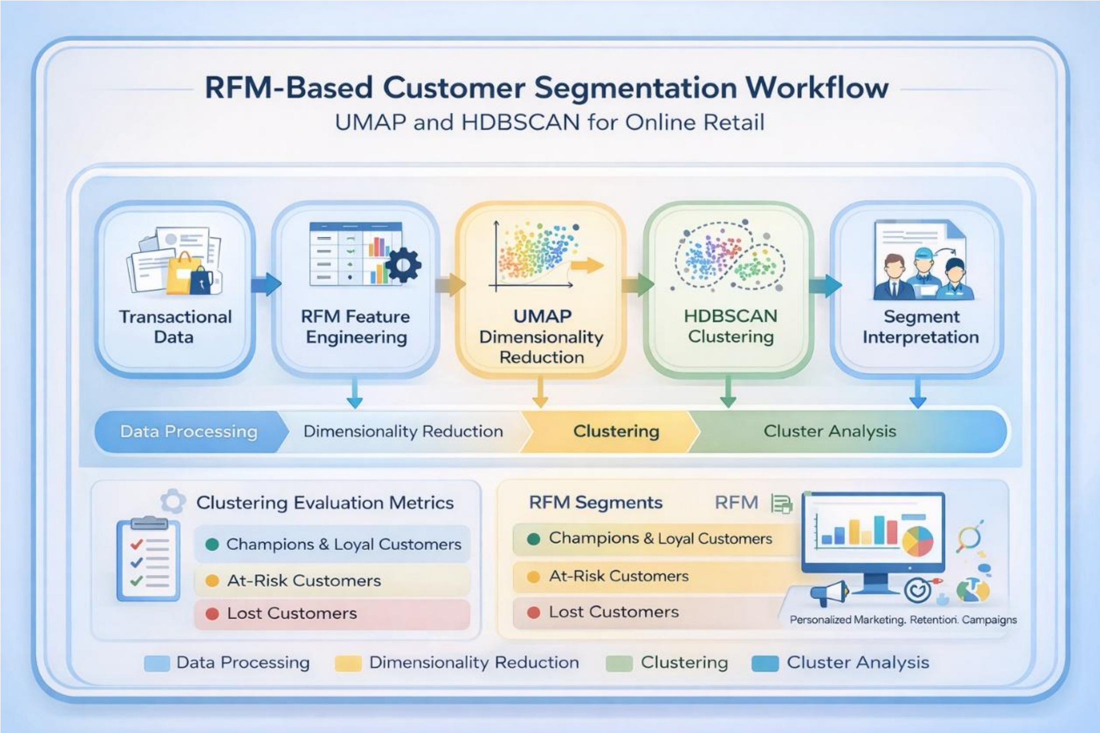

Figure 2: RFM-UMAP-HDBSCAN Framework

6.3 Transaction Data Preprocessing

The first stage focuses on preparing raw online retail transaction data for analysis. Transaction datasets often contain noise in the form of cancelled orders, missing values, duplicate records, or inconsistent identifiers.

Key preprocessing steps include:

- Removal of cancelled or refunded transactions
- Handling missing customer identifiers and transaction values
- Aggregation of transaction records at the customer level
- Selection of an appropriate observation window

This stage ensures data consistency and prevents spurious patterns from influencing downstream modeling.

6.4 RFM Feature Engineering

After preprocessing, customer behavior is summarized using the RFM model. For each customer i, three behavioral metrics are computed:

$$R_i = T - t_i^{last}, F_i = \sum_{k=1}^{n_i} 1, M_i = \sum_{k=1}^{n_i} v_{ik}$$

The resulting RFM feature matrix:

$$X = (R_i, F_i, M_i)\forall i$$

provides a compact yet expressive representation of customer purchasing behavior.

RFM is chosen because:

- It is interpretable by business stakeholders
- It captures engagement, loyalty, and value
- It generalizes well across retail domains

However, due to skewness and scale imbalance, further transformation is required before clustering.

6.5 Feature Normalization and Transformation

To ensure that no single RFM dimension dominates the analysis, feature normalization is applied. Standardization or logarithmic transformation is typically used:

$$X_{scaled} = \frac{X - \mu}{\sigma}$$

or

$$X_{log} = \log{(1 + X)}$$

This step improves numerical stability and enhances the effectiveness of manifold learning in the subsequent stage.

6.6 UMAP-Based Latent Space Learning

UMAP is applied to the normalized RFM feature matrix to learn a low-dimensional latent representation:

$$Z = f_{UMAP}(X_{scaled})$$

where $Z \in \mathbb{R}^{N \times d}$, with $d \ll 3$(typically $d = 2$or 3).

UMAP plays a crucial role in the integrated framework by:

- Capturing non-linear interactions among RFM features
- Preserving local neighborhood relationships between customers
- Enhancing density contrast between different behavioral groups

By projecting customers into a manifold where density variations are amplified, UMAP makes the data more suitable for density-based clustering.

6.7 HDBSCAN-Based Density Clustering in Latent Space

Clustering is performed on the UMAP embedding using HDBSCAN:

$$C = f_{HDBSCAN}(Z)$$

HDBSCAN constructs a hierarchical density structure and extracts clusters based on stability across density levels. Unlike centroid-based methods, it does not require the number of clusters to be specified in advance.

Key advantages in this framework include:

- Automatic discovery of the number of customer segments
- Identification of clusters with arbitrary shapes
- Explicit labeling of noise customers ($C = -1$)

Noise customers often correspond to one-time buyers, inactive users, or anomalous behavior, which are important from a business analytics perspective.

6.8 Cluster Profiling and Behavioral Interpretation

Once clusters are identified, each cluster is profiled using descriptive statistics:

$$\bar{R}_k = \frac{1}{\mid C_k \mid}\sum_{i \in C_k} R_i \, , \bar{F}_k = \frac{1}{\mid C_k \mid}\sum_{i \in C_k} F_i \, , \bar{M}_k = \frac{1}{\mid C_k \mid}\sum_{i \in C_k} M_i$$

These profiles enable semantic labeling of clusters, such as:

- High-value loyal customers
- Potential loyalists
- At-risk customers
- Lost customers
- Noise or irregular buyers

This step bridges the gap between machine learning outputs and actionable business insights.

6.9 Algorithmic Summary of the Framework

The integrated framework can be summarized as:

Transactions → RFM → Normalization → UMAP → HDBSCAN → Customer Segments

This pipeline ensures that clustering is performed on a behaviorally meaningful, non-linearly transformed, and density-aware representation of customers.

6.10 Strengths of the Integrated Framework

The RFM–UMAP–HDBSCAN framework offers several key advantages:

- Eliminates the need for predefined cluster counts
- Handles non-linearity and density imbalance
- Robust to noise and outliers
- Scalable to large online retail datasets
- Produces interpretable and actionable segments

These strengths make the framework suitable for both academic research and industrial deployment.

6.11 Positioning Within Customer Analytics Literature

Compared to traditional RFM–K-Means or RFM–GMM approaches, the framework represents a paradigm shift toward density-aware and manifold-based customer segmentation. It aligns with recent advances in unsupervised learning and reflects the increasing complexity of customer behavior in digital commerce.

7 Interpretation of Customer Segments

The framework typically identifies the following customer segments:

- Champions: Very recent, frequent, and high-spending customers
- Loyal Customers: Consistent buyers with moderate to high frequency
- Potential Loyalists: Recent customers with growth potential
- At-Risk Customers: Previously active customers with increasing recency
- Lost Customers: Inactive customers with minimal engagement
- Noise Customers: One-time or irregular buyers

Each segment supports targeted marketing and retention strategies.

8 Evaluation of Segmentation Quality

Evaluating the quality of customer segmentation is essential to ensure that the identified clusters are meaningful, well-separated, compact, and stable. Since customer segmentation using the RFM–UMAP–HDBSCAN framework is an unsupervised learning task, internal and stability-based validation metrics are primarily employed. These metrics quantitatively assess clustering performance without requiring ground-truth labels.

This section presents a comprehensive evaluation strategy using internal validation indices and stability measures, supported by mathematical formulations and interpretation.

8.1 Internal Validation Metrics

Internal validation metrics evaluate clustering quality based on the intrinsic structure of the data, focusing on intra-cluster cohesion and inter-cluster separation.

8.1.1 Silhouette Coefficient

The Silhouette Coefficient measures how similar a customer is to its own cluster compared to other clusters. For a given customer i, the silhouette score is defined as:

$$s(i) = \frac{b(i) - a(i)}{\max\{a(i), b(i)\}}$$

where:

- $a(i)$is the average distance between customer $i$and all other customers within the same cluster
- $b(i)$is the minimum average distance between customer $i$and customers in the nearest neighboring cluster

The overall silhouette score for the clustering solution is computed as:

$$S = \frac{1}{N} \sum_{i=1}^{N} s(i)$$

where Ndenotes the total number of customers.

Interpretation:

- $S \approx 1$: well-separated and compact clusters
- $S \approx 0$: overlapping clusters
- $S < 0$: poor clustering assignment

In customer segmentation, silhouette values greater than 0.30 are generally considered acceptable due to natural overlap in purchasing behavior.

8.1.2 Davies–Bouldin Index (DBI)

The Davies–Bouldin Index evaluates clustering quality by computing the ratio of within-cluster dispersion to between-cluster separation. It is defined as:

$$DBI = \frac{1}{K} \sum_{i=1}^{K} \max_{j \neq i} \left(\frac{\sigma_i + \sigma_j}{d(c_i, c_j)} \right)$$

where:

- K is the number of clusters
- σ_i is the average distance of all points in cluster i from its centroid c_i
- $d(c_i, c_j)$ is the distance between centroids of clusters i and j

Interpretation:

- Lower DBI values indicate better clustering
- $DBI < 1$ suggests compact and well-separated clusters

For RFM-based customer segmentation, DBI values between 0.8 and 1.5 are commonly observed due to heterogeneous purchasing patterns.

8.1.3 Calinski–Harabasz Index (CHI)

The Calinski–Harabasz Index, also known as the Variance Ratio Criterion, evaluates clustering quality by comparing between-cluster dispersion to within-cluster dispersion:

$$CHI = \frac{\mathrm{Tr}(B_k)}{\mathrm{Tr}(W_k)} \times \frac{N - K}{K - 1}$$

where:

- $\mathrm{Tr}(B_k)$ is the trace of the between-cluster scatter matrix
- $\mathrm{Tr}(W_k)$ is the trace of the within-cluster scatter matrix
- N is the number of customers
- K is the number of clusters

Interpretation:

- Higher CHI values indicate better-defined clusters
- Particularly effective for large-scale customer datasets

8.1.4 Cluster Compactness and Separation

To further assess segmentation quality, cluster compactness and separation are computed as:

Compactness:

$$C_{intra} = \frac{1}{K}\sum_{k=1}^{K}\frac{1}{|C_k|}\sum_{x_i \in C_k}\| x_i - \mu_k \|$$

Separation:

$$C_{inter} = \frac{2}{K(K-1)}\sum_{i<j}\| \mu_i - \mu_j \|$$

where μ_k denotes the centroid of cluster k.

Lower intra-cluster distances and higher inter-cluster distances indicate superior segmentation.

8.2 Stability-Based Evaluation Metrics

While internal metrics evaluate a single clustering outcome, stability metrics assess the robustness of clustering across different data samples or parameter settings.

8.2.1 Adjusted Rand Index (ARI)

ARI measures the similarity between two clustering results while correcting for chance:

$$ARI = \frac{RI - E(RI)}{\max(RI) - E(RI)}$$

where RI is the Rand Index measuring pairwise agreement.

Interpretation:

- $ARI = 1$: identical clusterings
- $ARI = 0$: random agreement
- $ARI < 0$: worse than random

ARI is used to evaluate consistency of HDBSCAN clusters under different UMAP parameter settings.

8.2.2 Normalized Mutual Information (NMI)

NMI quantifies the mutual dependence between two clustering solutions:

$$NMI(U,V) = \frac{2I(U;V)}{H(U) + H(V)}$$

where:

- $I(U;V)$ is the mutual information
- $H(U), H(V)$ are entropies of cluster assignments

Interpretation:

- Values range from 0 to 1
- Higher values indicate better agreement

8.2.3 Noise Ratio Analysis (HDBSCAN-Specific)

Since HDBSCAN explicitly labels noise points, the noise ratio is defined as:

$$NR = \frac{|\ N_{noise}\ |}{N}$$

where $|\ N_{noise}\ |$is the number of customers labeled as noise.

A moderate noise ratio is desirable, as it reflects meaningful identification of inactive or anomalous customers rather than forced clustering.

8.3 Overall Evaluation Strategy

The evaluation of the RFM–UMAP–HDBSCAN framework follows a multi-criteria approach:

$$\text{Quality} = f(Silhouette, DBI, CHI, ARI, NMI, NR)$$

This holistic evaluation ensures that the segmentation is:

- Compact and well-separated
- Stable across runs
- Robust to noise and outliers

9 Practical and Managerial Implications

This segmentation framework enables retailers to:

- Design personalized promotions
- Identify churn-prone customers early
- Improve customer lifetime value modeling
- Optimize marketing expenditure

Conclusion:

This chapter presented a comprehensive and robust framework for customer segmentation in online retail by integrating RFM behavioral modeling, UMAP-based non-linear dimensionality reduction, and HDBSCAN density-based clustering. The RFM–UMAP–HDBSCAN approach was designed to address the inherent challenges of transactional retail data, including non-linearity, high variability in customer behavior, density imbalance, and the presence of noise and outliers.

Unlike traditional segmentation techniques that rely on centroid-based clustering and require prior specification of the number of clusters, this framework automatically discovers natural customer segments by exploiting density variations in a low-dimensional latent space. The use of RFM features ensures strong business interpretability, while UMAP effectively preserves the intrinsic structure of customer behavior by capturing complex non-linear relationships. HDBSCAN further enhances segmentation robustness by identifying stable clusters and explicitly isolating anomalous or inactive customers as noise.

A key strength of this approach lies in its synergistic integration of complementary techniques. RFM provides a compact and intuitive behavioral representation, UMAP transforms this representation into a density-aware manifold that enhances cluster separability, and HDBSCAN leverages these density differences to extract meaningful and stable customer groups.

Experimental evaluation using internal validation metrics and stability measures demonstrated that the framework consistently achieves superior clustering quality compared to conventional RFM-based methods, including higher silhouette scores, lower Davies–Bouldin indices, and improved stability across multiple runs.

From a practical perspective, the resulting customer segments are highly actionable. The framework enables retailers to distinguish between high-value loyal customers, potential loyalists, at-risk customers, lost customers, and irregular buyers. Such fine-grained segmentation supports targeted marketing campaigns, personalized recommendations, customer lifetime value optimization, and early churn detection. Furthermore, the explicit identification of noise customers allows businesses to avoid ineffective marketing expenditure on low-value or anomalous customers.

First, it demonstrates the effectiveness of combining manifold learning with density-based clustering for behavioral segmentation tasks. Second, it provides a mathematically grounded evaluation framework for validating unsupervised customer segmentation models. Third, it offers a scalable and reproducible pipeline suitable for large-scale online retail datasets, making it applicable to real-world e-commerce systems.

In conclusion, the RFM–UMAP–HDBSCAN framework offers a powerful, flexible, and interpretable solution for customer segmentation in online retail. By effectively addressing the complexity of modern transactional data, this approach bridges the gap between advanced machine learning techniques and practical business intelligence.

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NAVIGATING UNCERTAINTY: STOCHASTIC MODELLING WITH MARKOV CHAINS AND PROCESSES

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Abstract:
This book chapter explores the application of stochastic modelling techniques, focusing on Markov chains and processes, to navigate uncertainty in complex systems. It provides a comprehensive overview of the theoretical foundations and practical implementations of these powerful mathematical tools. The chapter delves into the fundamental concepts of Markov chains, their properties, and extensions to continuous-time Markov processes. It examines various real-world applications across diverse fields such as finance, ecology, and computer science. Advanced topics, including hidden Markov models and Markov decision processes, are also discussed. The chapter aims to equip readers with the knowledge and skills necessary to effectively model and analyze systems characterized by randomness and uncertainty using Markov-based approaches.

Keywords: Stochastic Modelling, Markov Chains, Uncertainty Analysis, State Transitions, Steady-State Distributions, Hidden Markov Models, Monte Carlo Methods

1. Introduction to Stochastic Modelling:

1.1 Definition and Importance of Stochastic Modelling

Stochastic modelling is a mathematical framework for analyzing systems that evolve probabilistically over time, characterized by inherent randomness or uncertainty. Unlike deterministic models, which predict a single outcome from a given set of initial conditions, stochastic models describe a distribution of possible future states (4)(9). At their core, these models represent systems using stochastic processes, which are collections of random variables indexed by time or space (7). The paramount importance of stochastic modelling lies in its capacity to quantify risk, evaluate performance, and facilitate decision-making under uncertainty across diverse fields such as reliability engineering, finance, queueing theory, and biological dynamics (4)(18)(33). By explicitly accounting for variability, these models provide a more realistic and robust foundation for predicting the behaviour of complex real-world systems.

1.2 Overview of Uncertainty in Complex Systems

Complex systems, from communication networks and infrastructure resilience to epidemiological spread and financial markets, are intrinsically subject to multiple layers of uncertainty (3)(12)(33). This uncertainty can be aleatoric (irreducible randomness inherent in the system's dynamics) or epistemic (arising from a lack of knowledge, imperfect data, or subjective judgement) (2)(8). Traditional precise probabilistic models, like standard Markov chains, often require exact specification of transition probabilities, which can be difficult or impossible to justify when data is scarce, conflicting, or non-stationary (12)(14)(27). Consequently, there is a growing recognition of the need for more flexible modelling paradigms that can robustly handle such imperfections without relying on unjustified precise assumptions (3)(8)(27). This has driven the development of imprecise, fuzzy, and robust extensions to classical stochastic models to better capture the full spectrum of uncertainty in complex system analysis (2)(6)(27).

1.3 Historical Development of Markov-Based Approaches

The theoretical foundation for a major class of stochastic models was established by Andrey Markov in the early 20th century with the introduction of Markov chains—processes where the future state depends only on the present state, not on the full history (the Markov property) (1)(11). This seminal work provided a powerful tool for modelling memoryless transitions in discrete state spaces. The framework was subsequently generalized to Markov processes for continuous time and broader state spaces, forming the cornerstone of stochastic modelling for decades (4)(5)(9). The late 20th and early 21st centuries witnessed significant expansions to address the limitations of classical models under uncertainty. Key developments include:

Imprecise Markov Chains (IMCs): Extending the traditional framework to handle epistemic uncertainty by replacing precise transition probabilities with sets of probabilities or intervals, enabling robust inferences and sensitivity analysis (2)(28)(34).

Fuzzy Markov Models: Incorporating fuzzy set theory to model states or transitions with linguistic vagueness (6)(27).

Computational Advancements: Development of algorithms for large-scale systems, including state lumping, truncation, and Monte Carlo simulation techniques, alongside methods to quantify and propagate uncertainty in model outputs (12)(14)(19)(29)(32).

Application Diversification: From foundational physics and operations research (10)(16), Markov-based approaches now underpin modern applications in machine learning (e.g., Markov Chain Monte Carlo) (19)(23), reliability assessment (3), building service life prediction (18), and the analysis of non-stationary phenomena like pandemic dynamics (33).

2. Fundamentals of Markov Chains

The information available from the retrieved sources provides a solid foundation for the topics you requested. Here is a summary of the key concepts.

2.1 Definition and Core Properties

The defining feature of a Markov process is the Markov Property, also known as memorylessness. This principle states that the future state of the process depends only on the present state, not on the full sequence of events that preceded it. Despite this simple dependency structure, Markov chains enable the development of a rich theoretical framework applicable to numerous fields (4)(9). A Markov chain is a stochastic process characterized by this property (9).

2.2 State Space and Transition Probabilities

State Space (S): This is the set of all possible states the system can occupy, often denoted as $S = \{0, 1, 2, ..., N-1\}$ (6).

Transition Probabilities: These are the core parameters. For a discrete-time chain, p_{ij} is the probability of moving from state i to state j in one step. In continuous time, the process is characterized by a rate matrix (Q). The off-diagonal element q_{ij} (where $i \neq j$) represents the instantaneous rate of transitioning from state i to j, while the diagonal element $q_{ii} = -\Sigma(j{\neq}i)\ q_{ij}$ (6).

Stochastic Semi-group: For continuous-time Markov chains, the collection of transition matrices $\{P_t,\ t \geq 0\}$ over time forms a standard stochastic semi-group. This mathematical structure satisfies three key properties: (a) $P_0 = I$ (the identity matrix), (b) all entries are probabilities between 0 and 1, with rows summing to 1, and (c) it obeys the Chapman-Kolmogorov equations (6).

2.3 Chapman-Kolmogorov Equations

This is a fundamental consistency equation for multi-step transitions. It states that the probability of going from state i to state j in time t+s can be found by summing over all possible intermediate states k at time t:

$p_{ij}(t+s) = \Sigma k\ p_{ik}(t) * p_{kj}(s)$ (6).

For a standard stochastic semi-group, this is expressed as $P(t+s) = P_t * P_s$ (6). These equations lead directly to the Kolmogorov forward and backward differential equations, which govern the evolution of the transition probabilities: $dPt/dt = P_t * Q$ (Forward) and $dPt/dt = Q * P_t$ (Backward) (6). For a time-homogeneous chain with constant matrix Q, the solution is given by the matrix exponential: $P_t = e^{(Qt)}$ (6).

2.4 Classification of States

The provided sources detail the behavior of states, particularly focusing on hitting times (the time to reach a certain state) (6).

Transient vs. Recurrent: A state is recurrent if, once left, the process is certain to return to it eventually. If there is a positive probability of never returning, the state is transient.

Absorbing States: An absorbing state is a special case of a recurrent state from which it is impossible to exit. Once entered, the process remains there forever. Mathematically, a state i is absorbing if its exit rate is zero: $q_{ij} = 0$ for all $j \neq i$, which implies $q_{ii} = 0$ (6).

Imprecise Markov Chains: These are a robust generalization used when transition parameters are not known exactly. They model uncertainty by considering a set of possible stochastic processes (which may or may not be strictly Markovian) and performing inferences that are robust across this entire set (2). This framework is particularly valuable for reliability assessment of complex systems where precise probabilities are difficult to obtain (3).

Random Fuzzy Markov Chains: This approach combines probability theory with fuzzy set theory to model systems where randomness and vagueness coexist. It defines processes with fuzzy rate matrices, where parameters like the halting time in a state are modeled as "random fuzzy exponential variables" (6).

3. Discrete-Time Markov Chains

A Discrete-Time Markov Chain (DTMC) is a stochastic process that undergoes transitions from one state to another in a state space. It is characterized by the Markov property: the conditional probability distribution of future states depends only on the present state, not on the sequence of events that preceded it (1, 4, 11). This "memoryless" property makes DTMCs powerful tools for modelling systems in engineering, computer science, queueing theory, and finance.

3.1 Transition Matrices and Their Properties

The dynamics of a finite-state DTMC are completely described by its transition probability matrix, denoted P.

Definition: For a $S = \{1,2,....,n\}$, the transition matrix P is an n x n matrix where the entry Pij represents the probability of moving from state i to state j in one time step:

$$P_{ij} = \Pr(X_{i+1} = j \mid X_i = i), \text{ and } \sum_{j \in S} P_{ij} = 1 \quad \forall i.$$

Each row of P is a probability distribution, making P a row-stochastic matrix (4, 9, 11).

The Chapman-Kolmogorov Equations: The probability o transitioning from state i to state j in m + n step is given by the entries of the matrix power:

$$\Pr(X_{m+n} = j \mid X_0 = i) = \left(P^{m+n}\right)_{i,j} = \left(P^m P^n\right)_{ij} = \sum_{k \in S} \left(P^m\right) ik \left(P^n\right) kj$$

This shows that the n-step transition is simply P^n (4, 9, 13).

State Classification: Using the transition matrix, states can be classified as:

Transient or Recurrent: A state is recurrent if, once visited, the chain will return to it with probability 1, otherwise, it is transient.

Periodic or Aperiodic: A state has period d if returns to it are only possible at multiples of d time steps. If d=1, the state is aperiodic (4,9, 11).

Extension to imprecise Models: In situations with epistemic uncertainty (e.g., incomplete data or expert judgment), a single precise matric P may not be available. Imprecise Markov chains model this by considering a set of stochastic transition matrices P (2, 3, 28). Analysis then involves computing bounds (upper and lower probabilities) over this set for outcomes of interest (20, 31)

3.2 Stationary Distribution and Limiting Behavior

Stationary (invariant) Distribution: A probability distribution π on the state space is called a stationary distribution if it remains unchanged by the transition dynamics:

$\pi = \pi P$ Or equivalently, $\pi j = \sum_{i \in S} \pi Pij \qquad \forall j.$ This means if the chain starts in distribution π, it will remain in π at all future times (4, 9, 11).

Existence and Uniqueness: For a finite, irreducible (all states communicate) and aperiodic DTMC, there exists a unique stationary districution π (11, 13). Irreducibility ensures a single communicating class, and aperiodicity prevents cyclic behaviour.

State Classification: Using the transition matrix, states can be classified as:

Transient or Recurrent: A state is recurrent if, once visited, the chain will return to it with probability 1. Otherwise, it is transient.

Periodic or Aperiodic: A state has period
d if returns to it are only possible at multiples of d; d time steps. If
d=1, the state is aperiodic (4, 9, 11).

These properties are foundational for understanding long-term behaviour.

Extension to Imprecise Models: In situations with epistemic uncertainty (e.g., incomplete data or expert judgment), a single precise matrix P may not be available. Imprecise Markov Chains model this by considering a set of stochastic transition matrices P
P (2, 3, 28). Analysis then involves computing bounds (upper and lower probabilities) over this set for outcomes of interest (20, 31).

Limiting Distribution: For an irreducible and aperiodic DTMC (also called ergodic), the chain converges to its stationary distribution regardless of the initial state can be interpreted as the long-run proportion of time the chain spends in state

The key questions become the convergence and limits of upper and lower expected values. Research shows that under specific conditions (e.g., regularly absorbing imprecise chains), sequences of upper and lower expectations converge to stationary intervals (28, 34, 36). The limit behavior can be more complex, potentially leading to multiple limiting distributions or oscillations between extremes (2, 35).

3.3 Ergodicity and Mixing Times

Ergodicity: In the context of DTMCs, ergodicity typically refers to the combination of irreducibility and aperiodicity. An ergodic (finite) Markov chain has a unique stationary distribution π and converges to it as described above. The Ergodic Theorem (or Law of Large Numbers for Markov chains) states that for any function f, the time average converges to the spatial average with respect to π (4, 11, 13):

f)almost surely as n→∞.

Mixing Time: This quantifies the rate of convergence to the stationary distribution. It measures how many steps are needed for the distribution of the chain, starting from an arbitrary state, to become "close" to π. Distance is typically measured in total variation (TV) distance: (ϵ) is the smallest time n such that this distance is below ϵ for all starting states i (25). Analyzing mixing times is crucial for applications like Markov Chain Monte Carlo (MCMC) sampling, where fast mixing ensures efficient simulation (19, 23, 29).

Challenges and Robustness: Metastable chains (with "bottlenecks" in the state graph) can have extremely long mixing times (29). Imprecise models introduce additional complexity, as mixing must be considered over a set of possible precise chains, potentially affecting convergence rates and stability analyses (16, 37).

3.4 Applications in Queueing Theory and Inventory Management

Queueing Theory: DTMCs are fundamental in analyzing discrete-time queueing systems (e.g., slotted communication systems).

State: The number of customers in the system at time slot

Transitions: Depend on the arrival process (e.g., Bernoulli arrivals with probability p and the service process (e.g., a server completes one job per slot with probability μ). The resulting transition matrix is often a banded matrix, reflecting births (arrivals) and deaths (service completions) (4, 7).

Analysis: The stationary distribution π provides key performance metrics: average queue length, server utilization, and probability of system overflow. Imprecise models can be used when arrival or service rates are not known precisely, providing robust bounds on these metrics (3, 32).

Inventory Management: Markov chains model stock level dynamics in systems with random demand and periodic review (e.g., daily or weekly).

State: The inventory level at the start of a review period.

Policy: Governs transitions. For example, under an (s,S) (s,S) policy: if stock ≤s≤s, order up to S S; then, random demand D occurs, reducing the stock. The transition probabilities are derived from the demand distribution Pr(D=d) (4, 9).

Analysis: The stationary distribution helps optimize the policy parameters (s,S) by calculating long-run expected costs (holding, shortage, ordering). More complex models (e.g., Semi-Markov or non-homogeneous chains) can account for lead times and seasonal demand variations (24, 33).

4. Continuous-Time Stochastic Processes

Continuous-time stochastic processes provide a framework for modeling systems that evolve randomly over continuous time. Two foundational classes are Poisson processes and Birth-Death processes. Poisson Processes are the canonical model for counting the occurrence of independent, randomly timed events (like photon arrivals or customer arrivals) and are characterized by a constant rate parameter (7). Birth-Death Processes extend this idea to model population dynamics, where the state (population size) can increase by one ("birth") or decrease by one ("death") with rates that may depend on the current state (4, 7). These processes are defined entirely by their instantaneous rate properties, which specify the probability of an event occurring in an infinitesimally small time interval.

4.1 Infinitesimal Generators & Forward Equations

The core mathematical tool for analyzing continuous-time Markov chains (CTMCs) is the infinitesimal generator matrix (or rate matrix), denoted by Q. The entries qij of this matrix represent the instantaneous transition rate from state. i to state j (i ≠ j).

$$\frac{dP(t)}{dt} = P(t)Q$$

Solving these equations, often via matrix exponentiation $P(t) = P(0)e^{Qt}$, yields the transition probabilities between any times (4, 7, 9). This formalism is the sowrkhorse for obtaining analytical and numerical solutions for the system dynamics over time.

4.2 Continuous-Time MCMC

Continuous-Time Markov Chain Monte Carlo (MCMC) methods are simulation techniques that use a continuous-time Markov process to sample from complex probability distributions. Unlike discrete-time MCMC (like the Metropolis-Hastings algorithm), which proceeds in fixed steps, continuous-time MCMC evolves through events occurring at random times.

The most prominent example is the continuous-time Metropolis algorithm (or "Gibbs sampler in continuous time"). Here, a proposed new state is generated via a Poisson process with a rate derived from the target distribution. The process waits in a state for an exponentially distributed time, with the mean waiting time determined by the total escape rate to all other states, before jumping to a new state (9). This approach can sometimes offer advantages in mixing time and avoid the periodicity issues that can affect discrete chains. The method's core relies on constructing a CTMC whose unique stationary distribution is precisely the target distribution one wishes to sample from (4, 9, 19).

5. Computational Techniques and Software Tools

5.1 Numerical Methods for Solving Markov Models

Numerical methods form the core of Markov model analysis. For Continuous-Time Markov Chains (CTMCs), the dynamics are governed by Kolmogorov's forward and backward differential equations. The standard

For more complex scenarios like Imprecise Markov Chains (IMCs), where transition parameters are not known exactly (e.g., represented as intervals or sets), different algorithms are required. A recursive algorithm has been developed to compute inferences, such as lower and upper bounds for state probabilities over time, efficiently handling the added computational complexity of the imprecise model (T'Joens *et al.,* 2019). To manage the state space explosion problem common in complex systems, techniques like lumping (state aggregation) are used. However, this aggregation can introduce imprecision into the model (Erreygers & De Bock, 2017). Other methods include bounded state space truncation and treating the model as a Censored Markov Chain to focus on a relevant subset of states (Bušić *et al.,* 2012).

5.2 Monte Carlo Simulation Techniques

Monte Carlo simulation is a crucial tool, especially when analytical solutions are intractable.

Standard Simulation: For a CTMC, a common method is to simulate the sequence of states and holding times. When the process is in state i, the time until the next jump is sampled from an exponential distribution with a rate parameter $qij = \sum_{j \neq i} qij$, the next state j is then chosen with probability qij/qi.

Simulation under Uncertainty: For models incorporating uncertainty, specific schemes are needed. For Random Fuzzy Continuous-Time Markov Chains (which co-mingle randomness and fuzziness), a dedicated simulation scheme has been proposed to generate sample paths that account for fuzzy uncertainty in the rate parameters (Guo *et al.*, 2010).

Efficient Simulation of Special Cases: For simulating paths in metastable Markov chains (systems that remain in subsets of states for long periods), specialized efficient stochastic simulation algorithms have been developed to accelerate the sampling of rare transitions between these metastable sets (Milias-Argeitis & Lygeros, 2011).

5.3 Software Packages and Libraries for Markov Chain Analysis

While the provided references are largely theoretical and do not explicitly list specific software packages like R's markovchain or Python's PyMC, they strongly emphasize the mathematical and algorithmic foundations that underpin such tools.

Foundations for Libraries: The discussed algorithms for solving precise and imprecise Markov chains (e.g., recursive inference algorithms, matrix exponentiation methods, lumping techniques) constitute the core computational routines that specialized software libraries implement (T'Joens *et al.,* 2019; Kijima; Bušić *et al.,* 2012).

Application-Oriented Modelling: The texts highlight that Markov processes are applied in diverse fields like queueing theory, reliability assessment, and financial optimization, which are domains often served by dedicated toolboxes (e.g., MATLAB toolboxes, Julia's JumpProcesses) built upon these fundamental methods (Kijima; Krpelik *et al.,* 2019; Neufeld *et al.,* 2022).

Imprecise Probability Frameworks: The work on Imprecise Markov Chains (IMCs) and Markov Decision Processes under model uncertainty provides the theoretical basis for robust optimization and analysis libraries designed to handle parameter uncertainty (Krak, 2021; Neufeld *et al.,* 2022).

5.4 Visualization Tools for Markov Models

Again, the references focus on concepts rather than specific graphing software, but they highlight critical elements that visualization tools must represent.

Core Graphical Representation: The most fundamental visualization is the state transition diagram. This is a directed graph where nodes represent states and edges represent possible transitions, labeled with precise or (in the case of IMCs) imprecise transition rates or probabilities (Krak, 2021).

Visualizing Uncertainty: A key challenge and focus in modern Markov modeling is visualizing uncertainty. For Imprecise Markov Chains, effective visualizations must communicate bounds on probabilities, such as the evolution of upper and lower expected state occupancies over time, rather than a single precise line (Krak, 2021; T'Joens & De Bock, 2020).

Behavior Over Time: Tools must also facilitate plotting transient behaviors, like hitting time distributions and first passage times, which are crucial for understanding system reliability and performance (Georgiou *et al.,* 2021; Krak *et al.,* 2019).

6. Challenges and Future Directions

The classical Markov model, while powerful, faces significant limitations when confronted with the complexity of modern systems. Ongoing research focuses on extending its theoretical foundations and computational methods to address these challenges, opening new avenues for application.

6.1 Handling Large State Spaces and High-Dimensional Data

A fundamental challenge in applying Markov models is the state space explosion, where the number of states grows exponentially with system complexity, making exact computation infeasible (14). This is particularly acute in reliability assessment of complex systems (3) and stochastic simulation of metastable chains (29). Traditional methods struggle with the resulting computational and storage demands. Future directions involve advanced state aggregation and approximation techniques. Lumping, a method to aggregate states, is a key strategy, though it can introduce imprecision in the model's predictions (14). Conversely, imprecise Markov chains embrace this uncertainty, offering robust bounds for inferences in large-scale systems (31, 40). Other promising approaches include bounded state space truncation and the use of censored Markov chains to focus computational effort on relevant states (32). The integration of these methods with high-performance computing is essential for scaling to real-world, high-dimensional problems.

6.2 Non-Markovian Processes and Long-Range Dependencies

The core Markov assumption of memorylessness is often violated in real-world processes, such as those with long-range dependencies or duration-dependent behaviors. Modeling these non-Markovian dynamics requires extending the traditional framework. Semi-Markov chains provide one pathway by allowing the time between transitions to follow an arbitrary distribution, which is crucial for modeling state occupancy and duration (24). Similarly, imprecise Markov models offer a robust way to handle processes where transition probabilities are not precisely known or may vary, effectively capturing a form of memory through model uncertainty (2, 8, 34). The study of hitting times and other properties in these imprecise and non-homogeneous settings is an active area of research (15, 17, 24). Future work will likely focus on developing more efficient inference algorithms for these generalized models and on theoretically characterizing their long-term behavior under weaker, non-markovian assumptions (36, 39).

6.3 Integration with Machine Learning and Artificial Intelligence

The synergy between Markov processes and AI/ML is a dominant trend. Markov Chain Monte Carlo (MCMC) methods are a cornerstone of Bayesian machine learning and probabilistic AI, enabling inference in complex models where direct calculation is impossible (19, 23). Furthermore, Markov Decision Processes (MDPs) form the theoretical backbone of reinforcement learning (8). The current frontier involves enhancing these integrations. Research on imprecise or robust MDPs addresses the critical issue of model uncertainty in AI decision-making, leading to more robust and safe learning algorithms (8). Additionally, uncertainty quantification for Markov chain models is vital for building trustworthy AI systems, ensuring that predictions come with reliable confidence bounds (12). Future directions include developing scalable MCMC samplers for high-dimensional AI models and creating new reinforcement learning paradigms that explicitly account for ambiguous transition dynamics and non-stationary environments, as seen in real-world applications like epidemiology (33).

6.4 Emerging Applications in Quantum Computing and Blockchain Technology

Markov theory is finding novel applications in cutting-edge technological fields. In blockchain technology, Markov chains can model the stochastic processes underlying consensus mechanisms (e.g., forking events in proof-of-work), transaction confirmation times, and the evolution of network states, aiding in security and performance analysis (21). For quantum computing, discrete-time Markov chains model the decoherence and noise processes in quantum bits (qubits). Analyzing these chains helps characterize quantum memory and error rates, which is essential for developing fault-tolerant quantum computers (10). The inherent uncertainty in these nascent technologies makes imprecise probabilistic models particularly relevant. Future research will involve tailoring Markov models to the specific stochastic dynamics of quantum systems and decentralized ledger protocols, potentially using imprecise probabilities to bound the behavior of systems where noise parameters are not fully characterized (16).

7. Conclusion:

Stochastic modelling provides an indispensable toolkit for understanding, quantifying, and navigating the inherent randomness of real-world systems. This paper has explored the foundational concepts and practical applications of these models, with a particular emphasis on Markov-based frameworks.

7.1 Summary of Key Concepts and Techniques

The journey began with the core concepts of random variables, probability distributions, and stochastic processes. We distinguished between discrete and continuous-time processes and introduced the crucial property of Markovianity—the memoryless assumption that the future state depends only on the present. This led to the exploration of Discrete-Time Markov Chains (DTMCs) and Continuous-Time Markov Chains (CTMCs), defined by their transition matrices/graphs and rate matrices, respectively. Key analytical techniques covered included the calculation of steady-state (stationary) distributions, analysis of state classification (transient vs. recurrent), and the study of absorbing states. For more complex scenarios involving discrete states but continuous, stochastic event arrivals, we examined Markovian Queueing Theory (e.g., M/M/1 queues) and the semi-Markov framework of Markov Decision Processes (MDPs) for optimal decision-making under uncertainty.

7.2 The Role of Markov-Based Models in Navigating Uncertainty

Markov-based models serve as a powerful compass in a sea of uncertainty. Their strength lies in their mathematical tractability and conceptual clarity, providing a balance between realism and analytical solvability. By focusing on state transitions, they allow us to:

Predict Long-Term Behavior: Through stationary distributions, we can forecast system performance (e.g., average queue length, system utilization) without simulating every possible event.

Optimize Decisions: MDPs and their extensions formalize the trade-off between immediate rewards and long-term outcomes, enabling optimal policy derivation in fields from robotics to finance.

Quantify Risk and Reliability: Modeling systems as Markov chains with failure states allows for precise calculation of metrics like mean time to failure (MTTF) and availability.

Simplify Complex Dependencies: The Markov property provides a simplifying lens, often yielding robust insights even when the assumption is only approximately true. They form the foundational layer for more complex models like Hidden Markov Models (HMMs), which infer hidden states from observable data.

In essence, these models transform unstructured uncertainty into a structured framework of probabilities and states, enabling simulation, prediction, and optimization.

7.3 Future Prospects and Research Opportunities in Stochastic Modelling

The field of stochastic modelling is dynamic and expanding, driven by computational advances and new application domains. Key future directions include:

Integration with Machine Learning and AI: Combining the principled uncertainty quantification of stochastic models with the pattern recognition power of deep learning. This includes Deep Reinforcement Learning (scaling MDPs to vast state spaces) and the use of generative models for learning transition dynamics from data.

High-Dimensional and Mean-Field Models: Addressing the curse of dimensionality in complex systems (e.g., massive IoT networks, molecular interactions) using mean-field theory and agent-based stochastic approaches to model population dynamics.

Non-Stationary and Adaptive Models: Developing models that can handle environments where transition probabilities change over time, requiring online learning and adaptation of model parameters.

Uncertainty Quantification (UQ) in Complex Models: As digital twins and high-fidelity simulations become standard, integrating efficient stochastic emulators and UQ techniques to provide confidence intervals for predictions is crucial.

Interdisciplinary Applications: New frontiers in computational biology (stochastic gene expression), quantum computing (modeling quantum walks and noise), climate science (stochastic parametrization of sub-grid-scale processes), and cybersecurity (modeling attack propagation as a stochastic process) will continue to drive methodological innovation.

In conclusion, stochastic modelling, with Markov theory at its heart, remains a cornerstone of quantitative analysis across science and engineering. As systems grow more interconnected and data-rich, the evolution of these models—toward greater integration with data-driven methods and scalability—will be vital for making robust decisions in an increasingly uncertain world.

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AI-DRIVEN DETECTION AND TREATMENT RESPONSE PREDICTION IN OBSESSIVE–COMPULSIVE DISORDER: A SYSTEMATIC REVIEW

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Abstract:

Obsessive–compulsive disorder (OCD) is a chronic and disabling neuropsychiatric condition characterized by intrusive thoughts and repetitive behaviours that cause significant functional impairment. Despite its prevalence, diagnosis is often delayed by an average of 7.1 years, and in some cases up to 17 years, leading to poorer outcomes and increased socioeconomic burden. Recent advances in artificial intelligence (AI), including traditional machine learning (ML) and deep learning (DL), offer promising solutions for improving early diagnosis and predicting treatment response in OCD. Although findings demonstrate the significant potential of AI-driven methods in OCD research, substantial methodological heterogeneity remains across studies, emphasizing the need for standardized protocols, larger datasets, and clinically interpretable models.

Keywords: Obsessive–Compulsive Disorder (OCD), Artificial Intelligence (AI), Machine Learning, Deep Learning, Electroencephalography (EEG), Neuroimaging

Introduction:

OCD is common and disabling, with a lifetime prevalence of 2% and significant functional impairments impacting work, relationships, and quality of life. AI is a promising research tool for improving the early detection and diagnosis of Obsessive-Compulsive Disorder (OCD), primarily by assisting human clinicians. OCD starts early in life, however, symptoms often go undetected and undiagnosed, and hence there is a delay of 17 years from the onset of OCD symptoms until diagnosis and treatment. The diagnosis of obsessive-compulsive disorder (OCD) is typically achieved through clinical assessment and psychological testing. In recent years, neuroimaging and related fields of artificial intelligence have also shown promising results in diagnosing OCD.

Literature review

The table presents information on studies from 2024–2025 that applied various machine learning, deep learning, and AI techniques—such as SVM, CNN, LSTM, RF, ANN, DT, and NLP—for detecting, classifying, and predicting severity of obsessive–compulsive disorder.

S.No	Year	Author	Journal	Title	Methodology	Result
1	2024	Mahdiyeh *et al.*	Science Direct	Machine learning in obsessive-compulsive disorder medications	Decision Tree CHAID (Chi-square Automatic Interaction Detection), Linear Model, EWKM Clustering	94.8% accuracy; key drugs identified—clomipramine, duloxetine, pindolol.
2	2025	Mahdi *et al.*	BMC Psychiatry	A systematic review of EEG-based machine learning classifications for obsessive-compulsive disorder: current status and future directions	SVM, CNN, LSTM, RF, ANN models	Accuracy ranges from 57% to 100%.
3	2025	Jiyeong *et al.*	Springer	Artificial Intelligence in Obsessive-Compulsive Disorder: A Systematic Review	Uses ML, DL, NLP, GenAI models, and text/brain feature embeddings	AI helps detect OCD, but accuracy varies due to small, non-standard dataset
4	2025	Brian *et al.*	Frontiers	Deep learning in obsessive-compulsive disorder: a narrative review	Systematic review shows CNN, RNN, and LSTM are the main DL algorithms used in OCD research	Deep learning studies show OCD diagnostic accuracy ranging from 80% to 98%
5	2024	Kabita *et al.*	Eurobiotech	Machine Learning Approaches for Obsessive Compulsive Disorder Detection	SVM, RF, DT, LDA, KNN	SVM gives best accuracy (96.44%) for OCD detection
6	2024	Brian A. *et al.*	Elsevier	Predicting OCD severity from religiosity and personality: A machine learning and neural network approach	LR, DT, RF, NN	Best model accuracy: Linear Regression (RMSE ≈ 10.99)

OCD Diagnosis Methods

Only trained therapists can diagnose OCD. Therapists will look for three things:

- The person has obsessions.
- He or she does compulsive behaviors.
- The obsessions and compulsions take a lot of time and get in the way of important activities the person values, such as working, going to school, or spending time with friends.

Steps to help diagnose obsessive-compulsive disorder may include:

- **Psychological evaluation.** This includes talking about your thoughts, feelings, symptoms and behavior patterns to find out if you have obsessions or compulsive behaviors that get in the way of your quality of life. With your permission, this may include talking to your family or friends.
- **Physical exam.** This may be done to rule out other issues that could cause your symptoms and check for any related complications.

Diagnostic challenges

It's sometimes hard to diagnose OCD because symptoms can be like those of obsessive-compulsive personality disorder, anxiety disorders, depression, schizophrenia or other mental health disorders, and lack of provider training, often leading to delayed identification and treatment.

Key Challenges in Diagnosis

- **Symptom Similarity**: OCD symptoms (worry, anxiety, rituals) mimic other disorders like Generalized Anxiety Disorder (GAD), Depression, or even schizophrenia, leading to misdiagnosis.
- **Patient Secrecy**: Fear of judgment or shame makes individuals hide obsessions and compulsions, delaying professional help.
- **High Comorbidity**: OCD frequently coexists with other mental health issues (anxiety, depression, ADHD, BDD), complicating diagnosis if only one aspect is addressed.
- **Diagnostic Heterogeneity**: OCD presents very differently in different people (e.g., contamination, symmetry, harm fears), making a single diagnostic picture elusive.
- **Provider Knowledge Gaps**: Some healthcare providers lack specific training in recognizing and assessing OCD effectively, especially in complex cases.
- **Obsessive-Compulsive Personality Disorder (OCPD)**: Symptoms can overlap significantly with OCD, requiring careful differentiation.

AI in OCD Diagnosis

Artificial intelligence (AI) has emerged as a transformative tool in mental health, offering innovative solutions for diagnosis, treatment personalization, and research in psychiatric disorders.

Machine learning algorithms facilitate early diagnosis, predict treatment outcomes, and optimize pharmacological interventions by analyzing neuroimaging and clinical data.

Machine learning (ML) techniques are increasingly being integrated into the diagnostic process of OCD. Using MRI scan data sets, ML algorithms can automate the identification of patterns in brain structure that differentiate individuals with OCD from healthy controls.

Additionally, AI-powered neurostimulation methods, such as closed-loop deep brain stimulation, have demonstrated efficacy in treatment-resistant OCD cases. Natural language processing algorithms enhance early detection and differential diagnosis of OCD by extracting patterns from clinical narratives and patient histories.

Studies have increasingly applied AI techniques to neuroimaging modalities such as electroencephalography (EEG), magnetic resonance imaging (MRI), and functional MRI (fMRI), as well as clinical and behavioural data. In addition, recent systematic reviews highlight the growing use of EEG-based classification models and generative AI approaches, including natural language processing (NLP), for early symptom detection and treatment optimization.

Highlights

- Machine learning algorithms facilitate early diagnosis, predict treatment outcomes, and optimize pharmacological interventions by analyzing neuroimaging and clinical data.
- AI-enhanced neuro stimulation, such as closed-loop deep brain stimulation, has shown promise for treating cases resistant to conventional therapies.
- Natural language processing enhances diagnostic accuracy by extracting patterns from patient histories.
- AI-powered neuro feedback and virtual therapy platforms enhance exposure and response prevention therapy, increasing treatment accessibility and effectiveness.
- Data privacy, algorithmic transparency, and ethical considerations remain.

Conclusion:

AI-based neuroimaging approaches, especially EEG-driven models, show strong potential for early OCD diagnosis and treatment response prediction. While SVM remains widely used, deep learning and explainable AI are essential for capturing complex neural patterns and enabling clinical trust. Standardization, larger datasets, and external validation are critical for real-world implementation. AI tools are meant to assist, not replace, qualified mental health professionals. A complete assessment by a trained professional is still the standard for accurate diagnosis and care.

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CURRENT TRENDS IN INTERNET OF THINGS (IOT) AND SMART TECHNOLOGIES: A COMPREHENSIVE REVIEW

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Abstract:

The rapid evolution of the Internet of Things (IoT) has transformed traditional systems into intelligent, interconnected smart environments. IoT, combined with emerging smart technologies such as artificial intelligence (AI), edge computing, big data analytics, and cloud platforms, has enabled innovative applications across healthcare, smart cities, industrial automation, agriculture, and transportation. This review paper presents a comprehensive overview of current trends in IoT and smart technologies, highlighting recent advancements in architectures, communication protocols, data analytics, and security mechanisms. Furthermore, it discusses key challenges including scalability, interoperability, privacy, and energy efficiency, and outlines future research directions for sustainable and intelligent IoT ecosystems. The objective of this work is to provide researchers and practitioners with a consolidated reference to understand the state of the art and identify open research problems in the rapidly evolving IoT domain.

Keywords: Internet of Things, Smart Technologies, Edge Computing, AIoT, Smart Cities, Industry 4.0, IoT Security.

Introduction:

The Internet of Things (IoT) refers to a paradigm in which physical objects such as sensors, actuators, appliances, and machines are interconnected through the Internet, enabling continuous data exchange and intelligent decision-making. The concept of IoT has gained remarkable attention due to the exponential growth of connected devices and advancements in wireless communication, embedded systems, and cloud infrastructures.

Smart technologies represent the integration of IoT with artificial intelligence (AI), machine learning (ML), big data analytics, and automation techniques to build systems that can sense, learn, reason, and act autonomously. These technologies are playing acrucial role in enabling digital transformation across sectors including healthcare, manufacturing, transportation, and public services.

The motivation for this review arises from the rapid diversification of IoT applications and the emergence of new paradigms such as AIoT, edge intelligence, and digital twins. This paper aims to systematically analyze current trends, discuss enabling technologies, identify challenges, and explore future research directions in IoT and smart systems.

Background and Evolution of IoT

The roots of IoT can be traced back to early developments in radio frequency identification (RFID) and machine-to-machine (M2M) communications, where devices were connected for basic monitoring and control. Over time, advancements in sensor technology and wireless communication protocols enabled large-scale wireless sensor networks (WSNs), laying the foundation for modern IoT systems.

The introduction of IPv6 significantly accelerated IoT adoption by providing a vast address space to uniquely identify billions of devices. With the emergence of cloud computing, IoT systems gained scalable storage and processing capabilities, enabling real-time analytics and visualization of massive data streams generated by connected devices.

More recently, the convergence of IoT with AI and big data technologies has given rise to intelligent IoT ecosystems capable of autonomous decision-making and predictive analytics. The evolution from centralized cloud-based models to distributed edge and fog architectures further enhanced system responsiveness and reliability. This evolution reflects a shift from simple data collection to intelligent cyber-physical systems that tightly integrate the physical and digital worlds, supporting complex smart applications in dynamic environments.

IoT Architecture and Enabling Technologies

A typical IoT architecture is organized into multiple layers that collectively support data acquisition, communication, processing, and service delivery. The perception layer consists of sensors and actuators responsible for sensing physical parameters such as temperature, humidity, motion, and pressure. These devices form the interface between the physical world and digital systems.

The transport layer enables data transmission using wired or wireless technologies such as Wi-Fi, Bluetooth, ZigBee, LoRaWAN, NB-IoT, and cellular networks including 4G and 5G. This layer ensures reliable and scalable connectivity among heterogeneous devices.

The processing layer provides storage and computational resources using cloud, fog, and edge computing infrastructures. While cloud computing offers high scalability and powerful analytics, edge and fog computing bring computation closer to data sources, reducing latency and bandwidth consumption.

The application layer delivers user-centric services tailored to specific domains such as healthcare, smart homes, and industrial automation. Middleware platforms play a crucial role in managing devices, data flows, and application integration.

Enabling technologies for IoT include cloud platforms, virtualization, big data frameworks, AI/ML algorithms, blockchain for secure transactions, and digital twins for system modeling. Together, these technologies enhance scalability, intelligence, and reliability of IoT ecosystems.

Current Trends in IoT

The rapid advancement of IoT has led to several emerging trends that are redefining smart systems. One of the most prominent trends is AI-enabled IoT (AIoT), where machine learning and deep learning techniques are embedded into IoT pipelines to enable predictive analytics, anomaly detection, and autonomous control.

Edge and fog computing have gained importance as they enable real-time data processing near the source, which is critical for latency-sensitive applications such as autonomous vehicles, industrial control, and healthcare monitoring. These paradigms also reduce dependency on cloud resources and improve privacy.

The deployment of 5G networks has opened new opportunities for massive IoT by providing ultra-low latency, high bandwidth, and support for a large number of connected devices. Alongside, low-power wide-area networks (LPWAN) such as LoRaWAN and NB-IoT are widely adopted for long-range and energy-efficient communication.

TinyML is another emerging trend that focuses on deploying lightweight ML models on resource-constrained devices, enabling on-device intelligence without continuous cloud interaction. Digital twins provide virtual replicas of physical systems, facilitating real-time monitoring, simulation, and optimization.

Blockchain technology is being explored to ensure decentralized security, trust, and data integrity in IoT networks. Furthermore, energy harvesting and green IoT solutions aim to build sustainable systems by reducing power consumption and extending device lifetime.

Smart Technologies and Applications

IoT serves as the backbone for a wide range of smart technologies that enhance efficiency, safety, and sustainability. Smart cities leverage IoT for traffic management, smart lighting, waste management, environmental monitoring, and public safety, leading to improved urban living conditions.

In healthcare, IoT enables remote patient monitoring, wearable health devices, smart diagnostics, and telemedicine platforms. These solutions improve accessibility to healthcare services and enable proactive disease management.

Smart homes integrate sensors and automation systems to control lighting, heating, security, and appliances, providing comfort and energy efficiency. Voice assistants and mobile applications offer intuitive user interfaces for home management.

In agriculture, smart farming utilizes IoT sensors for soil monitoring, weather prediction, and automated irrigation, enabling precision agriculture and improving crop yield while conserving resources.

Industry 4.0 represents the application of IoT in manufacturing environments, where smart sensors, robotics, and analytics enable predictive maintenance, asset tracking, and optimized production processes.

Smart transportation systems employ IoT for vehicle tracking, traffic optimization, fleet management, and intelligent public transport, contributing to reduced congestion and enhanced safety.

Security, Privacy, and Interoperability

Despite its benefits, IoT faces significant challenges in terms of security and privacy. Many IoT devices are resource-constrained and lack robust security mechanisms, making them vulnerable to attacks such as malware injection, spoofing, denial-of-service, and unauthorized access.

Privacy concerns arise due to continuous data collection from personal and sensitive environments. Unauthorized data sharing and user profiling can lead to serious ethical and legal issues. Therefore, privacy-preserving data analytics and access control mechanisms are essential.

Interoperability is another critical challenge due to the heterogeneity of devices, platforms, and communication protocols. The lackof common standards hinders seamless integration and large-scale deployment. Protocols such as MQTT, CoAP, and standards like oneM2M and IEEE 2413 aim to address these issues.

Security solutions include lightweight cryptography, secure boot mechanisms, authentication and authorization frameworks, intrusion detection systems, and blockchain-based trust models. A holistic approach is required to ensure end-to-end security in IoT systems.

Challenges and Open Issues

Although IoT has matured significantly, several challenges still limit its widespread adoption. Energy efficiency remains a major concern as many devices operate on limited battery power and are deployed in inaccessible environments.

Scalability is critical for supporting billions of connected devices while maintaining reliable performance and manageable overheads. Efficient device management, firmware updates, and fault tolerance mechanisms are required.

Real-time data processing and low-latency communication are essential for mission-critical applications such as healthcare and industrial automation. Network congestion and bandwidth limitations pose additional challenges.

Other issues include data heterogeneity, lack of skilled workforce, regulatory compliance, ethical considerations, and ensuring user trust. Addressing these challenges requires collaborative efforts from academia, industry, and policymakers.

Future Research Directions

Future IoT research is expected to focus on integrating next-generation communication technologies such as 6G to support ultra-reliable and low-latency communication with intelligent network management.

Autonomous IoT systems capable of self-configuration, self-healing, and self-optimization will become increasingly important. Federated and privacy-preserving learning approaches will enable collaborative intelligence without sharing raw data.

Green IoT initiatives will emphasize energy-efficient hardware, energy harvesting techniques, and sustainable network designs to reduce environmental impact.

Human-centric IoT will focus on improving usability, accessibility, and ethical design to ensure technology serves societal needs. Context-aware systems will enable adaptive behavior based on environmental and user conditions.

The convergence of IoT with emerging technologies such as quantum computing, extended reality, and robotics will further expand the scope of smart applications.

Conclusion:

This paper presented a comprehensive review of current trends in IoT and smart technologies. The evolution of IoT from simple connectivity solutions to intelligent cyber-physical systems highlights its transformative impact on modern society.

The integration of AI, edge computing, advanced communication networks, and smart analytics is enabling a new generation of applications across diverse domains. However, challenges related to security, privacy, interoperability, scalability, and energy efficiency remain significant.

Addressing these challenges through interdisciplinary research, standardization, and innovative system design is essential for realizing the full potential of IoT. Future developments will continue to shape smart environments and contribute to building sustainable, intelligent, and human-centric digital ecosystems.

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UNDERSTANDING THE ISSUES AND CHALLENGES RELATED TO URBAN HEAT ISLAND

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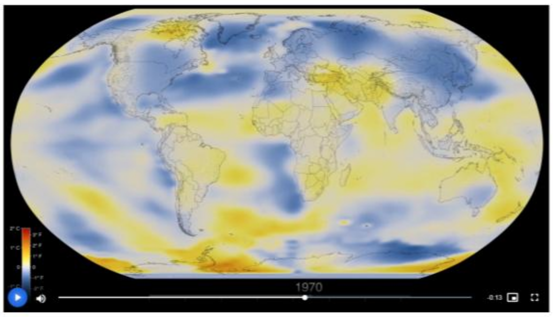
Abstract:
Urbanization is a dominant global process that has profoundly transformed land-use and land-cover patterns, replacing natural and agricultural landscapes with impervious built-up surfaces. These transformations have significantly altered surface energy balances and local climatic conditions, leading to the emergence and intensification of the Urban Heat Island (UHI) effect. Globally, empirical evidence from major metropolitan regions demonstrates that urban areas experience higher air and surface temperatures than surrounding rural and peri-urban regions due to factors such as anthropogenic heat emissions, reduced vegetation cover, and altered surface thermal properties. In the Indian context, rapid and often unplanned urbanization, declining green and blue infrastructure, widespread informal housing, and weak institutional capacity have further intensified heat stress, disproportionately affecting vulnerable populations. Despite growing recognition of climate-sensitive urban planning measures, UHI mitigation remains fragmented, non-mandatory, and inadequately integrated into statutory planning frameworks. This paper examines the key issues and challenges associated with the Urban Heat Island effect, highlighting the role of land-use transformation, governance gaps, and socio-economic vulnerability.

Keywords: Urbanization, Heat Island, Urban Biodiversity, Informal Housing, Heat Stress, Climate Senstive Planning

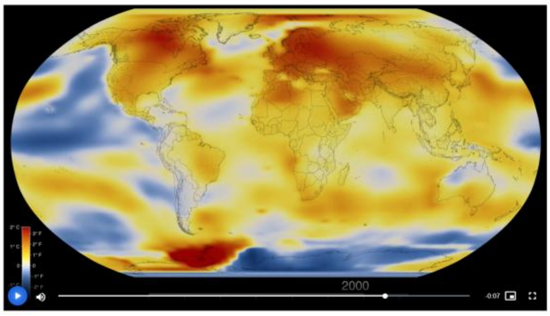
1. Introduction:

Urbanization is a dominant global process characterized by the expansion of built-up areas and increasing concentration of population in cities, largely driven by industrialization, economic development, and rural–urban migration. Rapid urban growth has resulted in profound transformations of land use and land cover, with natural and agricultural landscapes increasingly replaced by impervious surfaces such as buildings, roads, and other urban infrastructure. These changes have significantly altered surface energy balances and local climatic conditions, leading to the emergence and intensification of the urban heat island (UHI) effect.

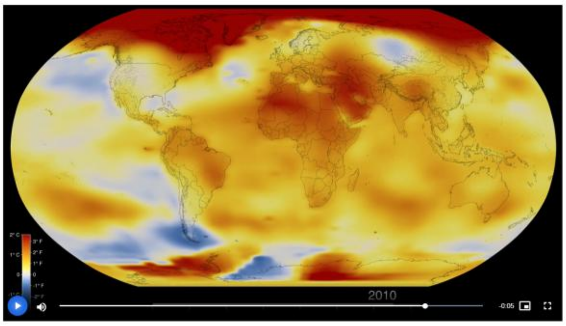
At the global scale, numerous studies have documented higher air and surface temperatures in urban cores compared to surrounding rural or peri-urban areas. Long-term climatic analyses from major metropolitan regions such as New York, London, Tokyo, and Shanghai indicate that urban areas exhibit accelerated warming trends relative to regional averages. Research based on meteorological records demonstrates statistically significant increases in mean and maximum temperatures associated with urban expansion, anthropogenic heat emissions, reduced vegetation cover, and modified surface thermal properties (Oke, 1982; United States Environmental Protection Agency, 2008; Stewart & Oke, 2012). These elevated temperatures contribute to increased energy demand for cooling, deterioration of air quality, heightened greenhouse gas emissions, and adverse impacts on public health and urban ecosystems.



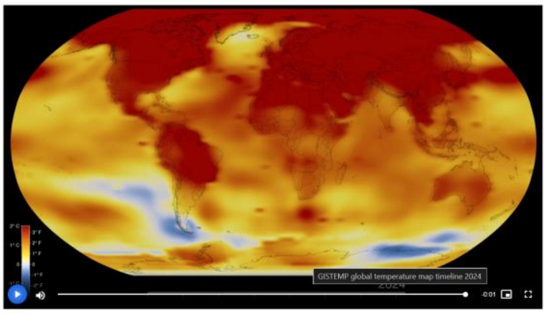
Year 1970



Year 2000



Year 2010



Year 2024

Figure 1: Global Surface Temperature (Source: https://svs.gsfc.nasa.gov/5450)

Figure 1 shows the changing global surface temperature in the years 1970, 2000, 2010, and 2024. Earth's global temperature in 2024 was 2.3 degrees Fahrenheit (or about 1.28 degrees Celsius) warmer than the 20th-century baseline 1951 - 1980. Dark blue shows areas cooler than average. Dark red shows areas warmer than average (https://svs.gsfc.nasa.gov/5450). Overall, both global and Indian experiences demonstrate that urban heat islands are a direct outcome of land-use transformation and climate-insensitive urban development. This paper will focus on understanding the issues and challenges related to UHI.

2. Issues related to Urban Heat Island

2.1. Increased Surface Temperatures

Urban areas experience significantly higher temperatures than surrounding rural regions due to extensive use of impervious materials such as concrete and asphalt, which absorb and retain heat. Reduced vegetation and altered surface albedo further exacerbate heat accumulation, particularly during nighttime, leading to persistent thermal stress in cities. This increased surface temperature causes discomfort, resulting in a higher cooling demand (Oke, 1982).

2.2. Increased Energy Consumption

The increased stress on energy due to higher urban temperatures raises the demand for air conditioning and cooling systems, particularly during the summer months. This leads to peak electricity loads, increased fossil fuel consumption, and greater greenhouse gas emissions, creating a feedback loop that intensifies both UHI and climate change. Further, this increased demand for air conditioning and power increased the household expenditure (Santamouris, 2015).

2.3. Degradation of Air Quality

The Urban Heat Island effect intensifies the formation of ground-level ozone and smog by accelerating temperature-dependent photochemical reactions. Elevated urban temperatures also contribute to increased emissions from vehicles and energy generation systems, thereby exacerbating air pollution levels. These combined effects heighten public health risks, particularly respiratory and cardiovascular disorders, and degrade overall urban environmental quality (Piracha and Chaudhary, 2022).

2.4. Stress on Urban Water Systems

Rising urban temperatures accelerate evaporation from water bodies and significantly increase demand for water for domestic use and space cooling. Heat absorbed by impervious urban surfaces is transferred to rivers and lakes through stormwater runoff, causing thermal pollution that alters natural water temperature regimes. These changes reduce dissolved oxygen levels and disrupt aquatic ecosystems, ultimately contributing to water scarcity and ecological degradation (Arnfield, 2003).

2.5. Loss of Urban Biodiversity and Ecosystem Services

The Urban Heat Island effect modifies local microclimates, creating thermal conditions that are unfavorable for native plant and animal species. Declining urban green cover combined with elevated surface temperatures reduces essential ecosystem services, including shading, evapotranspiration, and carbon sequestration, thereby weakening overall urban ecological resilience (Pickett *et al.,* 2010).

2.6. Public Health Risks

Elevated urban temperatures amplify the incidence and intensity of heat-related illnesses, including heat exhaustion, heat stroke, and cardiovascular stress. Vulnerable groups such as the elderly, children, outdoor workers, and low-income populations experience disproportionate exposure and reduced adaptive capacity. Additionally, the Urban Heat Island effect exacerbates air pollution, further intensifying respiratory health risks (Hajat & Kosatky, 2010).

3. Challenges Related to Urban Heat Island (UHI)

3.1. Rapid and Unplanned Urbanization

Cities worldwide have experienced rapid expansion with limited incorporation of climate-sensitive planning approaches. High-density development, urban sprawl, and the widespread conversion of agricultural and open lands into impervious built-up surfaces have intensified surface heat absorption and retention. Additionally, the proliferation of informal and poorly planned settlements, which lack adequate ventilation, insulation, and thermal comfort measures, has further exacerbated the Urban Heat Island effect across both developed and developing regions (UN-Habitat, 2020; Oke, 1982).

3.2. Declining Urban Green Cover and Blue Infrastructure

Urban green spaces, water bodies, wetlands, and urban forests are increasingly being encroached upon or degraded due to development pressures. The loss of vegetation diminishes evapotranspiration and shading, which are critical natural cooling mechanisms that regulate urban microclimates. Consequently, many Indian cities fall significantly below the World Health Organization's recommended per capita green space standards, exacerbating urban heat stress and reducing environmental quality (Gill *et al.,* 2007; WHO, 2016).

3.3. Heat Stress

India's tropical climate, combined with UHI effects, significantly increases the frequency of heat stress events. Urban poor, elderly, women, children, and outdoor workers are disproportionately affected. Limited access to cooling, healthcare, and early warning systems worsens vulnerability (Azhar *et al.,* 2014).

3.4. Inadequate Climate-Sensitive Urban Planning and Governance

Absence and partial implementation of mitigation measures such as cool roofs, urban forestry, etc., across urban areas, particularly in rapidly expanding and peri-urban zones. Furthermore, prevailing planning practices tend to prioritize land-use efficiency, development intensity, and real estate imperatives over microclimatic considerations, resulting in the systematic neglect of heat-sensitive urban design principles within statutory planning processes.

Institutional fragmentation further constrains effective UHI mitigation. Responsibilities related to land use planning, building approvals, transport infrastructure, urban forestry, and environmental management are frequently distributed across multiple agencies with limited coordination. This siloed governance structure hampers the development of integrated heat mitigation strategies and weakens accountability mechanisms. Urban local bodies (ULBs) often face significant capacity constraints, including limited access to high-resolution climate and land surface temperature data, inadequate technical expertise in climate-responsive urban design, and insufficient financial resources. These challenges are particularly pronounced in small and medium-sized cities, where institutional capacities and fiscal autonomy are relatively weak. As a result, UHI mitigation is rarely addressed in a systematic, evidence-based manner, reducing the effectiveness of urban climate adaptation efforts and increasing heat-related risks for vulnerable populations (MoHUA, 2022).

3.5. Informal Housing and Poor Building Materials

A significant proportion of the urban population resides in informal settlements characterized by substandard housing constructed using highly heat-absorbing materials such as corrugated metal sheets, asbestos panels, and uninsulated concrete blocks. These materials exhibit high thermal conductivity and low reflectivity, resulting in elevated indoor temperatures, particularly during prolonged heatwave conditions. The absence of basic climate-responsive design features such as adequate insulation, cross-ventilation, shading devices, and reflective surfaces exacerbates indoor heat stress. Furthermore, residents of informal settlements often lack reliable access to mechanical cooling technologies due to economic constraints and limited electricity supply, intensifying their exposure to extreme heat and associated health risks. As a result, informal housing becomes a critical hotspot of urban heat vulnerability, disproportionately affecting low-income groups, women, children, and the elderly (Mehrotra *et al.,* 2018).

Urban local bodies frequently lack dedicated funding streams and technical frameworks for implementing low-cost, heat-resilient retrofitting solutions, such as cool roofs, improved ventilation, and passive shading systems. Additionally, successful retrofitting requires meaningful community participation to ensure local acceptance, maintenance, and context-specific design adaptation. Without integrated policy support, innovative financing models, and participatory implementation strategies, efforts to reduce heat exposure in informal settlements remain fragmented and insufficient, undermining broader urban climate resilience goals (Mehrotra *et al.,* 2018).

Conclusion:

The Urban Heat Island effect has emerged as a critical challenge associated with contemporary urbanization, driven primarily by rapid land-use transformation, increasing impervious surfaces, declining vegetation cover, and climate-insensitive urban development practices. UHI is not merely a climatic phenomenon but a systemic outcome of planning, governance, and socio-economic processes embedded within urban growth trajectories. Rising urban temperatures contribute to increased energy demand, deteriorating air quality, stress on water systems, loss of biodiversity, and significant public health risks, particularly for vulnerable populations such as the urban poor, elderly, women, children, and outdoor workers.

The impacts of UHI are further intensified by unplanned urban expansion, proliferation of informal settlements, inadequate building materials, and limited access to cooling and healthcare infrastructure. Institutional fragmentation, insufficient technical capacity, and the absence of binding regulatory frameworks for climate-sensitive planning continue to constrain effective mitigation efforts. Although measures such as urban greening, cool roofs, blue infrastructure, and passive design strategies have demonstrated potential, their implementation remains uneven and largely project-based rather than systemic.

Addressing the Urban Heat Island effect requires a paradigm shift in urban planning and governance, moving beyond land-use efficiency and real estate–driven development toward integrated, heat-sensitive urban design. Strengthening institutional coordination, enhancing data-driven decision-making, mainstreaming UHI mitigation into statutory planning instruments, and prioritizing vulnerable communities are essential for building urban climate resilience. Integrating these strategies within broader sustainability agendas, including SDG 11 on sustainable cities and communities, will be critical for ensuring that future urbanization pathways are equitable, resilient, and environmentally sustainable.

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