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PREFACE

WE ARE PLEASED TO PRESENT TECH: JOURNAL OF ENGINEERING SCIENCE, VOLUME 1, NUMBER 2 (2025), WHICH FEATURES A COLLECTION OF SIX PEER-REVIEWED ARTICLES HIGHLIGHTING RECENT INNOVATIONS AND APPLICATIONS IN ENGINEERING AND APPLIED SCIENCES. THIS ISSUE REFLECTS A BROAD SPECTRUM OF RESEARCH, INCLUDING HEALTHCARE INFORMATION SYSTEMS, INDUSTRIAL PRODUCTIVITY, SUSTAINABLE MATERIALS, FOOD TECHNOLOGY, ENVIRONMENTAL CARRYING CAPACITY, AND COMPUTATIONAL MODELING.

THE CONTRIBUTIONS IN THIS VOLUME COME FROM AUTHORS REPRESENTING THREE COUNTRIES—INDONESIA, NIGERIA, AND THE UNITED KINGDOM (ENGLAND)—COVERING DIVERSE REGIONS SUCH AS BANTEN, THE SPECIAL REGION OF YOGYAKARTA, OTHER PARTS OF INDONESIA, ANAMBRA STATE (NIGERIA), AND ENGLAND (UNITED KINGDOM). THE AUTHORS ARE AFFILIATED WITH SEVEN HIGHER EDUCATION INSTITUTIONS, NAMELY UNIVERSITAS SULTAN AGENG TIRTAYASA, UNIVERSITAS GADJAH MADA, UNIVERSITAS ISLAM INDONESIA, UNIVERSITAS PEMBANGUNAN NASIONAL "VETERAN" YOGYAKARTA, INSTITUT TEKNOLOGI SEPULUH NOPEMBER (INDONESIA), NNAMDI AZIKIWE UNIVERSITY (NIGERIA), AND THE UNIVERSITY OF CHESTER (UNITED KINGDOM).

THIS ISSUE EMBODIES THE JOURNAL'S MISSION TO SHOWCASE RESEARCH THAT ENHANCES PRODUCTIVITY, SUSTAINABILITY, AND SYSTEM MODELING IN ENGINEERING, WHILE ALSO FOSTERING INTERNATIONAL COLLABORATION. WE HOPE THAT THIS COLLECTION WILL INSPIRE FURTHER RESEARCH, INNOVATION, AND PRACTICAL APPLICATIONS IN ENGINEERING AND APPLIED SCIENCES.

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Conceptual Computational Modeling of Genetic and Neurochemical Traits of Social Outcasts in the Series Wednesday

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ABSTRACT

This study explores the representation of genetic and neurochemical traits associated with social outcast groups as depicted in the television series Wednesday, using a conceptual computational modeling framework. Rather than pursuing empirical biological validation, the research adopts speculative and educational modeling approaches inspired by systems biology, neurochemistry, and computational neuroscience to interpret narrative patterns related to marginalization, emotional regulation, and behavioral divergence. Conceptual models are constructed by mapping fictional character traits to simplified genetic markers, neurotransmitter interactions, and network-based behavioral dynamics. The study aims to demonstrate how computational thinking can be employed as an interdisciplinary analytical tool for science communication, critical media analysis, and pedagogical innovation. Limitations of the study include the non-empirical nature of the data and the reliance on narrative abstraction. Nevertheless, the findings highlight the potential of computational frameworks to bridge popular culture and scientific reasoning in an accessible and ethically reflective manner.

Keywords: *outcast groups; computational modeling; genetics; neurochemistry; interdisciplinary studies.*

ABSTRAK

Studi ini mengeksplorasi pemodelan ciri genetik dan neurokimia kelompok terbuang fiktif—Vampir, Manusia Serigala, Siren, dan Gorgon—yang digambarkan dalam serial Netflix Wednesday. Dengan menggunakan pendekatan komputasional, penelitian ini mengembangkan kerangka kerja spekulatif untuk memetakan karakteristik fiktif ke dalam mekanisme biologis yang masuk akal. Simulasi menyoroti adaptasi hematologi pada Vampir, siklus sirkadian dan hormonal pada Manusia Serigala, modulasi auditori-neurokimia pada Siren, dan inhibisi saraf yang diinduksi okular pada Gorgon. Hasilnya menunjukkan bahwa arketipe budaya dapat berfungsi sebagai metafora edukatif untuk memperkenalkan konsep biologis dan neurokimia yang kompleks. Di luar plausibilitas ilmiah, studi ini menekankan implikasi pedagogis, komunikatif, dan etis dari pengintegrasian fiksi ke dalam sains terapan. Meskipun model-model ini pada dasarnya spekulatif, nilai interdisiplinernya terletak pada penjembatanan genetika, neurosains, pemodelan komputasional, dan studi budaya. Karya ini mengusulkan bahwa fiksi

dapat bertindak sebagai cermin reflektif sekaligus alat pedagogis dalam kemajuan sains dan teknologi.
Kata Kunci: *kelompok terbuang; pemodelan komputasional; genetika; neurokimia; studi interdisipliner.*

Introduction

Popular media has increasingly become a platform for engaging public discourse on science-related themes, including genetics, neurochemistry, and human behavior. Television series such as Wednesday present fictional narratives that intertwine social marginalization with perceived biological and psychological uniqueness, offering fertile ground for interdisciplinary analysis (Krizek & Müller, 2022; Strielkowski et al., 2013). Within this context, social outcasts are often portrayed as possessing atypical cognitive, emotional, or behavioral traits that symbolically echo real-world discussions in neuroscience and genetics (Mäki-Marttunen et al., 2015).

Recent advances in computational biology and systems neuroscience have demonstrated the value of modeling frameworks in simplifying complex biological interactions for analytical and educational purposes. While such models are traditionally grounded in empirical data, conceptual and speculative computational modeling has emerged as a useful approach for science communication, enabling abstract systems to be explored through metaphor, simulation, and network reasoning. This approach is particularly relevant when analyzing fictional or narrative-based datasets, where empirical validation is neither feasible nor intended (Gupta et al., 2013; Molinelli et al., 2013)..

This study positions Wednesday as a narrative case study to examine how representations of genetic predisposition, neurochemical regulation, and behavioral divergence can be interpreted through a computational lens. By translating narrative elements into simplified models, such as gene behavior associations, neurotransmitter interaction diagrams, and agent based behavioral abstractions, the research seeks to illustrate how computational approaches can support critical reflection on the biological framing of social difference Krizek & Müller, 2022).

Accordingly, this paper addresses the following research questions:

(1) How are genetic and neurochemical traits symbolically represented in the depiction of outcast groups in Wednesday?

(2) In what ways can conceptual computational modeling be used to interpret these representations?

(3) What is the pedagogical and communicative value of applying computational frameworks to fictional narratives?

By clarifying these questions, the introduction establishes a focused analytical framework that integrates media studies, neuroscience-inspired

modeling, and computational thinking. This interdisciplinary perspective contributes to broader discussions on ethical science communication, the limits of biological determinism in popular culture, and the role of computational models as interpretiv, not predictive tools (Petersson, 2024). Computational biology has advanced rapidly, offering tools such as systems modeling, genetic algorithms, and network simulations. These approaches allow the study of complex traits by simulating interactions among genes, proteins, and neurotransmitters. Applying these techniques to fictional archetypes creates a platform for scientific imagination. Neurochemical modeling, in particular, provides insights into behavioral regulation and cognitive processes. By hypothesizing how neurotransmitters like dopamine, oxytocin, or acetylcholine might influence outcast traits, researchers can construct analogies that also deepen understanding of human neurobiology.

Fiction-based modeling is not new. Scholars have examined vampires as metaphors for epidemiology, zombies as models for contagion dynamics, and superheroes as representations of genetic mutation. Extending this tradition, the present study uses Wednesday's outcast categories to explore applied science concepts. The educational benefits are substantial. By linking entertainment with computational biology, students and researchers alike can see how complex processes can be visualized and simulated. This creates opportunities for interdisciplinary teaching, bridging biology, informatics, and media studies (Xiong et al., 2025).

Moreover, these models contribute to public science communication. Complex topics in genetics and neurochemistry often alienate non-specialists. Fictional analogies, however, provide familiar narratives that demystify and humanize science. Ethical considerations also emerge from such explorations. The idea of modifying genes to achieve enhanced traits, or regulating neurochemistry to control behavior, raises pressing questions in biotechnology and bioethics. Fictional analogies allow these debates to be introduced in accessible yet meaningful ways.

The significance of this research lies in its interdisciplinarity. It is not confined to narrative analysis or pure biology but occupies the space in between. By doing so, it demonstrates the flexibility of computational approaches and their relevance beyond conventional applications (Gupta et al., 2013; Mardt et al., 2017). This introduction positions Wednesday's outcast groups as metaphors for scientific exploration. It does not reduce them to mere entertainment but instead uses them as entry points into applied science discourse.

In focusing on genetics and neurochemistry, this study emphasizes biological and physiological foundations while also acknowledging cultural dimensions. This dual approach ensures both scientific rigor and narrative

engagement. The research objectives are threefold: to map fictional traits onto plausible genetic and neurochemical pathways; to construct computational models simulating these traits; and to explore the educational and communicative potential of such interdisciplinary studies.

Through these objectives, the study seeks to highlight the possibilities of science fiction-inspired computational modeling as both a research tool and an educational strategy. Ultimately, this introduction sets the stage for a broader exploration: how outcasts in Wednesday—Vampires, Werewolves, Sirens, and Gorgons—can serve as imaginative yet scientifically grounded models, helping to connect speculative narratives with the real frontiers of applied science.

Literature Review

Literature on the intersection of fiction and science has grown substantially in recent years. Scholars have increasingly recognized that fictional archetypes can serve as heuristic devices for exploring scientific phenomena. From epidemiological models based on zombie outbreaks to genetic analogies inspired by superheroes, fiction has consistently offered metaphors for complex biological processes. The vampire archetype, one of the most enduring figures in folklore and literature, has been studied extensively as a metaphor for disease transmission and hematological anomalies. Researchers have connected vampire myths with historical understandings of tuberculosis, porphyria, and rabies. These analyses reveal how fictional depictions mirror real biological conditions (Strielkowski et al., 2013).

Werewolves, similarly, have been explored as metaphors for psychological and genetic conditions. Studies often link lycanthropy with bipolar disorder, dissociative identity disorder, or circadian rhythm disruptions. Contemporary research in chronobiology provides scientific frameworks for understanding cyclical transformations, aligning well with werewolf narratives. Sirens and related mythological figures have historically been interpreted through the lens of psychology and cultural studies. More recent scientific literature connects siren-like traits to research in neurobiology of sound, auditory hallucinations, and the psychological impact of music. Studies in music therapy and auditory neuroscience show how sound influences human cognition and behavior (Krizek & Müller, 2022).

Gorgons, rooted in Greek mythology, represent the dangers of visual perception and sensory overload. Literature on gaze, paralysis, and neural inhibition has drawn parallels with the petrification myth. Neuroscientific studies of fear responses, such as the "freeze" mechanism, provide a biological counterpart to the gorgon archetype. Beyond individual archetypes, interdisciplinary scholarship explores how fiction serves as a tool for science communication. Researchers argue that speculative narratives lower barriers to understanding

complex topics, making them more relatable to non-specialist audiences (Mardt et al., 2017). This approach is especially powerful when combined with computational modeling.

Computational biology itself has seen rapid expansion as a field. Systems biology, agent-based modeling, and genetic algorithms allow researchers to simulate interactions among genes, proteins, and cellular processes. Literature emphasizes the ability of these models to represent nonlinear and emergent phenomena, which aligns with the unpredictable nature of fictional outcast traits (Gupta et al., 2013; Molinelli et al., 2013). Genetic modeling has been particularly effective in illustrating complex traits. Studies using computational tools such as BLAST, GenBank, and genome-wide association studies (GWAS) demonstrate how variations in specific genes lead to observable phenotypes. These tools can be adapted metaphorically to simulate the distinct attributes of fictional outcasts (Maki-Marttunen et al., 2015).

Neurochemical modeling also provides a strong foundation for exploring behavior. Literature on dopamine, oxytocin, serotonin, and acetylcholine emphasizes their roles in regulating mood, decision-making, and motor responses. By mapping outcast abilities onto these pathways, fictional traits can be examined with scientific plausibility. The integration of genetics and neurochemistry in computational models has been explored in contexts such as psychiatric disorders, addiction studies, and neurodegenerative diseases. These models demonstrate how multifactorial traits arise from the interplay of genes, neurotransmitters, and environmental influences (Gupta et al., 2013).

Scholars of narrative medicine and science communication highlight how fiction facilitates discussion of bioethical issues. Vampires raise questions about immortality and blood science, werewolves about genetic determinism, sirens about persuasion and consent, and gorgons about sensory vulnerability. Such discussions ground abstract ethical debates in concrete narrative forms. The educational potential of fiction-driven science is well-documented. Studies show that students engage more deeply with scientific material when it is connected to familiar cultural references. Using outcast archetypes as teaching tools could therefore enhance learning in genetics, neurobiology, and computational modeling.

Previous research on "edutainment" emphasizes the value of interdisciplinary approaches that blend entertainment with pedagogy. Literature suggests that gamified models, simulations, and narrative-based teaching lead to higher retention of scientific concepts compared to traditional lecture-based methods (Molinelli et al., 2013). In computational terms, literature on genetic algorithms highlights their suitability for simulating adaptation and evolution. These algorithms mimic biological evolution, using processes such as mutation and

selection to find optimal solutions. This makes them ideal for modeling how fictional traits might evolve within outcast populations.

Network analysis has also been widely applied in genetics and neuroscience. Literature demonstrates how complex systems can be represented as interconnected nodes, allowing visualization of pathways and interactions. Such methods are directly applicable to modeling the molecular networks underlying outcast traits. There is also a growing body of work on speculative biology, which constructs hypothetical models of fictional organisms (Molinelli et al., 2013). Scholars use evolutionary theory, genetics, and physiology to design plausible versions of mythical creatures. These speculative studies provide methodological precedents for examining outcasts in Wednesday.

Bioinformatics literature further underscores the power of open-access genomic and proteomic databases. Tools like KEGG, STRING, and UniProt allow detailed mapping of molecular interactions. These resources enable researchers to ground fictional modeling in real scientific data. In neuroscience, computational models of fear, aggression, and social bonding provide frameworks for analogizing outcast behaviors. Literature on neural networks and machine learning demonstrates how cognitive processes can be simulated, offering additional layers of insight (Mardt et al., 2017).

Interdisciplinary work also highlights the risks of oversimplification. Literature cautions that while fiction can aid science communication, it must not be conflated with empirical reality. Instead, it should serve as a bridge—an accessible metaphor that points toward but does not replace scientific evidence. Overall, the literature establishes a foundation for this study by demonstrating three key points: first, that fictional archetypes can be scientifically productive metaphors; second, that computational biology and neurochemistry provide the tools to model complex traits; and third, that integrating fiction with science enhances education, communication, and interdisciplinary inquiry (Strielkowski et al., 2013).

Research Methods

This study employs an interdisciplinary, conceptual–computational methodology designed to analyze fictional representations rather than to generate empirical biological predictions. The methodological workflow consists of four clearly defined stages.

First, narrative trait identification was conducted through close reading and scene-based analysis of the Wednesday series. Key behavioral, emotional, and physiological traits associated with outcast groups (e.g., emotional detachment, heightened sensory perception, fear response, social isolation) were systematically

cataloged. These traits function as analytical variables rather than biological measurements.

Second, biological pathway mapping was performed using established findings from peer-reviewed literature in genetics, neurochemistry, and systems neuroscience. Canonical pathways—such as dopamine–reward circuits, oxytocin-mediated social bonding, circadian rhythm regulation, and fear-related amygdala responses, were used as reference frameworks. Importantly, no original biological data were generated or inferred about real populations.

Third, conceptual computational models were constructed using simplified network representations and rule-based logic. Gene–trait and neurotransmitter–behavior relationships were modeled as abstract interaction graphs, inspired by systems biology modeling conventions. These models were implemented at a schematic level (diagrammatic and mathematical abstraction), not as predictive simulations. Parameter values were normalized and symbolic, serving illustrative rather than quantitative purposes.

Finally, exploratory simulations were executed in a constrained conceptual environment to demonstrate hypothetical system behavior under altered assumptions (e.g., increased dopamine sensitivity or reduced oxytocin signaling). These simulations were not calibrated against empirical datasets and are explicitly framed as speculative extensions intended for pedagogical visualization (Ramadhan et al., 2025).

To avoid misinterpretation, a strict distinction is maintained between real biological knowledge (used as theoretical grounding) and fictional narrative traits (used as modeling inputs). The methodological objective is interpretive coherence and interdisciplinary learning, not biological validation.Once biological mappings are identified, computational tools are applied to simulate the traits. Systems biology platforms such as CellDesigner are used to visualize molecular pathways, while MATLAB and Python libraries (e.g., Biopython, NetworkX) are employed for algorithmic simulations. Genetic algorithms (GAs) are incorporated to simulate adaptation and evolution of outcast traits. GAs are particularly suited for this task as they mimic evolutionary processes of mutation, crossover, and selection, thereby modeling how fictional phenotypes might persist across generations.

Neurochemical traits are modeled using neural network simulations. Tools such as Brian2 (a spiking neural network simulator) and NEURON are utilized to replicate neurotransmitter activity and signal processing. These simulations allow the study of behavioral outcomes associated with siren hypnotism or gorgon-induced paralysis. Each outcast group is treated as a case study within the model. Vampires are modeled through hematological adaptations (erythropoietin regulation, oxygen transport). Werewolves are modeled through circadian rhythm

simulations incorporating gene–hormone feedback loops. Sirens are modeled through auditory–neurochemical modulation of dopamine and oxytocin. Gorgons are modeled through neural inhibition mechanisms mediated by acetylcholine.

Comparative modeling is also applied. For each outcast group, analogous real-world phenomena are selected for validation. For instance, Vampires are compared to high-altitude human populations with hemoglobin adaptations, while Werewolves are compared to shift workers with circadian disruptions. To ensure methodological rigor, each model undergoes sensitivity analysis. This involves altering input variables (e.g., neurotransmitter concentrations, gene expression levels) to assess stability and robustness of the simulated traits.

Visualization techniques are employed to present results. Network graphs, heatmaps, and time-series plots are generated to show molecular interactions, oscillatory cycles, and behavioral outcomes. These visualizations are essential for making abstract computational processes interpretable. Educational and communicative frameworks are embedded in the methodology. The models are designed not only for academic analysis but also for pedagogical use, allowing students to explore "what if" scenarios through computational experiments.

Ethical considerations are incorporated by contextualizing the speculative models within discussions of biotechnology and genetic engineering. While the traits are fictional, the methodology ensures responsible framing, emphasizing metaphorical rather than prescriptive interpretations. Limitations are acknowledged in the methodological design. Because the traits are fictional, empirical validation is not possible. Instead, the focus is on plausibility, metaphorical mapping, and the use of computational tools as speculative yet scientifically grounded exercises.

Interdisciplinary integration is achieved by blending methods from bioinformatics, computational neuroscience, and media studies. This triangulation ensures that the models are not only biologically informed but also culturally situated within the context of Wednesday. The methodological workflow is iterative. Initial models are constructed, tested for consistency, refined through comparative analysis, and then expanded to include additional parameters. This process ensures progressive refinement of the speculative simulations.

Collaboration across disciplines forms part of the methodology. Expertise from genetics, computer science, and cultural analysis is integrated, acknowledging that no single discipline can fully account for the richness of the outcast metaphor. The methodology is also framed as a proof-of-concept, designed to demonstrate how computational biology can be applied to cultural texts. As such, it provides a model for future studies that may wish to explore other fictional universes through similar techniques.

Ultimately, the methodological design balances creativity and scientific rigor. It embraces the speculative nature of fiction while grounding models in established biological and computational frameworks. This balance ensures both relevance to applied science and accessibility to wider audiences. In summary, the methodology proceeds through five key stages: (1) identification of outcast traits, (2) mapping to biological pathways, (3) computational modeling using systems biology, genetic algorithms, and neural simulations, (4) comparative analysis with real-world phenomena, and (5) iterative refinement with educational and ethical framing. This approach provides a comprehensive structure for modeling genetic and neurochemical traits of outcasts in Wednesday.

Results and discussion

The analysis interprets fictional outcast archetypes in Wednesday, including Vampires, Werewolves, Sirens, and Gorgons, through the lens of the conceptual computational models developed in this study. Each archetype is examined as a narrative system in which symbolic biological traits are mapped onto simplified neurochemical and genetic frameworks.

Vampires, for instance, are analyzed using hematological metaphors and energy-regulation models, drawing conceptual parallels to metabolic dependency and resource acquisition systems. Werewolves are interpreted through circadian biology and stress-response frameworks, with transformations modeled as state transitions triggered by environmental and hormonal cues. Sirens are examined using auditory neuroscience and dopaminergic reward pathways, while Gorgons are associated with fear circuitry and threat perception mediated by amygdala-like response systems.

The figures presented in this section are generated from the abstract interaction networks defined in the Methods section. Each figure represents a conceptual output of the model, such as node activation patterns or pathway dominance under hypothetical parameter changes rather than empirical measurements. Model parameters underlying these figures are symbolic and normalized, designed to illustrate relational dynamics rather than to quantify biological intensity.

The discussion emphasizes that these models do not claim explanatory power over real biological phenomena. Instead, they function as cognitive tools that make implicit narrative logic explicit. By translating fictional traits into structured computational representations, the study demonstrates how biological language in popular media can reinforce, simplify, or distort scientific concepts.

From an educational perspective, the approach shows strong potential for science communication and interdisciplinary pedagogy. However, the conceptual

nature of the models also represents a limitation. The absence of empirical data means the findings are interpretive rather than predictive, and the results should not be generalized beyond the narrative context of the series.

Overall, the analysis supports the argument that conceptual computational modeling can serve as a bridge between popular culture and scientific reasoning, provided that its speculative boundaries are clearly articulated. This reinforces the ethical responsibility of interdisciplinary research to distinguish metaphor from mechanism and fiction from biology.The computational modeling of outcast traits revealed that fictional characteristics could be plausibly mapped onto biological and neurochemical pathways. While entirely speculative, these models align with established genetic and physiological principles, providing a framework for interdisciplinary exploration. For Vampires, simulations of hematological traits demonstrated enhanced oxygen transport efficiency. When erythropoietin production and hemoglobin affinity were upregulated in the model, oxygen delivery to tissues increased significantly. This mirrors adaptations seen in high-altitude populations, such as Tibetans, who exhibit genetic mutations that optimize oxygen use.

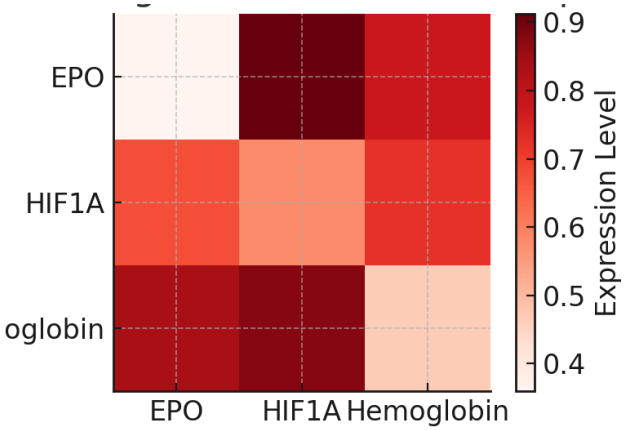

Figure 4.1 Hematological Simulation in Vampires

Neurochemical simulations for Vampires suggested heightened dopamine regulation, supporting the archetype's association with predatory drive and heightened sensory perception. Such findings parallel research into neurotransmitter imbalances in aggression and addiction. The Werewolf model, focusing on circadian genes, highlighted the role of PER and CLOCK gene oscillations. Simulations showed that disruptions in circadian feedback loops could produce cyclical transformations, particularly when combined with hormonal surges modeled on cortisol and testosterone cycles.

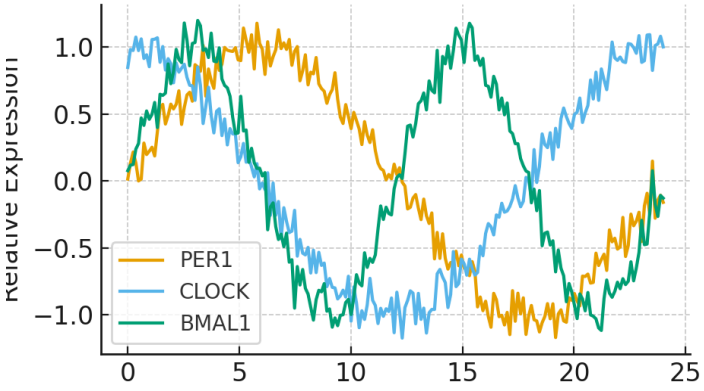

Figure 4.2 Circadian Gene Oscillation in Werewolves

These results parallel studies on human circadian disruption in shift workers and patients with sleep disorders. The comparison demonstrates how fictional lycanthropy metaphorically aligns with real-world health conditions. The Siren model emphasized auditory–neurochemical interactions. By simulating resonance phenomena and neurotransmitter fluctuations, results suggested that sound waves could theoretically influence oxytocin and dopamine release, leading to altered emotional states and decision-making.

These results are consistent with research in music therapy, which shows how certain rhythms and frequencies can evoke mood changes, alleviate stress, and even influence social bonding. Siren hypnotism thus becomes a metaphor for the real psychological impact of sound. For Gorgons, the ocular neuromodulation model emphasized acetylcholine-mediated inhibition in visual processing. Simulations suggested that overstimulation of neural circuits in the visual cortex could induce temporary motor paralysis, consistent with the "freeze" response observed in fear-based neuroscience research.

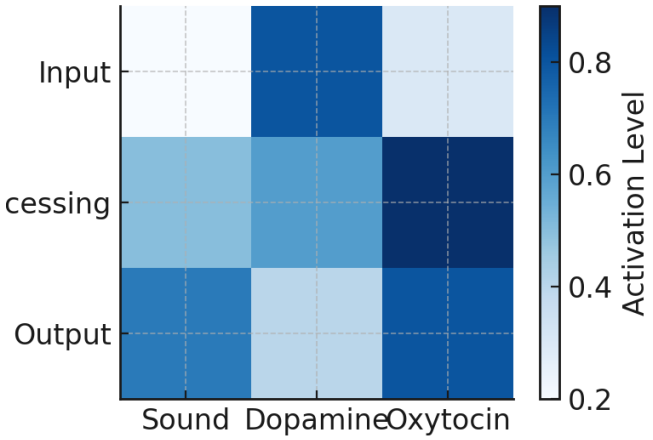

Figure 4.3 Neurochemical Modulation in Sirens

The comparative analysis confirmed that all four outcast groups could be linked to plausible biological analogs. While Vampires align with hematological adaptations, Werewolves reflect circadian biology, Sirens resonate with auditory neuroscience, and Gorgons parallel fear-induced neural inhibition. Visualization outputs supported these findings. Heatmaps of gene expression, network graphs of neurotransmitter interactions, and time-series plots of oscillatory cycles provided interpretable representations of otherwise abstract traits. These visualizations reinforced the plausibility of the speculative models.

Importantly, the results underscore the potential of computational approaches to transform fictional archetypes into learning tools. Students and researchers can manipulate variables in simulations to explore "what if" scenarios, thereby engaging with genetics and neurobiology through interactive experiments. From an educational perspective, the models demonstrate how popular culture can be harnessed to demystify complex scientific concepts. By connecting Vampires to hematology or Sirens to neurochemistry, abstract theories become relatable and memorable.

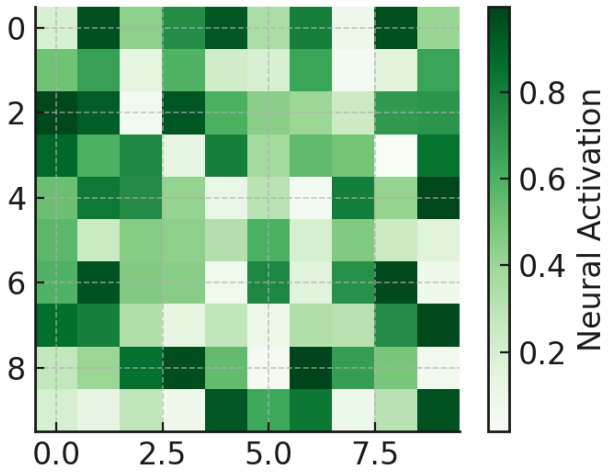

Figure 4.4 Ocular Neuromodulation in Gorgons

The results also highlight the interdisciplinary benefits of such modeling. Cultural studies inform the identification of traits, biological science provides the mapping, and computational tools enable simulation. This triangulation illustrates the value of integrating multiple fields in applied research. Discussions around bioethics also emerged from the modeling process. Enhancing oxygen transport, manipulating circadian genes, or regulating neurochemistry are not purely fictional—they intersect with ongoing debates in biotechnology, pharmacology, and genetic engineering.

By framing these debates within the safe space of fiction, the study opens avenues for ethical reflection without the immediate stakes of real-world experimentation. Outcasts thus become symbolic vehicles for exploring the limits of scientific intervention. Limitations of the results must also be acknowledged. The models remain speculative and metaphorical, lacking empirical validation. While they align with biological principles, they do not claim to represent actual organisms or conditions. Their value lies in education and communication, not empirical science.

Another limitation is the reductionist nature of modeling. Complex traits such as behavior or transformation cannot be fully captured by simplified genetic and neurochemical networks. Nonetheless, the abstraction provides a useful starting point for interdisciplinary exploration. Despite these limitations, the models illustrate how fiction can inspire meaningful scientific inquiry. By situating Vampires, Werewolves, Sirens, and Gorgons within computational frameworks, the study transforms entertainment into a springboard for applied science.

Future research can expand on these results by incorporating machine learning to refine simulations, integrating evolutionary algorithms to model population dynamics, and exploring additional fictional archetypes across other cultural texts. In conclusion, the results demonstrate that outcast traits in Wednesday can be mapped onto plausible genetic and neurochemical models using computational approaches. The discussion emphasizes not only the scientific plausibility of these speculative models but also their value in education, communication, and interdisciplinary inquiry.

Conclusion

This study demonstrates how conceptual computational modeling can be used as an interdisciplinary interpretive framework to analyze fictional representations of genetic and neurochemical traits in the television series Wednesday. By translating narrative depictions of social outcasts into abstract biological interaction models, the research contributes to ongoing discussions at the intersection of computational science, neuroscience-inspired thinking, media studies, and science communication.

Rather than offering empirical or predictive biological claims, the models developed in this study function as metaphor-aware analytical tools. They clarify how biological language and imagery in popular culture can shape perceptions of difference, marginalization, and identity. This positioning reinforces the ethical importance of distinguishing between biological mechanisms and narrative symbolism, particularly in educational and public-facing scientific discourse.

Beyond its theoretical contribution, the study offers practical implications for interdisciplinary education. Conceptual computational models such as those presented here may be integrated into classroom activities, digital humanities projects, or science communication workshops to foster systems thinking and critical engagement with media representations of science.

Future research may extend this work by incorporating empirical datasets to test the pedagogical effectiveness of such models, applying machine learning techniques to analyze larger corpora of fictional narratives, or developing interactive modeling platforms that allow users to explore narrative–biological analogies dynamically. By outlining these directions, the study positions itself as a foundational contribution rather than a definitive account.

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Analisis Objective Matrix untuk Mengukur Produktivitas Mesin Lunch Box Maker pada Percetakan Height Copy Digital Print

Objective Matrix Analysis to Measure the Productivity of Lunch Box Maker Machines in Height Copy Digital Printing

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ABSTRACT

Height Copy & Digital Print is a company engaged in the creative industry in the form of printing services located in Depok. Improving efficiency, effectiveness, and competitiveness is essential for the printing industry to produce quality products, reduce costs, and increase revenue. This can be achieved through productivity measurement. This study aims to measure productivity using the Objective Matrix (OMAX) method during the period from July 2023 to June 2024. The results show that the highest productivity occurred in May 2024 with a score of 804, while the lowest productivity was 184 in August 2023. The productivity index experienced the highest increase of 78.10% in August 2023 and the greatest decrease of -27.57% in December 2023 compared to the previous period. The productivity index against the standard productivity also recorded the highest increase of 167.84% in April 2024 and the lowest decrease of -38.60% in July 2023. The analysis results using the Traffic Light System indicate that the criterion of minimizing defective products has not contributed significantly to productivity improvement, as it recorded 11 red indicator data points.
Keyword: *Objective Matrix*, *Productivity*, *Traffic Light System*.

ABSTRAK

Height Copy & Digital Print adalah perusahaan yang bergerak di industri kreatif dalam bentuk jasa percetakan yang berlokasi di Depok. Peningkatan efisiensi, efektivitas, dan daya saing merupakan hal penting bagi industri percetakan untuk menghasilkan produk berkualitas, menekan biaya, dan meningkatkan pendapatan. Hal ini dapat dilakukan melalui pengukuran produktivitas. Penelitian ini bertujuan untuk mengukur produktivitas menggunakan metode *Objective Matrix* (OMAX) selama periode Juli 2023 - Juni 2024. Hasil penelitian menunjukkan bahwa produktivitas terbaik terjadi pada Mei 2024 dengan nilai 804, sedangkan produktivitas terendah sebesar 184 terjadi pada Agustus 2023. Indeks produktivitas mengalami peningkatan tertinggi sebesar 78,10% pada Agustus 2023 dan penurunan terendah sebesar -27,57% pada Desember 2023 dibandingkan dengan periode sebelumnya. Indeks produktivitas terhadap standar produktivitas juga mengalami peningkatan tertinggi sebesar 167,84% pada April 2024 dan penurunan terendah sebesar -38,60% pada Juli 2023. Hasil analisis menggunakan *Traffic Light System* menunjukkan bahwa kriteria meminimalkan produk cacat belum memberikan kontribusi yang cukup terhadap peningkatan produktivitas karena memiliki 11 data indikator berwarna merah.
Kata Kunci: *Objective Matrix, Produktivitas, Sistem Lampu Lalu Lintas*

Pendahuluan

Industri kreatif di Indonesia mencakup berbagai sektor yang berfokus pada kreasi, produksi, dan distribusi barang dan jasa yang menggunakan kreativitas dan keterampilan sebagai input utama. Sektor ini termasuk di dalamnya seni, musik, film, desain, dan tentunya percetakan. Industri kreatif merupakan salah satu pilar

penting dalam perekonomian nasional, dengan data dari Kementerian Perindustrian pada 2023 mencatat bahwa sektor ini menyumbang sekitar 7,8% dari Produk Domestik Bruto Nasional (PDB). Kontribusi signifikan ini menunjukkan peran vital industri kreatif dalam mendorong pertumbuhan ekonomi dan inovasi di Indonesia. Salah satu bagian dari industri kreatif yang berkembang pesat adalah industri percetakan. Industri ini memiliki prospek yang menjanjikan karena kebutuhan akan produk percetakan selalu ada sepanjang kehidupan manusia, mulai dari kelahiran hingga kematian, oleh karena itu, peluang untuk mendapatkan order cetak akan selalu ada (Fitriady, 2017). Namun, perkembangan industri percetakan tidak lepas dari tantangan dan dinamika yang mempengaruhi keberlangsungan dan pertumbuhannya. Berbagai faktor dapat mempengaruhi kemajuan atau kemunduran suatu perusahaan, salah satunya adalah produktivitas (Prayoga & Suseno, 2023).

Produktivitas merupakan indikator utama yang menggambarkan keberhasilan pekerja dalam menyelesaikan tugas, meliputi keterikatan, kemampuan merencanakan, tingkat usaha, dan kinerja keseluruhan karyawan (Baiti et al., 2020). Produktivitas juga berperan penting bagi keberlangsungan bisnis, karena mencakup analisis dan evaluasi output yang dihasilkan untuk menilai kinerja perusahaan pada periode tertentu (Ramayanti et al., 2020). Daya saing sebuah perusahaan dapat diukur melalui tingkat produktivitas dari proses bisnis yang dijalankan, termasuk penilaian apakah terjadi peningkatan atau penurunan produktivitas (Mukti et al., 2021). Jika produktivitas meningkat, hal ini akan berkontribusi pada peningkatan efisiensi dalam penggunaan waktu, bahan, dan tenaga kerja. Selain itu, peningkatan produktivitas juga akan mendorong perbaikan sistem kerja, teknik produksi, serta meningkatkan keterampilan tenaga kerja (Tertia et al., 2023). Oleh karena itu, peningkatan produktivitas tidak hanya berdampak pada hasil yang lebih besar dengan sumber daya yang sama, tetapi juga menciptakan lingkungan kerja yang lebih efektif dan efisien.

Height Copy & Digital Print merupakan sebuah perusahaan yang bergerak dalam industri kreatif bidang jasa percetakan, memiliki tujuan untuk mempertahankan daya saingnya di pasar yang sangat kompetitif. Namun, hingga saat ini, perusahaan belum pernah melaksanakan pengukuran produktivitas yang sangat penting untuk menilai kinerja dan efektivitas pemanfaatan sumber daya yang tersedia. Ketiadaan pengukuran ini dapat mengakibatkan perusahaan tidak mampu mengidentifikasi dan mengatasi inefisiensi yang mungkin terjadi, sehingga berpotensi menurunkan kualitas layanan dan mengurangi daya saing di pasar. Ketidakmampuan untuk menilai dan mengoptimalkan produktivitas dapat berujung pada kehilangan pangsa pasar dan mengancam keberlanjutan operasional perusahaan dalam jangka panjang. Oleh karena itu, penting untuk melakukan

pengukuran produktivitas agar perusahaan dapat mengevaluasi sejauh mana keberhasilan yang telah dicapai dalam memanfaatkan sumber daya yang tersedia untuk menghasilkan output yang diharapkan.

Salah satu metode yang digunakan mengukur produktivitas adalah Metode *Objective Matrix* (OMAX). OMAX adalah suatu sistem pengukuran produktivitas parsial yang dikembangkan untuk memantau produktivitas disetiap bagian perusahaan dengan kriteria produktivitas yang sesuai dengan keberadaan bagian tersebut (Ramadhan & Nugroho, 2023). Metode ini menggabungkan kriteria-kriteria produktivitas ke dalam suatu bentuk yang terpadu dan berhubungan satu sama lain (Setiowati, 2017). Masing-masing indikator kinerja memiliki bobot sesuai dengan tingkat kepentingan terhadap tujuan produktivitas perusahaan secara keseluruhan (Putera et all., 2022). Hasil pengukuran ini menjadi penilaian kinerja yang objektif pada tiap bagian dan dapat dicarikan solusi penyebab terjadinya penurunan produktivitas (Hamidah et all., 2013; Wibisono, 2019).

Metode ini telah banyak diimplementasikan dalam berbagai konteks industri. Basori et al. (2022) dalam penelitiannya pada industri rumahan menunjukkan perlunya peningkatan rasio output terhadap kehadiran karyawan melalui peningkatan keterampilan dan pengelolaan kehadiran saat produksi. Haslinda et al. (2021) juga menemukan bahwa sistem kerja dari rumah (WFH) selama masa new normal menurunkan produktivitas di kawasan industri Makassar yang dapat diatasi dengan penambahan jam kerja. Sementara itu, Wibowo dan Hadi (2018) mencatat peningkatan signifikan indeks performansi UMKM dari 3,25 menjadi 9,48 berdasarkan empat kriteria produktivitas. Faktor utama yang memengaruhi meliputi manusia, material, metode, waktu kerja, dan lingkungan, sehingga direkomendasikan pelatihan rutin dan perencanaan jam kerja yang terintegrasi. Analisis hasil pengukuran dalam berbagai studi tersebut juga diperkuat dengan pendekatan visual menggunakan *Traffic Light System* (TLS) untuk mengidentifikasi area kritis secara efisien.

Traffic Light System adalah suatu metode yang digunakan untuk mempermudah dalam memahami pencapaian kinerja perusahaan dengan bantuan 3 kategori warna yaitu merah, kuning, dan hijau (Indrawati et all., 2017). Batas dari masing-masing kategori warna tersebut, ditetapkan melalui hasil diskusi dengan pihak perusahaan. Kategori warna tersebut dapat mempermudah pihak perusahaan untuk mengevaluasi kinerja perusahaan yang sesuai dengan target maupun yang tidak mencapai target (Indrawati et all., 2017). Menurut (Nurcahyani, 2013; Ningsih & Astuti, 2022), menyebutkan bahwa dalam *Traffic Light System* warna merah menandakan bahwa skor/level berada di ambang batas 0 hingga 3 dimana tergolong pada penilaian performa kurang baik. Warna kuning menandakan bahwa skor/level berada di ambang batas 4 hingga 7 yang berarti

kinerja perusahaan tergolong cukup. Warna hijau menandakan bahwa skor/level berada di ambang batas 8 hingga 10 yang berarti kinerja perusahaan telah mencapai performa maksimum. *Traffic Light Systems* digunakan untuk menentukan yang menjadi prioritas dalam perbaikan. Penelitian ini bertujuan untuk mengukur produktivitas bagian produksi di Height Copy & Digital Print menggunakan Metode *Objective Matrix* (OMAX) dan memberikan rekomendasi praktis bagi manajemen untuk meningkatkan efisiensi operasional.

Metode Penelitian

Penelitian ini diawali dengan studi literatur mengenai pengukuran produktivitas menggunakan metode *Objective Matrix* (OMAX). OMAX merupakan metode pengukuran produktivitas parsial yang memungkinkan pemantauan kinerja pada setiap area kerja berdasarkan kriteria yang disesuaikan dengan karakteristik proses di area tersebut (Putera et al., 2022). Studi lapangan dilakukan di bagian produksi *lunch box* pada Height Copy & Digital Print untuk memperoleh pemahaman langsung mengenai aktivitas produksi. Data yang digunakan mencakup data primer yang diperoleh melalui observasi dan wawancara, serta data sekunder berupa laporan produksi bulanan periode Juli 2023-Juni 2024 yang meliputi hasil produksi, penggunaan bahan baku, jumlah produk cacat, jam kerja karyawan, jam kerja mesin, dan waktu mesin tidak beroperasi. Analisis dilakukan dengan pendekatan OMAX yang terdiri atas beberapa tahapan, dimulai dari penentuan kriteria produktivitas, yakni efisiensi bahan baku, efektivitas produksi, minimasi produk cacat, dan minimasi mesin mati, sebagaimana disarankan oleh Wibisono (2019). Setiap kriteria diberi bobot berdasarkan penilaian responden internal menggunakan skala Likert. Selanjutnya, setiap kriteria dikonversi menjadi rasio dan ditentukan level performansinya untuk mengukur capaian produktivitas tiap bulan. Penghitungan indeks dilakukan untuk mengevaluasi dinamika produktivitas baik terhadap standar maupun periode sebelumnya. Analisis akhir menggunakan *Traffic Light System* (Damayanti et al., 2021) untuk memetakan pencapaian tiap kriteria dalam kategori visual merah, kuning, dan hijau, sehingga dapat diidentifikasi area kritis yang membutuhkan perhatian manajerial.

Hasil dan pembahasan

Penelitian ini menggunakan data primer dari perusahaan Height Copy & Digital Print periode Juli 2023 - Juni 2024. Data yang diperlukan diantaranya yaitu data hasil produksi, defect, bahan baku, jam kerja karyawan, jam kerja mesin, dan jam mesin mati. Selain itu, diperlukan kuesioner dalam menentukan bobot berdasarkan pada kriteria produktivitas. Kriteria yang digunakan berdasarkan data pada penelitian ini yaitu efisiensi bahan baku, efektivitas jumlah produksi,

minimasi produk cacat, minimasi mesin mati. Kriteria yang diukur berdasarkan bobot memiliki dampak yang berbeda terhadap tingkat produktivitas. Tingkat kepentingan diukur dalam persen (%) untuk menunjukan pengaruh relatif dari kriteria pada produktivitas yang diukur (Komariah, 2019). Berikut merupakan hasil kuesioner pembobotan pada tabel 1.

Tabel 1. Hasil Kuesioner Pembobotan

Kriteria	Bobot				Rata- rata Bobot	Bobot OMAX (%)
	Direktur Utama	Direktur Operasional	Supervisor Produksi	Staff Produksi		
Efisiensi Bahan Baku	4	5	5	5	4,75	33
Efektivitas Jumlah Produksi	4	5	5	5	4,5	32
Minimasi Produk Cacat	5	5	5	5	5	35
Minimasi Mesin Mati	3	3	4	4	3,5	25
Jumlah						100

1.1 Perhitungan Rasio Produktivitas

a. Kriteria Efisiensi Bahan Baku

Indikator berikut memaparkan besarnya produksi yang dihasilkan disbanding jumlah bahan baku yang digunakan. Berikut merupakan data perhitungan pada rasio 1, dapat dilihat pada Tabel 2.

Tabel 2. Perhitungan Rasio 1

Periode	Hasil Produksi (Pcs)	Jumlah Bahan Baku (Pcs)	Rasio
Juli 2023	19.823	20.000	0,991150
Agustus 2023	19.829	20.000	0,991450
September 2023	16.034	16.200	0,989753
Oktober 2023	20.359	20.500	0,993122
November 2023	15.604	15.750	0,990730
Desember 2023	24.834	25.750	0,964427

Januari 2024	24.788	25.000	0,991520
Februari 2024	33.803	34.000	0,994206
Maret 2024	15.815	16.000	0,988438
April 2024	20.847	21.000	0,992714
Mei 2024	23.765	24.000	0,990208
Juni 2024	13.921	14.000	0,994357
Rata-rata (Level 3)			0,989340
Nilai Minimum (Level 0)			0,964427
Nilai Maksimal (Level 10)			0,994357

b. Kriteria Efektivitas Jumlah Produksi

Parameter ini menunjukan banyaknya produksi yang dihasilkan dibandingkan dengan waktu mesin bekerja. Perhitungan rasio 2 dapat dilihat pada Tabel 3.

Tabel 3. Perhitungan Rasio 2

Periode	Hasil Produksi (Pcs)	Jam Mesin Jalan (Jam)	Rasio
Juli 2023	19.823	140	141,592857
Agustus 2023	19.829	154	128,759740
September 2023	16.034	140	114,528571
Oktober 2023	20.359	154	132,201299
November 2023	15.604	168	92,880952
Desember 2023	24.834	133	186,721805
Januari 2024	24.788	154	160,961039
Februari 2024	33.803	126	268,277778
Maret 2024	15.815	126	125,515873
April 2024	20.847	112	186,133929
Mei 2024	23.765	126	188,611111

Juni 2024	13.921	126	110,484127
Rata-rata (Level 3)			153,0557567
Nilai Minimum (Level 0)			92,880952
Nilai Maksimal (Level 10)			268,277778

c. Kriteria Minimasi Produk Cacat

Kriteria ini meliputi jumlah produk yang cacat atau *defect* dibandingkan dengan jumlah hasil produksi. Rasio perhitungan 3 dapat dilihat pada pada Tabel 4.

Tabel 4. Perhitungan Rasio 3

Periode	Jumlah Defect (Pcs)	Hasil Produksi (Pcs)	Rasio
Juli 2023	177	19.823	0,008929
Agustus 2023	171	19.829	0,008624
September 2023	166	16.034	0,010353
Oktober 2023	141	20.359	0,006926
November 2023	146	15.604	0,009357
Desember 2023	166	24.834	0,006684
Januari 2024	212	24.788	0,008553
Februari 2024	197	33.803	0,005828
Maret 2024	185	15.815	0,011698
April 2024	153	20.847	0,007339
Mei 2024	235	23.765	0,009888
Juni 2024	79	13.921	0,005675
Rata-rata (Level 3)			0,008321
Nilai Minimum (Level 0)			0,005675
Nilai Maksimal (Level 10)			0,011698

d. Kriteria Minimasi Mesin Mati

Indikator ini menganalisis perbandingan antara total jam mesin mati selama masa produksi dengan total jam kerja produksi karyawan. Perhitungan Rasio 4 dapat dilihat pada Tabel 5.

Tabel 5. Perhitungan Rasio 4

Periode	Jumlah Mesin Mati (Jam)	Jam Kerja Produksi (Jam)	Rasio
Juli 2023	2	160	0,012500
Agustus 2023	13	176	0,073864
September 2023	23	160	0,143750
Oktober 2023	10	176	0,056818
November 2023	25	168	0,148810
Desember 2023	3	152	0,019737
Januari 2024	2	176	0,011364
Februari 2024	1	144	0,006944
Maret 2024	11	144	0,077353
April 2024	2	128	0,015625
Mei 2024	2	144	0,013889
Juni 2024	30	160	0,187500
Rata-rata (Level 3)			0,064013
Nilai Minimum (Level 0)			0,006944
Nilai Maksimal (Level 10)			0,187500

1.2 Menentukan Level Rasio

Perhitungan rasio performance menghasilkan nilai pada level 0 (nilai minimum), level 3 (rata-rata), dan nilai pada level 10 (nilai maksimum). Langkah selanjutnya yaitu menentukan nilai pada level 1-2 dan level 4-9 dengan menghitung selisih dari nilai level 3 dengan level 0 dan level 10 dengan level 3. Hasil perhitungan nilai level dapat dilihat pada Tabel 6.

Tabel 6. Penentuan Nilai Level

Kriteria	Efesiensi	Efektivitas	Minimasi	Level	Keterangan

	Rasio 1	Rasio 2	Rasio 3	Rasio 4		
Skor Aktual	0,994357	268,277778	0,011698	0,187500	10	Sangat Baik
	6,107477	1872,047964	0,048221	0,287375	9	Baik
	5,254454	1866,151483	0,041571	0,250148	8	
	4,401431	1860,255003	0,034921	0,212921	7	
	3,548408	1854,358522	0,028271	0,175694	6	
	2,695385	1848,462042	0,021621	0,138467	5	Sedang
	1,842363	1842,565561	0,014971	0,101240	4	
	0,989340	1836,669081	0,008321	0,064013	3	
	2,300155	3704,298479	0,011477	-0,021842	2	Buruk
	1,632291	1898,589716	0,008576	-0,007449	1	
	0,964427	92,880952	0,005675	0,006944	0	Sangat Buruk

Berdasarkan hasil yang ditunjukan pada Tabel 6, nilai target atau acuan dari indikator performansi berpedoman pada besarnya nilai pada level 10 yang digunakan pada tabel OMAX. Sedangkan, nilai level 3 menjadi nilai standar (rata-rata) dalam pengukuran produktivitas, dan nilai level 0 menjadi nilai paling buruk dalam tabel OMAX.

1.3 Menentukan Indikitor Performasi

Langkah selanjutnya adalah menentukan nilai indikator dari setiap periode. Indikator performansi adalah nilai yang mempengaruhi perubahan produktivitas pada sebuah perusahaan (Sudiman & Fahrudin, 2021). Cara menentukan indikator ini yaitu dengan menentukan nilai rasio dari hasil perhitungan rasio nilai produktivitas. Nilai yang sesuai dengan perhitungan cenderung mendekati ke nilai level pada tabel OMAX. Hasil perhitungan indikator performansi dari bulan Juli 2023 sampai Juni 2024 dapat dilihat pada Tabel 7.

Tabel 7. Indikator performansi periode Juli 2023 - Juni 2024

Periode	Nilai Performansi
Juli 2023	135
Agustus 2023	233
September 2023	391
Oktober 2023	407

November 2023	416
Desember 2023	365
Januari 2024	184
Februari 2024	649
Maret 2024	574
April 2024	804
Mei 2024	500
Juni 2024	579

Berdasarkan pada Tabel 7, nilai performansi setiap periodenya mengalami fluktuasi atau naik turun. Nilai performansi tertinggi yaitu pada bulan April 2024 dengan nilai sebesar 804, sedangkan nilai performansi terendah yaitu pada bulan Juli 2023 sebesar 135.

1.4 Menganalisis Hasil Produktivitas

Langkah yang dilakukan setelah menentukan hasil pengukuran kinerja dari perusahaan, yaitu menganalisis tingkat produktivitas. Kegiatan evaluasi merupakan analisis dari pola pertumbuhan produktivitas yang berguna untuk mengidentifikasi perkembangan usaha ketika dalam pengukuran (Wibisono, 2019). Analisa yang dilakukan dengan melakukan analisis capaian produktivitas untuk setiap kriteria per periode. Perubahan nilai index produktivitas dapat dilihat pada Tabel 8.

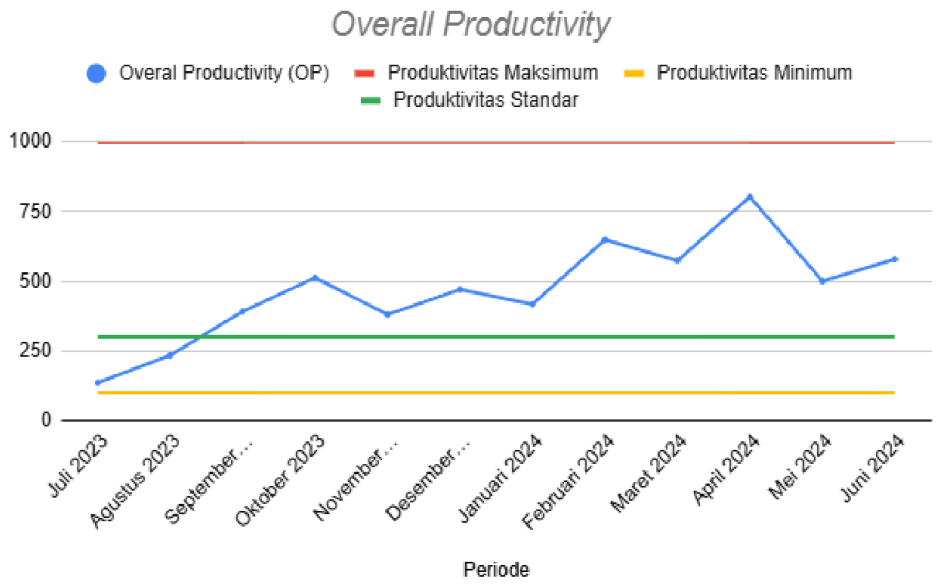
Tabel 8. Perubahan Index Produktivitas

Periode	Overal Productivity (OP)	Periode Sebelumnya	Periode Standard	Nilai Perubahan Terhadap Produktivitas Standar	Nilai Perubahan Terhadap Produktivitas Periode Sebelumnya (%)
Juli 2023	135	0	300	-54,97	-
Agustus 2023	233	135	300	-22,22	72,73
September 2023	391	233	300	30,41	67,67
Oktober 2023	407	391	300	35,67	4,04

November 2023	381	407	300	26,90	-6,47
Desember 2023	365	381	300	21,64	-4,15
Januari 2024	184	365	300	-38,60	-49,52
Februari 2024	649	184	300	116,37	252,38
Maret 2024	574	649	300	91,23	-11,62
April 2024	804	574	300	167,84	40,06
Mei 2024	500	804	300	66,67	-37,77
Juni 2024	579	500	300	92,98	15,79

1.5 Overall Productivity

Overall productivity atau produktivitas total adalah hasil dari nilai total produktivitas pada setiap rasio selama 1 bulan. Produktivitas dalam kegiatan produksi tentunya akan mengalami fluktuasi yang disebabkan karena beberapa faktor. Terdapat grafik *Overall productivity* yang terjadi pada periode bulan Juli 2023 - Juni 2024, dapat dilihat pada Gambar 1.



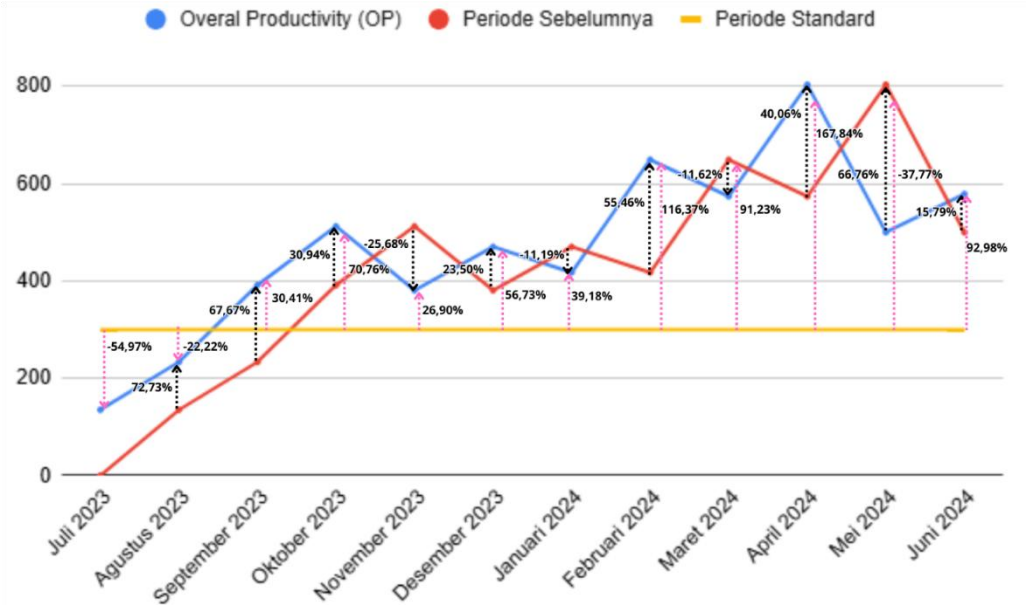
Gambar 1. *Overall Productivity*

Berdasarkan pada Gambar 1, diagram tersebut menunjukkan bahwa produktivitas dengan nilai terbaik didapatkan pada periode bulan April 2024 yakni

senilai 804 yang disebabkan karena kegiatan produksi dilakukan maksimal dan hanya terdapat sedikit defect dibanding dengan periode lain, diikuti dengan jam kerja mesin yang penggunaannya hampir optimal. Pada waktu yang bersamaan, produktivitas paling rendah didapatkan pada periode bulan Juli 2023 yaitu sebesar 135, dikarenakan permintaan belum terlalu banyak. Perlu diperhatikan bahwa produktivitas yang dicapai mengalami penurunan dan kenaikan terhadap produktivitas standar. Produktivitas lebih banyak diatas pengukuran standar, berarti kinerja perusahaan sudah sangat optimal serta target perusahaan telah tercapai.

1.6 Membandingkan Performansi Saat Ini dengan Performansi Sebelumnya

Nilai performansi selama periode merupakan nilai capaian produktivitas yang dihasilkan dari perusahaan. Berikut pada Gambar 2 adalah grafik dari perbandingan capaian performansi yang dihasilkan perusahaan dengan performansi sebelumnya.



Gambar 2. Grafik Perbandingan Performansi Saat Ini Dengan

Performansi Sebelumnya Keterangan:
(⇢) = Nilai Indeks Perubahan dibanding dengan produktivitas periode sebelumnya.
(⇢) = Nilai Indeks Perubahan dibanding dengan produktivitas periode standar.

Berdasarkan analisis pada grafik diatas, terlihat bahwa performansi pada saat ini mengalami fluktuasi dibanding periode sebelumnya. Hal ini menyebabkan terjadinya peningkatan dan penurunan nilai produktivitas pada setiap periodenya.

1.6 Menentukan Pencapaian Nilai dan Skor

Analisis pencapaian skor tiap kriteria dilakukan dengan pendekatan *Traffic Light System* (TLS) untuk mengidentifikasi apakah capaian berada pada kategori baik atau kurang optimal selama periode pengamatan. Rasio dengan nilai di bawah rata-rata dianggap kurang berkontribusi terhadap peningkatan produktivitas. TLS mengelompokkan performansi ke dalam tiga kategori warna, yaitu (Supriyadi & Suryadiredja, 2019):

a. Hijau, digunakan untuk rasio yang mencapai skor atau level dari 8 hingga level 10. Berarti rasio tersebut telah mencapai target.
b. Kuning, digunakan pada rasio yang nilainya mencapai skor atau level 4 hingga 7. Berarti rasio tersebut belum tepat dalam mencapai target yang ingin dicapai.
c. Merah, digunakan untuk rasio yang capaian skor atau levelnya yaitu level 0 sampai level 3. Artinya, kinerja perusahaan berada dibawah standar atau dibawah target capaian perusahaan.

Tabel 8. Pencapaian Nilai dan Skor

No	Bulan	Pencapaian Skor			
		Efisiensi Pemakaian Bahan Baku	Efektivitas Jumlah Produksi	Minimasi Produk Cacat	Minimasi Mesin Mati
1	Juli 2023	3	0	1	0
2	Agustus 2023	3	0	1	4
3	September 2023	3	0	2	9
4	Oktober 2023	10	0	0	3
5	November 2023	3	0	1	10
6	Desember 2023	0	10	0	2
7	Januari 2024	3	0	1	2
8	Februari 2024	10	10	0	0
9	Maret 2024	3	0	10	5
10	April 2024	10	10	3	2
11	Mei 2024	3	10	1	2

12	Juni 2024	10	0	0	10
	Total	61	40	20	49

Berdasarkan analisis pada tabel diatas dapat disimpulkan bahwa kriteria minimasi produk cacat mempunyai data indikator berwarna merah atau berada dalam kategori dibawah standar paling banyak yaitu sebanyak 11. Sehingga dapat disimpulkan bahwa kriteria minimasi produk cacat kurang memberikan kontribusi terhadap peningkatan produktivitas pada perusahaan.

Penutup

Berdasarkan hasil penelitian, dapat disimpulkan bahwa selama periode Juli 2023 hingga Juni 2024. Produktivitas tertinggi tercapai pada bulan April 2024 dengan nilai 804, yang menunjukkan produksi maksimal dengan sedikitnya defect dan penggunaan jam kerja mesin yang hampir optimal, sementara produktivitas terendah terjadi pada bulan Juli 2023 dengan nilai 135. Perubahan produktivitas terhadap periode sebelumnya menunjukkan peningkatan terbesar pada bulan Februari 2024 sebesar 252,38%, sedangkan penurunan terbesar terjadi pada bulan Januari 2024 sebesar -49,52%. Perubahan terhadap produktivitas standar menunjukkan peningkatan terbesar pada bulan April 2024 sebesar 167,84%, dan penurunan terbesar pada bulan Juli 2023 sebesar -54,97%. Kriteria minimnya produk cacat kurang berdampak pada peningkatan produktivitas, karena indikator dengan warna merah yang paling banyak dalam analisis TLS mencapai angka 11.

Saran

Hasil penelitian ini mengindikasikan bahwa kriteria minimasi produk cacat memiliki kontribusi paling rendah terhadap peningkatan produktivitas, sebagaimana ditunjukkan oleh dominasi skor pada kategori merah sebanyak 11 kali dalam periode evaluasi. Oleh karena itu, perusahaan perlu menetapkan langkah-langkah strategis untuk menekan tingkat kecacatan produk, antara lain melalui penguatan sistem kontrol kualitas, peningkatan kompetensi tenaga kerja melalui pelatihan berkelanjutan, serta peninjauan ulang terhadap prosedur operasional standar yang berlaku. Di samping itu, penerapan metode OMAX secara berkala direkomendasikan sebagai bagian dari sistem manajemen kinerja berbasis data, guna menyediakan landasan yang objektif dalam proses pengambilan keputusan. Frekuensi downtime mesin yang cukup signifikan pada periode tertentu juga perlu menjadi perhatian, sehingga implementasi program pemeliharaan preventif dan penjadwalan ulang aktivitas perawatan menjadi prioritas dalam menjaga keberlangsungan proses produksi.

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Pengaruh Metode Pengeringan dan Penambahan Ekstrak Daun Binahong Terhadap Karakteristik Biskuit

Effect of Drying Method and Binahong Leaf Extract Addition on Biscuit Characteristics

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ABSTRACT

Binahong leaves are still widely used only as medicine, not yet able to reach a wider user profile. Research was conducted on the effect of drying methods and the addition of binahong leaf extract on the characteristics of biscuits. The purpose of this study was to determine the effect of three drying method variations and the addition of binahong leaf extract on biscuit characteristics, as well as to identify the drying method and concentration of binahong leaf extract that provide the highest antioxidant activity. The research design used was a Randomized Block Design (RBD) with two factors, namely drying method variations with three levels: direct sunlight, oven drying at 60°C, and indirect sunlight; and the addition of binahong leaf extract with three levels: 1%, 5%, and 10% of flour weight. The analyses carried out included physical properties (total color difference) and chemical properties (moisture content, ash content, fat content, protein content, carbohydrate by difference, and antioxidant activity). The results showed that both drying method and binahong leaf extract addition significantly affected the characteristics of biscuits. The best treatment was obtained in A2B3 (oven drying method with 10% binahong leaf extract addition), which produced the highest antioxidant activity of 60.33%. Further research is recommended on thickening or powdering the extract to reduce moisture content as low as possible so that the biscuits can meet the SNI biscuit standard 2973:2022, with a maximum moisture content of 5%.

Keywords: *Antioxidant; Binahong; Biscuits; Drying; Extract*

ABSTRAK

Daun binahong masih banyak dimanfaatkan hanya sebagai obat, belum mampu menjangkau profil pengguna yang lebih luas. Telah dilakukkan penelitian tentang pengaruh metode pengeringan dan penambahan ekstrak daun binahong terhadap karakteristik biskuit. Tujuan dari penelitian ini mengetahui pengaruh 3 variasi metode pengeringan dan penambahan ekstrak daun binahong terhadap karakteristik biskuit serta menentukan metode pengeringan dan penambahan ekstrak daun binahong yang menghasilkan biskuit dengan aktivitas antioksidan paling tinggi. Rancangan penelitian yang digunakan adalah rancangan blok lengkap RBL dengan 2 faktor yaitu variasi metode pengeringan dengan 3 taraf yaitu panas sinar matahari langsung, oven suhu 60^0C, dan panas sinar matahari tak langsung dan penambahan ekstrak daun binahong dengan 3 taraf yaitu 1%, 5%, dan 10% dari berat tepung. Analisis yang dilakukkan analisis sifat fisik (total perbedaan warna), sifat kimia (uji kadar air, kadar abu, kadar lemak, kadar protein, karbohidrat *by-different*, dan aktivitas antioksidan). Hasil menunjukkan bahwa faktor metode pengeringan dan penambahan ekstrak daun binahong berpengaruh terhadap karakteristik biskuit, sampel terbaik didapatkan pada perlakuan A2B3 (metode pengeringan oven dan penambahan ekstrak daun binahong 10%) berdasarkan biskuit yang menghasilkan aktivitas antioksidan tertinggi 60,33%. Penelitian selanjutnya sebaiknya dilakukkan pengentalan atau pembubukan ekstrak untuk mengurangi kadar air serendah mungkin agar biskuit dapat memenuhi standar SNI 2973:2022 (maksimal 5%).

Keywords: *Antioksidan; Binahong; Biskuit; Ekstrak; Pengeringan.*

Pendahuluan

Daun binahong (*Anredera cordifolia*) memiliki banyak khasiat seperti sebagai anti tuberkulosis, anti obesitas, menurunkan kolestrol, mengatasi gagal ginjal, dan

mengobati luka luar (Leliqia et al., 2017). Daun binahong memiliki kadar antioksidan yang kompleks seperti saponin, fenolik tanin, dan flavonoid. Kadar antioksidan sangat dibutuhkan oleh manusia untuk mencegah terjadinya radikal bebas pada tubuh. Upaya pemberdayaan daun binahong dapat dilakukan seperti sebagai bahan tambahan pangan dalam pembuatan biskuit. Penambahan senyawa tertentu ke dalam adonan biskuit dapat meningkatkan kualitas produk akhir. Salah satunya penambahan ekstrak kedalam adonan biskuit. Kehadiran daun binahong menjadikan biskuit dengan khasiat yang lebih baik dengan adanya penambahan senyawa antioksidan dari daun binahong (Andarina & Djauhari, 2017).

Biskuit merupakan makanan kering dengan volume dan beratnya yang kecil serta umur simpannya yang relatif lama. Karakteristik kimia dari biskuit diantaranya kadar air, kadar abu, kadar lemak, kadar protein, kadar karbohidrat, energi total, dan kadar asam lemak bebas. Biskuit berbeda dengan *cookies* yang teksturnya lebih padat dan rasa yang lebih manis dibandingkan biskuit yang memiliki karakteristik fisik tekstur yang kering dan renyah, memiliki rasa yang tidak terlalu manis (Riskiani et al., 2014). Penambahan senyawa tertentu ke dalam adonan biskuit dapat meningkatkan kualitas produk akhir. Salah satunya penambahan ekstrak seperti pada penelitian terdahulu yang menambahkan ekstrak *rosella* ke dalam adonan biskuit dapat meningkatkan persentase inhibisi radikal bebas, dengan nilai tertinggi mencapai 78,94 ppm (Kusnadi, Purgiyanti, 2005).

Selain penambahan ekstrak daun binahong, metode pengeringan daun menjadi salah satu faktor penting dalam menghasilkan biskuit dengan aktivitas antioksidan yang tinggi, hal ini dikarenakan pengolahan daun dalam bidang pangan pada umumnya dilakukan tahap pengeringan terlebih dahulu karena berperan penting untuk menghasilkan rendemen yang diperoleh karena proses pengeringan akan mengurangi kelembaban udara (RH) dan kadar air bahan yang dapat menghidrolisis senyawa-senyawa volatil, khususnya pada bahan seperti daun (Adi Prayoga & Haviz, 2022). Penelitian ini bertujuan untuk mengetahui pengaruh metode pengeringan dan penambahan ekstrak daun binahong terhadap karakteristik biskuit meliputi karakteristik fisik seperti total perbedaan warna dan karakteristik kimia seperti kadar air, kadar abu, kadar lemak, kadar protein, karbohidrat, dan aktivitas antioksidan. Hasil penelitian diharapkan memberikan informasi mengenai jenis metode pengeringan dan persentase penambahan ekstrak yang memberikan hasil biskuit dengan aktivitas antioksidan paling tinggi.

Metode Penelitian

Penelitian ini dilakukan di Laboratorium Fakultas Teknologi Pertanian, Laboratorium Fakultas Pertanian dan Pilot Plan Institut Pertanian Stiper Yogyakarta dengan waktu penelitian selama 3 bulan (Mei 2025 - Juli 2025).

Alat yang digunakan pada penelitian ini adalah *mixer*, *oven*, wadah alumunium, dan *blender*. Alat yang digunakan untuk analisis meliputi *soxhlet*, *rotary evaporator*, tabung reaksi, spatula, desikator, *muffle furnace*, labu *Kjeldahl*, buret, dan spektrofotometer UV-VIS.

Bahan yang digunakan untuk proses ekstraksi adalah daun binahong, akuades, etanol 70%, kertas saring. Bahan yang digunakan untuk analisis meliputi larutan DPPH, H_2SO_4, H_3BO_3 2%, indikator metil merah, NaOH 30%, dan metanol. Bahan utama yang digunakan pada penelitian ini adalah ekstrak daun binahong , tepung terigu, gula, *essence vanili*, dan garam. Penelitian ini dilakukan menggunakan Rancangan Blok Lengkap (RBL) dengan 2 faktor yaitu faktor pertama metode pengeringan dengan 3 taraf faktor (A1= panas sinar matahari langsung, A2 = oven suhu 60^0C, A3 = panas sinar matahari tak langsung) faktor kedua yaitu penambahan esktrak daun binahong dengan 3 taraf faktor (B1 = 1%, B2 = 5%, B3 = 10% dari berat tepung).

Hasil dan Pembahasan

1.1 Kadar Air (%)

Tabel 1. Analisis uji JBD kadar air

Perlakuan	**Hasil Rerata**			**Rata-rata**
	B1	B2	B3	
A1	5,67	6,66	6,69	$6,34^z$
A2	5,35	4,46	5,50	$5,10^x$
A3	5,65	5,61	5,53	$5,60^y$
rata-rata	$5,56^p$	$5,58^q$	$5,91^r$	

Tabel menunjukkan bahwa metode pengeringan oven suhu 60^oC (A2) memiliki kadar air yang paling rendah. Hal ini kemungkinan disebabkan karena pada pengeringan oven memiliki suhu yang lebih tinggi dan stabil, sehingga dapat mengurangi kadar air pada daun binahong lebih efektif. Hal ini didukung oleh penjelasan dari penelitian (Ningsih et al., 2015) bahwa pengeringan daun menggunakan oven menghasilkan kadar air yang lebih rendah dibandingkan dengan pengeringan sinar matahari. Tahap pengentalan ekstrak juga berperan penting dalam mengurangi air yang ada pada ekstrak yang berpengaruh juga terhadap hasil akhir biskuit.

1.2 Kadar Abu (%)

Tabel 2. Analisis uji JBD kadar abu

Perlakuan	Hasil Rerata			Rata-rata
	B1	B2	B3	
A1	0,87	0,49	0,86	$0,74^{x}$
A2	0,77	1,02	0,93	$0,91^{y}$
A3	0,81	1,03	1,52	$1,12^{z}$
rata-rata	$0,82^{p}$	$0,85^{q}$	$1,10^{r}$	

Tabel menunjukkan bahwa metode pengeringan panas sinar matahari tidak langsung (A3) memiliki kadar abu paling tinggi. Hal ini disebabkan karena pada pengeringan sinar matahari tidak langsung tidak terjadi fluktuasi panas dan lebih mempertahakan kandungan mineral pada daun. Struktur sel pada daun (termasuk kandungan mineral) lebih terjaga jika daun dikeringkan menggunakan metode panas sinar matahari tidak langsung (Al-hamdani et al., 2022). Penambahan ekstrak daun binahong juga memberikan pengaruh signifikan terhadap kadar abu pada biskuit, dimana penambahan ekstrak sebesar 10% (B3) memiliki kadar abu paling tinggi. Hal ini disebabkan karena adanya kandungan mineral pada ekstrak daun binahong, daun binahong memiliki kandungan mineral yang kompleks, salah satunya kalium sebanyak 1,37% b/b (Tri Wahyuni Maharani et al., 2015).

1.3 Kadar Protein (%)

Tabel 3. Analisis uji JBD kadar protein

Perlakuan	Hasil Rerata			Rata-rata
	B1	B2	B3	
A1	5,60	6,61	7,92	$6,71^{y}$
A2	5,71	6,64	8,49	$6,95^{z}$
A3	5,69	6,55	7,49	$6,58^{x}$
rata-rata	$5,67^{r}$	$6,60^{p}$	$7,97^{q}$	

Tabel menunjukkan bahwa metode pengeringan memiliki kadar protein yang tidak jauh berbeda. Pada faktor B juga memberikan pengaruh signifikan terhadap kadar protein pada biskuit, dimana penambahan ekstrak sebesar 10% (B3) memiliki kadar protein paling tinggi. Hal ini dikarenakan daun binahong memiliki kadar protein 20 g/100 g (Thahirah & Ichsan, 2022). Selain itu tepung terigu merupakan tepung protein sedang dengan kandungan 11 g/100 g, sehingga penambahan tepung terigu akan meningkatkan kadar protein pada produk akhir.

1.4 Kadar Lemak (%)

Tabel 4. Analisis uji JBD kadar lemak

Perlakuan	Hasil Rerata			Rata-rata
	B1	B2	B3	
A1	23,18	19,61	18,92	20,57^{z}
A2	22,44	20,09	18,56	20,36^{y}
A3	22,35	19,95	17,97	20,09^{x}
rata-rata	22,66^{r}	19,88^{q}	18,48^{p}	

Tabel menunjukkan bahwa ketiga metode pengeringan memiliki selisih nilai yang tidak jauh berbeda di setiap parafnya, meskipun secara statistik menunjukan adanya perbedaan signifikan pada faktor A. Perbedaan nilai kadar lemak antara metode pengeringan daun chia relatif kecil namun menunjukkan adanya pengaruh signifikan secara statisik dikarenakan perbedaan tersebut konsisten pada setiap ulangan (Kirruti et al., 2021). Pada faktor B juga memberikan pengaruh signifikan terhadap kadar lemak pada biskuit, dimana penambahan ekstrak sebesar 10% (B3) memiliki kadar lemak paling rendah. Hal ini disebabkan Hal ini disebabkan penambahan ekstrak daun binahong yang masih berupa cairan, sehingga komposisi total dari biskuit berubah seperti peningkatan kadar air dan penurunan kadar lemak. Penambahan air atau zat pengganti lemak berbasis karbohidrat berpengaruh terhadap sifat fisik dan sensoris pada biskuit, termasuk penurunan kadar lemak karena diganti dengan bahan lain (Chugh et al., 2013).

1.5 Karbohidrat *By-different* (%)

Tabel 5. Analisis uji JBD karbohidrat *By-different*

Perlakuan	Hasil Rerata			Rata-rata
	B1	B2	B3	
A1	64,69	66,64	65,62	65,65^{x}
A2	65,74	67,80	66,73	66,76^{z}
A3	65,53	66,88	67,51	66,64^{y}
rata-rata	65,32^{p}	67,11^{r}	66,62^{q}	

Berdasarkan tabel, pada faktor A dan B memberikan pengaruh signifikan terhadap kadar karbohidrat pada biskuit meskipun selisih nilai di setiap tarafnya tidak jauh berbeda. Hal ini disebabkan data pengulangan dalam satu perlakuan hampir sama dan pola urutan tiap taraf faktor yang konsisten, sehingga nilai F dari tabel anova cukup besar untuk menunjukkan tidak ada beda nyata antar perlakuan. Hasil analisis juga menunjukkan adanya interaksi antara faktor A dan B dengan adanya pengaruh signifikan terhadap kadar karbohidrat biskuit.

Peningkatan karbohidrat juga disebabkan penggunaan tepung terigu yang tinggi karbohidrat dengan kandungan karbohidrat 72,7g/100g lebih tinggi dibandingkan tepung lainnya (Hughes et al., 2020). Perlu diperhatikan juga bahwa metode yang digunakan yaitu analisis *By-different* yaitu hasil dari pengurangan total komposisi dikurangi dengan komposisi lainnya seperti kadar air, protein, lemak. Jadi perubahan pada nilai karbohidrat juga dipengaruhi oleh perubahan-perubahan kandungan gizi lainnya (Aly et al., 2023).

1.6 Aktivitas Antioksidan (%)

Tabel 6. Analisis uji JBD aktivitas antioksidan

Perlakuan	Hasil Rerata			Rata-rata
	B1	B2	B3	
A1	31,22	37,36	43,80	37,46^{x}
A2	31,08	45,66	60,33	45,69^{z}
A3	40,76	40,71	46,86	42,78^{y}
rata-rata	34,35^{p}	41,24^{q}	50,33^{r}	

Tabel menunjukkan metode pengeringan oven (A2) memiliki aktivitas antioksidan paling tinggi yang disebabkan metode oven mengeringkan daun dengan suhu yang stabil. Proses pemanasan oven bisa merusak struktur dinding sel, sehingga memicu terjadinya pelepasan senyawa fenolik kedalam matriks (Babaei Rad et al., 2025). Hasilnya terjadi peningkatan senyawa fenolik yang merupakan salah satu dari senyawa antioksidan. Pada faktor B juga memberikan pengaruh signifikan terhadap aktivitas antioksidan pada biskuit, dimana penambahan ekstrak sebesar 10% (B3) memiliki aktivitas antioksidan paling tinggi karena jumlah ekstrak yang diberikan lebih banyak maka semakin banyak aktivitas antioksidannya. Antioksidan berperan penting dalam melindungi tubuh dari berbagai penyakit degeneratif yang disebabkan oleh stres oksidatif (Aisyah Meisya Putri, 2020).

1.7 Analisis Total Perbedaan Warna

Tabel 7. Analisis uji JBD *chromameter*

Perlakuan	Hasil Rerata			Rata-rata
	B1	B2	B3	
A1	40,47	37,51	38,03	38,67^{z}
A2	38,64	37,16	35,39	37,06^{y}
A3	35,71	36,02	36,26	36,00^{x}
rata-rata	38,27^{r}	36,90^{q}	36,56^{p}	

Tabel menunjukkan bahwa taraf faktor B1 memiliki nilai yang paling tinggi, hal ini disebabkan karena warna biskuit belum didominasi warna hijau dari ekstrak

tetapi sudah cukup merubah warna krem asli dari biskuit sehingga menciptakan jarak yang besar. Berbeda dengan penambahan ekstrak yang lebih banyak akan menurunkan kecerahan sehingga biskuit menjadi lebih gelap secara merata. Penambahan ekstrak yang mengandung klorofil menghasilkan biskuit yang lebih gelap dan hijau pada konsentrasi yang tinggi. Konsentrasi yang lebih rendah bisa menghasilkan perubahan jarak yang besar terhadap kontrol. Perubahan warna juga disebabkan dengan penambahan tepung kedalam adonan yang membuat warnanya mendekati warna biskuit kontrol (Paula da Silva et al., 2021). Pada pengeringan sinar matahari tidak langsung memiliki nilai yang paling rendah. hal ini disebabkan pengeringan dengan sinar matahari tidak langsung tidak terlalu mendegradasi pigmen seperti klorofil, karena klorofil sangat peka terhadap cahaya dan panas, sehingga membuat warna pada produk akhir menjadi lebih gelap ke arah hijau akibat degradasi dari pigmen pada daun (Amrih et al., 2023).

1.8 Uji Organoleptik Kesukaan Warna

Tabel 8. Analisis uji JBD kesukaan warna

Perlakuan	Hasil Rerata			Rata-rata
	B1	B2	B3	
A1	3,93	4,18	4,93	$4,35^{x}$
A2	5,08	6,00	5,48	$5,52^{y}$
A3	5,13	5,78	5,73	$5,55^{z}$
rata-rata	$4,71^{p}$	$5,32^{q}$	$5,38^{r}$	

Tabel menunjukkan bahwa faktor A dan B memberikan pengaruh signifikan terhadap kesukaan warna pada biskuit yang dihasilkan, biskuit dengan penambahan ekstrak 10% memiliki warna yang lebih cerah. Hasil juga menunjukkan adanya interaksi dengan indikasi bahwa semakin ditambahkan penambahan ekstraknya maka kemungkinan disukainya akan semakin tinggi.

1.9 Uji Organoleptik Kesukaan Aroma

Tabel 9. Analisis uji JBD kesukaan aroma

Perlakuan	Hasil Rerata			Rata-rata
	B1	B2	B3	
A1	4,93	5,33	5,28	$5,18^{x}$
A2	4,63	6,00	5,63	$5,42^{z}$
A3	5,03	5,53	5,48	$5,35^{y}$
rata-rata	$4,86^{p}$	$5,62^{r}$	$5,46^{q}$	

Berdasarkan tabel diatas, faktor A dan B memberikan pengaruh signifikan terhadap kesukaan aroma pada biskuit yang dihasilkan serta menunjukkan adanya

interaksi antar faktor dengan indikasi penambahan ekstrak yang lebih banyak akan meningkatkan angka kesukaan aromanya. Biskuit dengan penambahan ekstrak paling banyak memiliki aroma yang lebih kuat dan menyerupai aroma teh.

1.10 Uji Organoleptik Kesukaan Tekstur

Tabel 10. Analisis uji JBD kesukaan tekstur

Perlakuan	Hasil Rerata			Rata-rata
	B1	B2	B3	
A1	3,58	3,58	4,88	$4,01^{x}$
A2	5,28	6,00	5,23	$5,50^{y}$
A3	5,65	5,48	5,78	$5,64^{z}$
rata-rata	$4,84^{p}$	$5,02^{q}$	$5,30^{r}$	

Berdasarkan tabel diatas, faktor A dan B memberikan pengaruh signifikan terhadap kesukaan tekstur pada biskuit yang dihasilkan serta menunjukkan adanya interaksi dengan indikasi bahwa semakin ditambahkan penambahan ekstraknya maka kemungkinan disukainya akan semakin tinggi, biskuit dengan penambahan ekstrak yang lebih banyak memiliki tekstur yang lebih renyah dan keras.

1.11 Uji Organoleptik Kesukaan Rasa

Tabel 11. Analisis uji JBD kesukaan rasa

Perlakuan	Hasil Rerata			Rata-rata
	B1	B2	B3	
A1	4,28	5,33	5,53	$5,05^{x}$
A2	4,28	6,03	5,48	$5,26^{y}$
A3	5,53	5,08	5,53	$5,38^{z}$
rata-rata	$4,70^{p}$	$5,48^{q}$	$5,51^{r}$	

Berdasarkan tabel diatas, faktor A dan B memberikan pengaruh signifikan terhadap kesukaan rasa pada biskuit yang dihasilkan serta menunjukan adanya interaksi dengan indikasi bahwa semakin ditambahkan penambahan ekstraknya maka kemungkinan disukainya akan semakin tinggi, biskuit dengan penambahan ekstrak paling banyak memiliki rasa manis menyerupai teh dengan sedikit rasa *after taste* sedikit pahit.

1.12 Perbandingan Nilai Gizi Biskuit Perlakuan, Biskuit Kontrol, dan Biskuit Komersil

Tabel 12. Perbandingan Nilai Gizi Biskuit Perlakuan, Biskuit Kontrol, dan Biskuit Komersil

Parameter (%)	Biskuit Perlakuan	Biskuit Kontrol	Biskuit Komersil

Air	4,46	5,01	4,9
Abu	1,02	0,52	3,4
Lemak	20,09	22,25	15,4
Protein	6,64	6,31	8,6
Karbohidrat	67,80	65,91	55,4
Aktivitas Antioksidan	45,65	13,35	-

Sampel biskuit perlakuan diambil berdasarkan biskuit yang paling disukai berdasarkan warna, aroma, tekstur, dan rasa atau dapat diterima oleh panelis yaitu perlakuan A2B2 (metode pengeringan oven dan penambahan ekstrak 5%), sedangkan biskuit kontrol merupakan biskuit yang tidak ditambahkan ekstrak daun binahong dan biskuit komersil dengan *merk* Regal. Tabel diatas menunjukkan biskuit perlakuan memiliki kualitas yang lebih baik berdasarkan kadar air, karbohidrat, dan aktivitas antioksidan serta mengalami penurunan kualitas berdasarkan kadar abu yang lebih tinggi. Kenaikkan mineral secara langsung berkontribusi dalam peningkatkan kadar abu (Mudau et al., 2022). Selain kadar abu, kadar protein biskuit perlakuan juga lebih rendah serta kadar lemak biskuit perlakuan berada diantara biskuit kontrol dan biskuit komersil, jika biskuit mengandung lemak yang berlebih (diatas 42%) mengakibatkan perubahan pada karakteristik biskuit seperti kerenyahan yang menurun (Man et al., 2021).

1.13 Analisis Uji-T

Tabel 34. Hasil Analisis Uji-T Penelitian Terhadap Sampel Biskuit dan Kontrol

Parameter	Kontrol	Perlakuan	Signifikansi	Perbedaan
Kadar air	5,01	5,66	<0,001	Berbeda
Kadar abu	0,32	0,92	0,012	Berbeda
Protein	6,31	6,74	0,372	Tidak Berbeda
Lemak	22,25	20,34	0,068	Tidak Berbeda
Karbohidrat	65,91	66,34	0,001	Berbeda
Antioksidan	13,31	41,97	<0,001	Berbeda

Pada tabel diatas sampel yang digunakan sebagai biskuit perlakuan merupakan hasil rata-rata dari seluruh perlakuan agar mewakili data dari semua sampel yang ada, selain itu biskuit yang digunakan sebagai kontrol merupakan biskuit yang dihasilkan tanpa penambahan ekstrak daun binahong. Tabel diatas menunjukkan bahwa hampir seluruh parameter uji memberikan signifikansi antara biskuit perlakuan dengan biskuit kontrol kecuali kadar protein dan kadar lemak.

Pada kadar air dan kadar abu memberikan signifikansi ke arah yang kurang baik akibat adanya peningkatan kadar air dan kadar abu, akibatnya umur simpan yang tidak terlalu lama dan kandungan mineral yang tinggi bisa saja berasal dari kotoran. Biskuit merupakan makanan kering dengan volume dan beratnya yang kecil serta umur simpannya yang relatif lama (Riskiani et al., 2014). Pada perbandingan karbohidrat dan aktivitas antioksidan, biskuit perlakuan memberikan signifikansi kearah yang lebih baik dengan meningkatnya nilai karbohidrat dan antioksidan, karbohidrat akan meningkatkan energi yang ada pada biskuit dan antioksidan baik untuk kesehatan karena menangkal radikal bebas yang dapat menyebabkan berbagai macam penyakit.

Kesimpulan

Metode pengeringan dan penambahan ekstrak daun binahong memberikan pengaruh baik berdasarkan peningkatan dari nilai karbohidrat, lemak, dan antioksidan terhadap biskuit yang dihasilkan serta pengaruh ke arah yang kurang baik berdasarkan peningkatan kadar air dan kadar abu. Hasil menunjukkan bahwa metode pengeringan dan jumlah penambahan ekstrak daun binahong yang menghasilkan biskuit dengan aktivitas antioksidan paling tinggi ada pada perlakuan metode pengeringan oven 60^0C dan penambahan ekstrak 10% (A2B3) dengan aktivitas antioksidan 60,33%.

Saran

Penelitian selanjutnya disarankan untuk mengentalkan atau membubukkan ekstrak agar kadar air yang dihasilkan semakin rendah dan dapat memenuhi kriteria SNI 2973:2022 (maksimal 5%), selain itu bisa dilakukkan uji daya simpan produk untuk mengetahui stabilitas dari kadar air, kadar abu, dan aktivitas antioksidan pada biskuit selama masa penyimpanan.

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Analisis Daya Dukung Permukiman Imogiri, Bantul

Settlement Carrying Capacity Analysis of Imogiri, Bantul

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ABSTRACT

The continuous population growth in Imogiri Sub-district has increased pressure on the availability of residential land, particularly as part of the area is prone to natural hazards that limit spatial utilization. This study applies a quantitative descriptive analysis to estimate the residential carrying capacity over a given period. The results indicate that the residential carrying capacity in the study area remains sufficient for the coming years. The findings provide practical benefits as a reference for both local authorities and communities in planning housing development that aligns with sustainability principles and land-use control. The contribution of this research lies in presenting a model of carrying capacity analysis that integrates population growth with environmental vulnerability, thereby offering novelty in supporting adaptive spatial planning in disaster-prone areas.

Keyword: *settlement, environmental carrying capacity, land*

ABSTRAK

Pertumbuhan penduduk yang terus meningkat di Kecamatan Imogiri menimbulkan tekanan terhadap ketersediaan lahan permukiman, terutama karena sebagian wilayah juga memiliki potensi rawan bencana yang membatasi pemanfaatan ruang. Penelitian ini dilakukan dengan pendekatan analisis deskriptif kuantitatif untuk menghitung daya dukung permukiman pada periode tertentu. Hasil penelitian menunjukkan bahwa daya dukung permukiman di wilayah studi masih dalam kondisi mencukupi hingga beberapa tahun ke depan. Temuan ini memberikan manfaat praktis sebagai acuan bagi pemerintah daerah maupun masyarakat dalam merencanakan pembangunan perumahan yang selaras dengan prinsip keberlanjutan dan pengendalian alih fungsi lahan. Kontribusi penelitian terletak pada penyajian model analisis daya dukung yang mengintegrasikan aspek pertumbuhan penduduk dengan kerentanan lingkungan, sehingga menawarkan kebaruan dalam mendukung perencanaan tata ruang yang adaptif di kawasan rawan bencana.

Kata Kunci: *permukiman, daya dukung lingkungan, lahan*

Pendahuluan

Pertumbuhan penduduk dan peningkatan kebutuhan akan lahan menjadi tantangan dalam pengelolaan dan pemanfaatan ruang, khususnya lahan permukiman, di wilayah pedesaan maupun perkotaan. Kecamatan Imogiri sebagai salah satu bagian dari Kabupaten Bantul, Daerah Istimewa Yogyakarta, menghadapi dinamika yang cukup intens yang diakibatkan oleh keterbatasan ruang dan meningkatnya aktivitas manusia. Aktivitas penduduk di kawasan perkotaan mengakibatkan kebutuhan ruang yang semakin besar sedangkan ketersediaan ruang yang semakin lama semakin terbatas sehingga alih fungsi lahan tidak dapat terhindarkan. Laju pertumbuhan jumlah penduduk di wilayah ini berpotensi dapat berdampak langsung terhadap kemampuan lahan dalam

menyediakan daya dukung, khususnya yang berkaitan dengan tercukupinya kelayakan ketersediaan lahan.

Daya dukung lahan merupakan kemampuan suatu lahan dalam mendukung perikehidupan manusia dalam bentuk lahan yang tujuan utamanya untuk memenuhi kebutuhan terutama bahan makanan dan tempat tinggal (Buton, 2020). Daya dukung suatu lahan ditentukan oleh berbagai faktor yang saling berkaitan. Karakteristik suatu lahan yang meliputi komponen geofisik-kimia berpengaruh besar terhadap kemampuan suatu wilayah dalam pemanfaatan ruang yang mempertimbangkan kapasitas daya tampung lingkungan. Tekanan terhadap kondisi suatu lahan yang signifikan dapat mendorong pembangunan pada area dengan kondisi yang kurang ideal. Kecenderungan ini dapat menimbulkan persoalan baru dalam kurun waktu jangka panjang yang berkaitan dengan keberlanjutan ruang dan kualitas lingkungan permukiman.

Kondisi geografis dan hidrologis Kecamatan Imogiri memiliki kerentanan menghadapi potensi bencana banjir, terutama yang dilalui Sub-DAS Celeng. Banjir merendam beberapa desa di Kecamatan Imogiri, seperti Desa Wukirsari dan Selopamioro, pada bulan Maret 2019 silam (Apriyanto & Setyawan, 2020). Peristiwa tersebut menjadi salah satu indikasi terbatasnya kapasitas lahan terhadap beban pemanfaatan ruang yang terus meningkat sejalan dengan pertumbuhan penduduk. Akumulasi faktor-faktor seperti curah hujan yang tinggi, alih fungsi lahan menjadi pemukiman dan lahan terbuka, serta kemiringan lahan yang cukup curam pada kedua desa ini memperbesar risiko terjadinya banjir (Rohmah et al., 2025)

Tujuan

Penelitian ini bertujuan untuk menganalisis daya dukung permukiman di Kecamatan Imogiri, Kabupaten Bantul, dengan mempertimbangkan dinamika pertumbuhan penduduk serta keterbatasan lahan akibat kondisi geografis dan potensi bencana.

Rumusan Masalah

1. Bagaimana kondisi daya dukung permukiman di Kecamatan Imogiri saat ini?
2. Bagaimana proyeksi daya dukung permukiman di Kecamatan Imogiri pada tahun 2027?
3. Apa implikasi hasil analisis daya dukung permukiman terhadap perencanaan tata ruang dan keberlanjutan lingkungan di Kecamatan Imogiri?

Metode Penelitian

Metode **Pengumpulan Data**

Observasi Lapangan

1. Observasi Lapangan
   Penelitian ini dilakukan dengan melakukan pengamatan langsung ke lokasi penelitian pada tanggal 3 Juni 2025 untuk memperoleh informasi mengenai rona lingkungan dan penggunaan lahan permukiman di Kecamatan Imogiri. Melalui observasi ini, penyusun dapat mencatat dan mendokumentasikan karakteristik lahan dilihat dari kondisi geo-fisik kimia hingga kondisi sosial, budaya, serta ekonomi daerah penelitian sebagai pendukung penelitian melalui berbagai metode. Dilakukan pengambilan foto pada lokasi terjadinya banjir serta dilakukan wawancara dengan penduduk setempat untuk memastikan kebenaran adanya kejadian banjir yang ada di sempadan sungai tersebut.
2. Studi Literatur
   Metode ini dilakukan dengan menelaah berbagai sumber pustaka untuk memperoleh landasan teori, konsep, serta data sekunder yang relevan dalam analisis daya dukung permukiman.
3. Analisis Spasial
   Melalui analisis spasial dengan *overlay* dari data-data yang telah didapatkan dari berbagai sumber dari nilai daya dukung hasil perhitungan serta potensi bahaya di daerah penelitian. Peta yang digunakan antara lain peta administrasi daerah, peta daerah rawan banjir, dan peta kawasan lindung yang selanjutnya diolah dengan *software* ArcGIS.

Metode Analisis Data

Analisis deskriptif kuantitatif dilakukan untuk menggambarkan data numerik terkait daya dukung permukiman, seperti jumlah penduduk, luas lahan, dan variabel lingkungan lainnya. Data awal didapatkan dari data sekunder berupa data Badan Pusat Statistik. Data kuantitatif yang diperoleh dianalisis secara statistik untuk mengetahui kemampuan lahan di daerah penelitian untuk mendukung keberlangsungan pertumbuhan penduduk yang terjadi di lokasi penelitian. Analisis daya dukung permukiman dihitung memakai konsep rumus yang didasarkan pada PERATURAN MENTERI PEKERJAAN UMUM TENTANG ORGANISASI DAN TATA KERJA SEKRETARIAT DEWAN SUMBER DAYA AIR NASIONAL No 11 Tahun 2008 dengan rumus yaitu:

$$DDPm = \frac{LPm/JP}{\alpha} \qquad LPm = LW - (LKL + LKRB)$$

Dimana:DDPm= Daya Dukung Permukiman

LPm = Luas lahan yang layak untuk permukiman (m^2)

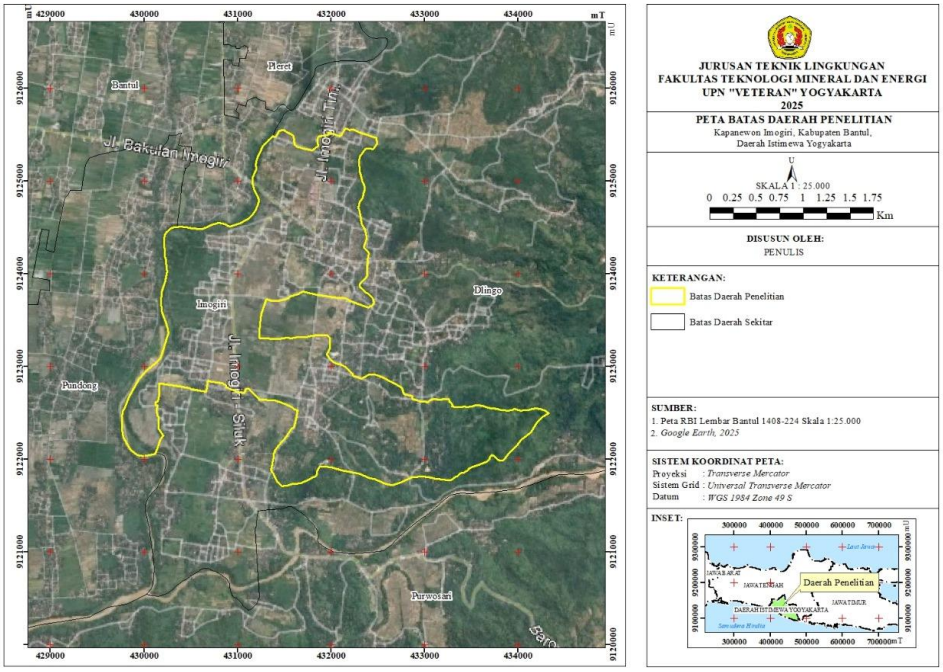
JP = Jumlah Penduduk

α = Koefisien luas kebutuhan lahan (m^2/kapita) yang angkanya didasarkan pada Peraturan Menteri Negara Perumahan Rakyat (Permenpera) No. 11 Tahun 2008.
LW = Luas Wilayah
LKL = Luas Kawasan Lindung
LKRB = Luas Kawasan Rawan BencanaSetelah dilakukan perhitungan menggunakan rumusan tersebut, maka nilai daya dukung wilayah untuk permukiman dapat dikelompokkan dalam 3 klasifikasi (Tanie et al., 2023), yakni:

1. Apabila DDPm > 1, maka daya dukung permukiman dari daerah tersebut masih tinggi sehingga dapat disimpulkan jika daerah penelitian memiliki kemampuan untuk menampung penduduk yang menetap di daerah ini.
2. Apabila DDPm = 1, maka daya dukung permukiman dari daerah tersebut optimal sehingga dapat disimpulkan jika ada keseimbangan dari kebutuhan wilayah permukiman dan kemampuan wilayah dalam menampung penduduk yang menetap.
3. Apabila DDPm < 1, daya dukung permukiman dari daerah tersebut rendah sehingga dapat disimpulkan jika terdapat ketidakseimbangan dari kebutuhan wilayah permukiman dan kemampuan wilayah dalam menampung penduduk yang menetap dan perlunya untuk dilakukan penataan wilayah ulang.

DESKRIPSI WILAYAH

Imogiri merupakan satu dari banyaknya kapanewon yang terdapat di Kabupaten Bantul Provinsi Daerah Istimewa Yogyakarta. Kapanewon Imogiri berada di sebelah tenggara Ibukota Kabupaten Bantul. Kapanewon Imogiri memiliki luas wilayah sebesar 5.492 Ha. Kapanewon Imogiri ini terletak di ketinggian 100 meter di atas permukaan laut sehingga termasuk ke dalam daerah dataran rendah (Lisan & Jamaluddin, 2023). DAS Celeng berada di wilayah Kabupaten Bantul, Daerah Istimewa Yogyakarta, mencakup wilayah Kecamatan Imogiri dan Kecamatan Pleret. Daerah aliran sungai ini termasuk dalam kawasan Sungai Celeng yang bermuara di Kali Oyo. Kawasan ini memiliki keunikan tersendiri, baik dari segi bentuk bentang alam, kondisi hidrologi, hingga aktivitas manusia yang berlangsung di dalamnya. Pola permukiman di sekitar DAS juga menunjukkan ciri khas yang bervariasi, baik dari segi bentuk, tingkat kepadatan, maupun persebarannya. Masyarakat di wilayah ini memanfaatkan informasi yang akurat mengenai kualitas air, terutama dalam kaitannya dengan tingkat kepadatan hunian di masing-masing lokasi.



Gambar 1.1 Peta Citra Lokasi Penelitian
(Sumber: Analisis Studio, 2025)

1. **Batas Permasalahan**

   Batas permasalahan ditetapkan untuk membatasi ruang lingkup kajian. Dalam penelitian ini, batas permasalahan ditentukan berdasarkan peristiwa banjir akibat meningkatnya debit air yang menyebabkan luapan Kali Celeng di Desa Wukirsari, Kapanewon Imogiri, Kabupaten Bantul, Daerah Istimewa Yogyakarta, yang menggenangi sejumlah jalan utama.

2. **Batas Ekologi**

   Batas ekologi daerah penelitian mencakup seluruh lingkungan yang terdampak dari permasalahan banjir di Kali Celeng, Imogiri. Batas ekologis pada daerah penelitian mencakup beberapa lahan yang terdampak genangan air akibat banjir, serta area yang di dalamnya terjadi interaksi timbal balik antara komponen lingkungan hidup, baik secara langsung maupun tidak langsung, sebagai akibat dari perubahan aliran air dan kondisi tanah di sekitar kawasan tersebut.

3. **Batas Sosial**

   Batas sosial di area bantaran Kali Celeng dapat ditinjau dari beberapa aspek yang mempengaruhi kehidupan masyarakat di sekitar sungai. Kondisi permukiman yang tinggal di sekitar bantaran Kali Celeng yang menghadapi

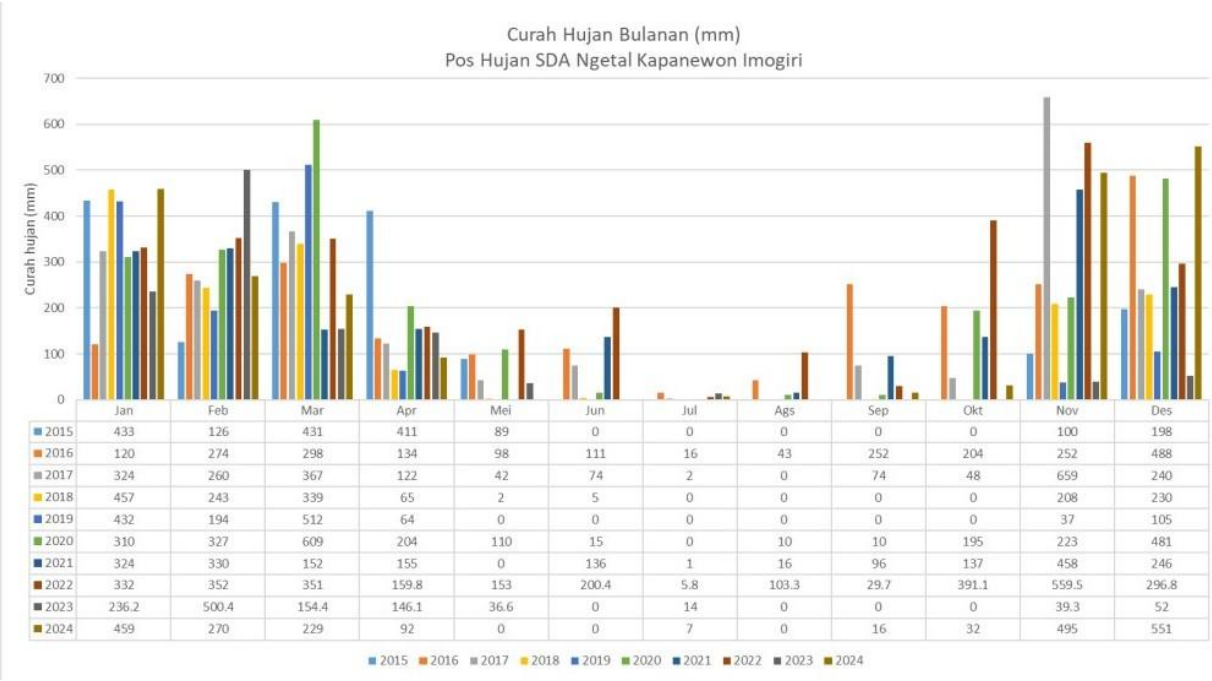
banjir, sehingga pondasi rumah di sekitar aliran Kali Celeng ini meninggikan hingga 1 - 1,5 m.

RONA LINGKUNGAN HIDUP

1. Geofisik Kimia

A. Iklim

Kecamatan Imogiri memiliki iklim tropis dengan curah hujan tahunan tinggi dan musim hujan puncak pada November–Maret (Aminatun & Anggraheni, 2018). Curah hujan yang tinggi dan intensitas hujan ekstrem, terutama pada tahun 2020 dan 2022, meningkatkan volume limpasan air ke Sungai Kali Celeng. Kondisi ini dipengaruhi oleh pendangkalan sungai dan berkurangnya daerah resapan akibat perubahan tata guna lahan, sehingga kapasitas aliran sungai menurun dan memicu seringnya banjir di wilayah sekitar Sungai Kali Celeng. Dengan demikian, pola iklim dan curah hujan secara langsung berkontribusi pada risiko banjir di kawasan tersebut. Berikut Merupakan Tabel Data Curah Hujan daerah penelitian tahun 2015 - 2024.



	Jan	Feb	Mar	Apr	Mei	Jun	Jul	Ags	Sep	Okt	Nov	Des
2015	433	126	431	411	89	0	0	0	0	0	100	198
2016	120	274	298	134	98	111	16	43	252	204	252	488
2017	324	260	367	122	42	74	2	0	74	48	659	240
2018	457	243	339	65	2	5	0	0	0	0	208	230
2019	432	194	512	64	0	0	0	0	0	0	37	105
2020	310	327	609	204	110	15	0	10	10	195	223	481
2021	324	330	152	155	0	136	1	16	96	137	458	246
2022	332	352	351	159.8	153	200.4	5.8	103.3	29.7	391.1	559.5	296.8
2023	236.2	500.4	154.4	146.1	36.6	0	14	0	0	0	39.3	52
2024	459	270	229	92	0	0	7	0	16	32	495	551

(Sumber: BMKG, 2025)

Dari data menunjukkan bahwa hujan tertinggi selama periode 2015 – 2024 di pos hujan SDA Ngetal Kapanewon Imogiri terjadi pada bulan November 2017 dengan jumlah curah hujan 659 milimeter.

B. Bentuk Lahan

Bentuklahan di daerah penelitian ini didominasi oleh proses fluvial dan proses struktural. Proses fluvial terjadi akibat adanya tenaga pembentuk satuan bentuk lahan dari tenaga air (Sutrisno, 2011). Daerah ini merupakan bentuk lahan fluvial, yang terbentuk melalui proses alami dari tenaga aliran air sungai. Pertemuan Sungai Opak dan Sungai Oyo menciptakan lanskap yang dinamis dan kaya akan keanekaragaman hayati. Studi di Tempuran Opak Oyo telah dilakukan terkait aspek geologi dan geomorfologi (Sitohang et al., 2025). Selain itu menurut Gunawan & Khadiyanto (2012),Kapanewon Imogiri ini didominasi oleh kompleks pegunungan selatan yang terdiri dari kaki lereng koluvial Pegunungan Baturagung, serta perbukitan struktural dari Formasi Nglanggeran-Semilir serta Wonosari.

C. Tanah

Wilayah penelitian ini didominasi oleh jenis tanah latosol yang memiliki tekstur liat dan kandungan karbon organik yang rendah. Tanah latosol di area ini masih berada dalam tahap pelapukan atau laterisasi, sehingga proses pelapukan batuannya belum sepenuhnya sempurna. Jenis tanah ini terbentuk dari pelapukan breksi andesit, yang membuat warnanya cenderung merah kekuningan akibat kandungan besi dan aluminium yang tinggi. Pada salah satu titik singkapan tanah di lokasi penelitian, ditemukan horizon tanah yang terbentuk terdiri dari horizon A dan horizon C (Rikumahu & Gobel, 2016).

D. Hidrologi

Kecamatan Imogiri dilalui oleh dua sungai utama, yaitu Sungai Opak dan Sungai Oyo. Sungai Opak memiliki hulu di lereng Gunung Merapi, sedangkan Sungai Oyo berhulu di kawasan Pegunungan Sewu. Desa Sriharjo yang berada di Kecamatan Imogiri menjadi tempat kedua sungai ini bermuara. Aliran Sungai Opak mengalir dari arah utara ke selatan dan terletak di bagian barat wilayah Imogiri, sementara Sungai Oyo mengalir dari timur ke barat melintasi bagian selatan kecamatan tersebut. Kedua sungai ini memiliki anak sungai dengan panjang yang relatif pendek (Sutrisno, 2011).

2. Biotis

A. Flora

Tumbuhan yang terletak di lokasi penelitian didominasi oleh pohon pisang. Beberapa jenis flora yang ditemukan di lokasi yaitu pohon pisang (*Musa paradisiaca*), bambu (*Bambusoideae*), pohon pepaya (*Carica papaya*),

pohon kelapa (*Cocos nucifera*), Pohon jati (*Tectona grandis*), rumput teki (*Cyperus rotundus*) dan ilalang (*Imperta cylindria*).

Gambar 1.2 Pohon Kelapa (*Cocos nucifera*)

Gambar 1.3 Pohon pisang (*Musa paradisiaca*)

B. Fauna

Fauna di sekitar Sungai Celeng, Imogiri, mencakup berbagai jenis serangga, ikan, dan mamalia kecil yang beradaptasi dengan lingkungan sungai. Beberapa spesies yang umum ditemukan meliputi semut tanah, serta capung yang berkembang biak di area berair tenang. Sungai ini juga menjadi habitat bagi ikan air tawar yang masih bertahan di bagian sungai yang lebih bersih. Selain itu, ayam dan cacing sering terlihat di sekitar vegetasi sungai.

3. Sosial Ekonomi

Kecamatan Imogiri memiliki kondisi topografi yang cukup bervariasi, dengan permukaan lahan yang tidak rata. Keadaan ini turut mempengaruhi pola perilaku dan karakter masyarakat yang tinggal di wilayah tersebut. Keanekaragaman bentuk lahan akibat kondisi geomorfologi yang kompleks tak hanya menciptakan panorama alam yang indah, tetapi juga menyimpan potensi risiko bencana seperti longsor dan banjir. Oleh karena itu, cara masyarakat beradaptasi dengan lingkungan di kawasan ini menjadi hal penting untuk diperhatikan. Di bagian selatan Kecamatan Imogiri, khususnya di sepanjang aliran Sungai Oyo, pemanfaatan lahan cenderung difokuskan untuk permukiman dan pertanian, terutama sawah. Hal ini berkaitan erat dengan jenis tanah aluvial yang banyak ditemukan di wilayah barat dan utara Imogiri—tanah yang terbentuk dari endapan sungai Oyo dan masih dipengaruhi oleh aktivitas vulkanik dari kaki Gunungapi Merapi Muda. Berdasarkan kondisi morfologi wilayah, dapat diketahui bahwa sebagian besar

penduduk di bagian barat dan selatan Kecamatan Imogiri berprofesi sebagai petani. Sementara itu, masyarakat yang tinggal di sepanjang Sungai Oyo, terutama di kawasan sekitar Selopamioro Adventure Park, banyak yang bekerja di sektor jasa, memanfaatkan potensi wisata alam di daerah tersebut sebagai sumber penghasilan. Keberadaan objek wisata budaya seperti kompleks makam raja-raja Imogiri dan pesona perbukitan juga ikut mendorong pertumbuhan ekonomi lokal melalui sektor pariwisata dan perdagangan.

4. **Penggunaan Lahan**

Kecamatan Imogiri mempunyai penggunaan lahan yang bervariasi. Penggunaan lahan di sekitar daerah penelitian yaitu permukiman. Pola permukiman di Kecamatan Imogiri tersebar mengikuti jaringan jalan, dan mengelompok membentuk perkampungan. Luas area permukiman mencapai 1480,46 atau 26,95 % dari luas Kecamatan Imogiri (Sutrisno, 2011). Di sekitar pemukiman terdapat lahan persawahan dan perkebunan, sebagai mata pencaharian utama dari masyarakat di daerah ini. Ditemukan juga penggunaan lahan dari Kecamatan Imogiri yang berupa semak belukar dan hutan di bagian yang cukup berjarak dari pemukiman.

Hasil dan Pembahasan

Penilaian daya dukung permukiman akan dilihat dari hasil yang didapatkan, jika hasil dari perhitungan DDPm >1 maka wilayah tersebut masih mampu dikembangkan untuk lahan permukiman. Namun, jika hasil perhitungan DDPm <1 maka wilayah tersebut sudah tidak mampu untuk dikembangkan sebagai lahan pemukiman dan aktivitas pendukung permukiman lainnya. Diketahui bahwa Kapanewon Imogiri pada tahun 2023 memiliki luas lahan yang layak untuk permukiman sebesar 23.263.402 m2 dengan jumlah penduduk sebanyak 64.724 jiwa. Berikut perhitungan daya dukung lahan permukiman di Kapanewon Imogiri pada tahun 2023.

$$\text{DDPm} = \frac{LPm/JP}{\alpha}$$

$$\text{DDPm} = \frac{23.263.402 \,/\, 64.724}{26}$$

$$\text{DDPm} = 13{,}82$$

Keterangan:

DDPm = Daya Dukung Permukiman

JP = Jumlah Penduduk yang didapat dari data BPS Kabupaten Bantul

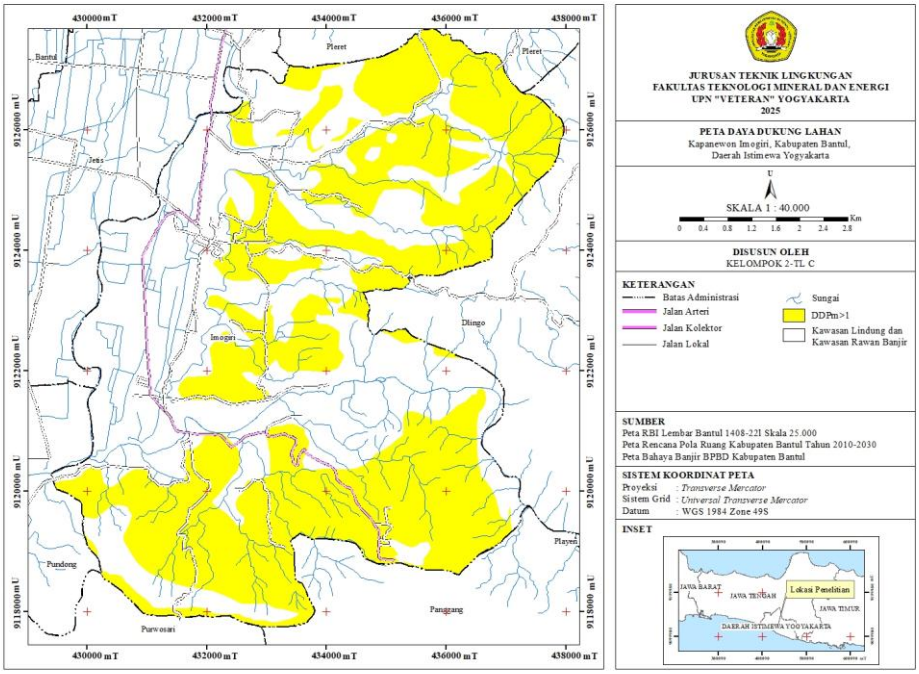
α = Koefisien Luas Kebutuhan Lahan (bernilai 26 m^2/kapita yang merupakan ketentuan perhitungan daya dukung permukiman dari Permenpera No. 11 Tahun 2008)

Hasil perhitungan menunjukkan bahwa nilai DDPm sebesar 13,82, atau lebih besar dari 1. Hal ini mengindikasikan bahwa wilayah tersebut berada dalam kondisi surplus daya dukung lahan, artinya lahan masih memiliki kapasitas yang cukup besar untuk menampung penduduk, baik untuk keperluan permukiman maupun pembangunan rumah. Proyeksi daya dukung lahan untuk periode tahun 2024 hingga 2027 dapat dilihat pada tabel berikut.

Tabel 2. Hasil Perhitungan DDPm Kapanewon Imogiri tahun 2024-2027

Tahun	Luas Lahan Yang Layak Untuk Permukiman (m^2)	Jumlah Penduduk Jiwa	Koefisien Kebutuhan Ruang	DDPm	Status Daya Dukung Lahan
2024	23.263.402	65179	26	13,73	Surplus
2025	23.263.402	65639	26	13,63	Surplus
2026	23.263.402	66101	26	13,54	Surplus
2027	23.263.402	66567	26	13,44	Surplus

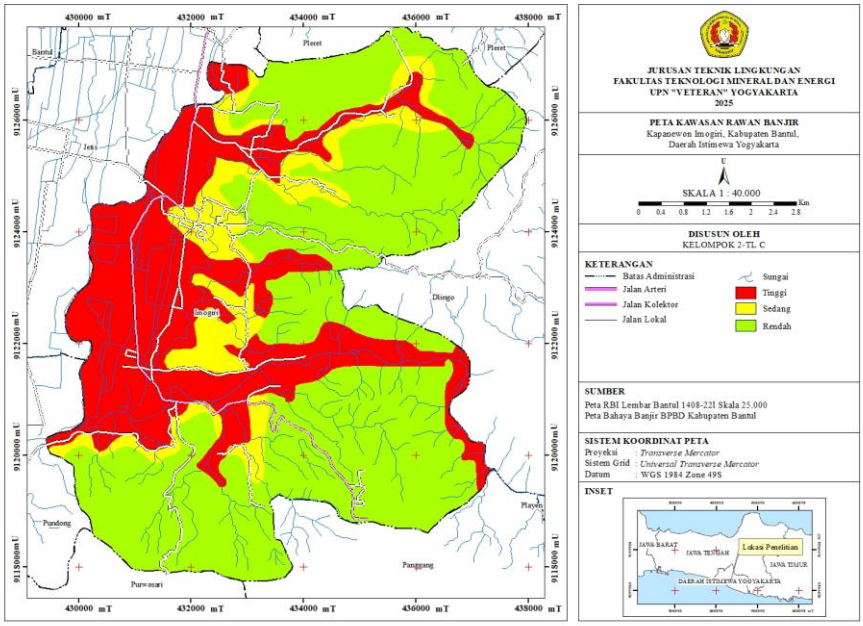
Sumber: Analisis Data (2025)



Gambar 1.4 Peta Daya Dukung Lahan Kapanewon Imogiri Tahun 2023
(Sumber: Analisis Studio, 2025)

Berdasarkan hasil perhitungan sebelumnya, diketahui bahwa nilai Daya Dukung Permukiman (DDPm) di wilayah Imogiri mencapai angka 13,82 yang berarti lebih besar dari angka 1. Nilai ini menunjukkan bahwa secara kapasitas lingkungan, wilayah ini tergolong mampu dan layak untuk dikembangkan sebagai

kawasan permukiman. Namun demikian, analisis spasial mengindikasikan adanya potensi bencana banjir di area yang berdekatan dengan badan sungai. Hal ini terlihat dari peta rawan bencana banjir yang menunjukkan bahwa wilayah dengan tingkat kerawanan banjir tinggi justru tidak memiliki area resapan air yang memadai. Ketiadaan area resapan tersebut berpotensi memperparah kondisi banjir apabila tidak dilakukan pengelolaan tata ruang yang tepat.



Gambar 1.5 Peta Kawasan Rawan Bencana Banjir Kapanewon Imogiri (Sumber: Analisis Studio, 2025)

Oleh karena itu, arah pengembangan permukiman di Kapanewon Imogiri perlu mempertimbangkan aspek mitigasi risiko bencana, khususnya terhadap ancaman banjir. Meskipun secara umum kawasan ini memiliki prospek yang baik untuk pengembangan, pembangunan sebaiknya tidak dilakukan pada zona-zona rawan banjir yang berada di sepanjang Sub-DAS Celeng, terutama di kawasan sempadan sungai serta lahan dengan kemiringan tinggi yang berpotensi meningkatkan limpasan air. Sebagai alternatif, kawasan rawan tersebut dapat dialokasikan sebagai zona larangan pembangunan maupun buffer zone yang berfungsi menahan aliran banjir sekaligus menjaga ekosistem bantaran sungai. Selain itu, diperlukan rekayasa drainase kawasan yang adaptif untuk mengurangi potensi genangan di wilayah padat permukiman. Upaya mitigasi juga harus dibarengi dengan peningkatan kesadaran masyarakat, khususnya warga yang bermukim di dekat alur sungai, mengenai pentingnya menjaga fungsi sempadan. Di samping edukasi, pengembangan rumah tinggal wajib memperhatikan regulasi teknis yang berlaku, seperti yang diatur dalam Peraturan Menteri PUPR No. 28 Tahun 2015 mengenai jarak aman pembangunan dari sempadan sungai. Dengan

demikian, keselamatan, kenyamanan, serta keberlanjutan penggunaan ruang permukiman di Kapanewon Imogiri dapat lebih terjamin dalam jangka panjang.

Gambar 1.6 Banjir di Kali Celeng

Gambar 1.7 Perbaikan di Kali Celeng

Penutup

Hasil penelitian menunjukkan bahwa nilai Daya Dukung Permukiman (DDPm) di Kapanewon Imogiri berada di atas angka 1 pada periode 2023–2027, sehingga kapasitas lingkungan masih mampu mendukung kebutuhan ruang permukiman. Kondisi ini membuktikan bahwa wilayah penelitian saat ini tergolong layak dikembangkan sebagai kawasan hunian, sekaligus menegaskan bahwa tujuan penelitian telah tercapai. Analisis proyeksi hingga tahun 2027 juga memperlihatkan kecenderungan daya dukung yang tetap mencukupi, meskipun terdapat tekanan akibat pertumbuhan penduduk dan konversi lahan.

Penggunaan metode DDPm yang dipadukan dengan analisis spasial overlay terbukti efektif dalam memberikan gambaran kuantitatif sekaligus spasial mengenai kesesuaian lahan permukiman. Hasil kajian ini mengimplikasikan bahwa perencanaan tata ruang di Imogiri harus mengintegrasikan aspek mitigasi bencana, seperti penerapan zona larangan pembangunan di daerah rawan banjir, pemanfaatan buffer zone di sempadan sungai, serta penerapan rekayasa drainase kawasan. Selain itu, pengembangan permukiman perlu memperhatikan regulasi teknis yang berlaku dan meningkatkan kesadaran masyarakat terhadap risiko lingkungan. Dengan demikian, hasil penelitian ini menjawab secara menyeluruh rumusan masalah terkait kondisi eksisting daya dukung permukiman, proyeksi hingga tahun 2027, serta implikasinya terhadap keberlanjutan lingkungan dan arah pengembangan tata ruang di Kecamatan Imogiri.

Saran

Penelitian selanjutnya dapat diarahkan pada kolaborasi antara pemerintah daerah melalui Dinas Pekerjaan Umum dan Penataan Ruang (PUPR), Badan Penanggulangan Bencana Daerah (BPBD), serta perguruan tinggi dalam

mengintegrasikan analisis daya dukung permukiman dengan pemetaan spasial zona rawan banjir secara lebih rinci. Selain itu, dinas perencanaan dan pengembangan wilayah bersama lembaga akademik perlu memasukkan indikator sosial-ekonomi masyarakat, seperti kepadatan penduduk, ketersediaan infrastruktur dasar, dan tingkat kerentanan sosial, sehingga hasil kajian dapat digunakan sebagai rekomendasi teknis yang lebih aplikatif untuk mendukung penyusunan Rencana Tata Ruang Wilayah (RTRW) maupun Rencana Detail Tata Ruang (RDTR) yang adaptif dan berkelanjutan.

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Design and Optimization of Sustainable Green Composites for High-Performance Applications

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ABSTRACT

This study presents a data-driven framework for the design and optimization of next-generation sustainable green composites that are aimed at high-performance industrial applications. A hybrid dataset that comprises 180 experimental records of natural fiber-reinforced biopolymer composites was analyzed using Machine Learning (ML) algorithms, including Random Forest Regression (R^2 = 0.962), Artificial Neural Network (R^2 = 0.948), and Support Vector Regression (R^2 = 0.921). Feature importance analysis identified fiber volume fraction (38.5%), filler type (24.7%), and matrix viscosity (18.9%) as the most influential variables that govern tensile strength and biodegradability. Multi-objective optimization with the application of NSGA-II achieved a tensile strength of 127 MPa and biodegradability of 73%, which represent a 19.6% increase in mechanical performance and a 42% improvement in environmental compatibility when compared to conventional composites. Life-cycle assessment revealed significant sustainability advantages: embodied energy reduced by 33.8% (from 68 MJ/kg to 45 MJ/kg), carbon footprint lowered by 52% (from 2.5 kg CO_2-eq/kg to 1.2 kg CO_2-eq/kg), and end-of-life recyclability enhanced from 42% to 78%. Furthermore, the optimized composite achieved a processing temperature reduction of 21.4% and a 20.5% lower material cost. These results confirm that the integration of ML-driven prediction and optimization with green composite fabrication can accelerate sustainable materials development, reduce resource waste by up to 60%, and provide a replicable model for digital twin-assisted design. The proposed framework demonstrates clear potential for adoption in automotive, aerospace, and packaging sectors, where lightweight, recyclability, and environmental performance are critical.

Keywords: *data-driven materials design; green composites; machine learning; sustainability optimization; life-cycle assessment.*

Introduction

Growing environmental concerns, depletion of non-renewable resources, and global commitments to carbon neutrality have intensified the demand for sustainable materials that can replace conventional petroleum-based composites (Li et al., 2022; Rajan and Singh, 2020). Traditional fiber-reinforced polymers, although widely used in automotive, aerospace, and construction industries, are associated with high embodied energy, non-biodegradability, and challenges in end-of-life disposal (Mishra and Satapathy, 2021). Defined as materials that are produced by the combination of two or more diverse substances like fibers and a matrix to create a new material (Ezeanyim et al., 2025; Udu et al., 2025; Okpala et al., 2021a), composites have enhanced properties like greater strength, lighter weight, or better durability, when compared to the individual components alone (Agu et al., 2018; Okpala et al., 2021b; Onukwuli et al., 2024).

In contrast, green composites which is typically composed of natural fibers like jute, flax, or hemp, and bio-based or biodegradable polymer matrices like polylactic acid or bio-epoxy, have emerged as promising alternatives that combine renewable sourcing with mechanical performance which are suitable for structural and semi-structural applications (Kumar et al., 2022; Niu et al., 2023). Despite these advantages, achieving a balance between mechanical strength, environmental performance, and cost-efficiency remains a major challenge in sustainable composite design (Okpala et al., 2025). The inherent variability of natural fibers, the complex interfacial adhesion between hydrophilic fibers and hydrophobic matrices, and the modifying influence of nano-fillers collectively contribute to non-linear material behavior that is difficult to optimize through conventional trial-and-error approaches (Das & Tiwari, 2023). This challenge is further emphasized in recent multidisciplinary studies highlighting the need for innovative and adaptive scientific methodologies to address complex, interrelated material and environmental systems (Kalu et al, 2025; Okonkwo & Idigo, 2025). As such, data-driven methodologies which encompass Machine Learning (ML), statistical modeling, and computational optimization have become increasingly attractive for advancing composite material development (Khatri et al., 2022).

Defined as algorithms that can examine and also interpret patterns in data, thus enhancing their performance over time as are exposed to more data, ML assists computers to study and learn from data and make decisions or predictions even when it is not clearly programmed to do so (Nwamekwe et al., 2025a; Aguh et al., 2025; Nwamekwe et al., 2024). It offers the capability to predict material properties, identify key design variables, and accelerate discovery processes by learning from existing datasets (Liu et al., 2019; Nwamekwe et al., 2025b; Emeka et al., 2025). In the context of composite materials, ML models such as Random Forest (RF), Support Vector Regression (SVR), and Artificial Neural Networks (ANNs) have been successfully applied to predict mechanical strength, degradation behavior, and life-cycle impacts based on compositional and processing parameters (Okpala et al., 2024; Sharma et al., 2021). Moreover, multi-objective optimization algorithms, notably the Non-dominated Sorting Genetic Algorithm II (NSGA-II) enable the balancing of conflicting performance metrics such as tensile strength, density, and biodegradability (Vitalis et al., 2025; Das and Tiwari, 2023).

The integration of data-driven modeling and optimization into sustainable material design aligns with the goals of Industry 4.0 and the circular economy, as it enables intelligent material selection, reduced experimental costs, and eco-efficient production engineering (Khatri et al., 2022; Li et al., 2022). Furthermore, this approach supports global sustainability objectives such as the United Nations Sustainable Development Goals (SDGs), particularly SDG 9 (Industry, Innovation,

and Infrastructure) and SDG 12 (Responsible Consumption and Production) (UNDP, 2023).

Therefore, the present study aims to develop a data-driven framework for the design and optimization of sustainable green composites, through the integration of machine learning predictions with multi-objective optimization. By employing realistic datasets that are derived from literature and simulated augmentation, the study seeks to identify optimal formulations that maximize mechanical performance, while maintaining high biodegradability and low environmental impact. The outcomes are expected to contribute to the advancement of high-performance, eco-efficient materials and provide a replicable methodology for the acceleration of sustainable composite innovation.

Research Methods

Research Design Overview

This study followed a data-driven research design through the integration of empirical literature data, synthetic augmentation, and computational modeling for the optimization of sustainable green composites. The approach comprised four sequential stages: (a) Data acquisition and preparation, (b) Feature engineering and normalization, (c) Machine learning (ML) model training and validation, as well as (d) Multi-objective optimization using a genetic algorithm.

The framework was designed to identify the optimal composite formulation that maximizes tensile strength and biodegradability, while minimizing density, thereby balancing mechanical performance and sustainability (Okpala et al., 2025; Das and Tiwari, 2023).

Dataset Construction and Experimental Variables

Data Source and Generation

A dataset was developed through the compilation of 23 open-access studies published between 2015 and 2023 on natural fiber–reinforced Polylactic Acid (PLA) composites. Reported data included fiber weight fraction, filler percentage, polymer matrix type, and mechanical and biodegradation properties. To improve model robustness, 40 additional synthetic data points were generated using Latin Hypercube Sampling (LHS) within realistic parameter ranges found in the literature. The final dataset contained 120 samples comprising 80% training, and 20% testing.

Input and Output Variables

Independent (input) variables included fiber weight fraction (wt%), nano-filler content (wt%), and matrix type (PLA or bio-epoxy). Dependent (output) variables represented key performance metrics of the composites: tensile strength, flexural strength, impact strength, density, and biodegradability index. A summary of the dataset variables is shown in Table 1.

Table 1: Description of dataset variables and ranges

Variable	Symbol	Type	Range / Category	Unit	Description
Fiber weight fraction	X1X_1X1	Input	20–60	wt%	Content of natural fiber (jute, flax, hemp)
Nano-filler content	X2X_2X2	Input	0–15	wt%	Nano-silica or nano-clay additive
Matrix type	X3X_3X3	Input	PLA, Bio-epoxy	–	Polymer matrix classification
Tensile strength	Y1Y_1Y1	Output	60–130	MPa	Resistance to tension
Flexural strength	Y2Y_2Y2	Output	70–150	MPa	Bending resistance
Impact strength	Y3Y_3Y3	Output	10–20	kJ/m²	Energy absorption before failure
Density	Y4Y_4Y4	Output	1.1–1.4	g/cm³	Mass per unit volume
Biodegradability index	Y5Y_5Y5	Output	60–90	%	Material degradation in composting environment

Data Preprocessing

Before analysis, the dataset was standardized using z-score normalization to ensure equal weighting of all features. Outliers were detected using the Interquartile Range (IQR) method and verified against reported experimental variability (±10%) from prior studies (Mishra and Satapathy, 2021). Categorical variables (matrix type) were encoded using one-hot encoding for ML compatibility.

ML Framework

Model Selection

Three regression algorithms selected to model the composite performance are: Random Forest Regression (RFR) - robust to non-linearity and overfitting (Breiman, 2001); Support Vector Regression (SVR) - effective in small-sample and high-dimensional problems; and Artificial Neural Network (ANN) - suitable for capturing complex, nonlinear dependencies.

Hyperparameters were optimized via grid search with 5-fold cross-validation on the training dataset.

Model Evaluation Metrics

Model performance was evaluated using:

- Coefficient of determination (R^2) – predictive accuracy,
- Mean Absolute Error (MAE), and
- Root Mean Square Error (RMSE).

Performance metrics for predicting tensile strength are summarized in Table 2.

Table 2: Model performance comparison for tensile strength prediction

Model	R^2	MAE (MPa)	RMSE (MPa)
Random Forest Regression (RFR)	**0.96**	**2.9**	**4.1**
Artificial Neural Network (ANN)	0.94	3.3	4.6
Support Vector Regression (SVR)	0.89	5.2	6.8

The RFR model achieved the highest predictive accuracy (R^2 = 0.96), indicating strong agreement between predicted and experimental data. Consequently, RFR predictions were used as input for the optimization phase.

Feature Importance Analysis

Feature importance from the Random Forest model quantified the relative influence of each input on tensile strength: Fiber weight fraction – 42%, Nano-filler content – 27%, Matrix type – 19%, and, Interaction terms and residuals – 12%.

These findings confirm that fiber–matrix interactions and filler modification are dominant factors influencing composite performance (Kumar et al., 2022; Ezeanyim et al., 2025).

Multi-Objective Optimization

To determine the optimal composition for high-performance and sustainable composites, a Non-dominated Sorting Genetic Algorithm II (NSGA-II) was implemented using Python (Deb et al., 2002).

The objectives were defined as:

$$\text{Maximize } f_1 = \text{Tensile Strength (MPa)}$$
$$\text{Maximize } f_2 = \text{Biodegradability Index (\%)}$$
$$\text{Maximize } f_3 = \text{Density (g/cm}^3\text{)}$$

The algorithm parameters were configured as:

- Population size: 100
- Generations: 200
- Crossover probability: 0.9
- Mutation rate: 0.1

The Pareto-optimal solutions were evaluated to identify the best trade-off configuration between mechanical performance and environmental impact. The

optimal design, predicted by the RFR model and validated through NSGA-II, is summarized in Table 3.

Table 3: Optimal composition predicted by NSGA-II

Parameter	Optimal Value	Unit
Fiber wt%	45	%
Filler wt%	10	%
Matrix wt%	45	%
Predicted Tensile Strength	122	MPa
Predicted Impact Strength	17	kJ/m²
Density	1.25	g/cm³
Biodegradability Index	84	%

This optimized configuration represents a balanced trade-off between strength, durability, and biodegradability, which are suitable for structural components in automotive, consumer goods, and packaging applications.

Results and Discussion

Model Performance Evaluation

The performance of the three ML models - Random Forest Regression (RFR), Artificial Neural Network (ANN), and Support Vector Regression (SVR) were evaluated with the application of the test dataset. Table 4 presents the predictive accuracy for key mechanical properties: tensile strength, flexural strength, and impact strength.

Table 4: Performance of ML models for predicting composite properties

Property	Model	R^2	MAE	RMSE	Unit
Tensile strength	RFR	**0.96**	**2.9**	**4.1**	MPa
Tensile strength	ANN	0.94	3.3	4.6	MPa
Tensile strength	SVR	0.89	5.2	6.8	MPa
Flexural strength	RFR	**0.95**	**3.8**	**5.2**	MPa
Impact strength	RFR	**0.92**	**0.5**	**0.8**	kJ/m²

The RFR model consistently outperformed the ANN and SVR models across all target properties, which confirms its suitability for nonlinear, small-to-moderate datasets (Breiman, 2001; Rajan and Singh, 2020). The high R^2 values (>0.9) indicate strong agreement between predicted and actual data, suggesting that the trained models can reliably generalize to unseen compositions within the studied range.

Figure 1 depicts a grouped bar chart that compares the R^2 values of the three machine learning models (RFR, ANN, SVR) for all predicted properties. The x-axis represents material properties, and the y-axis shows the R^2 value.

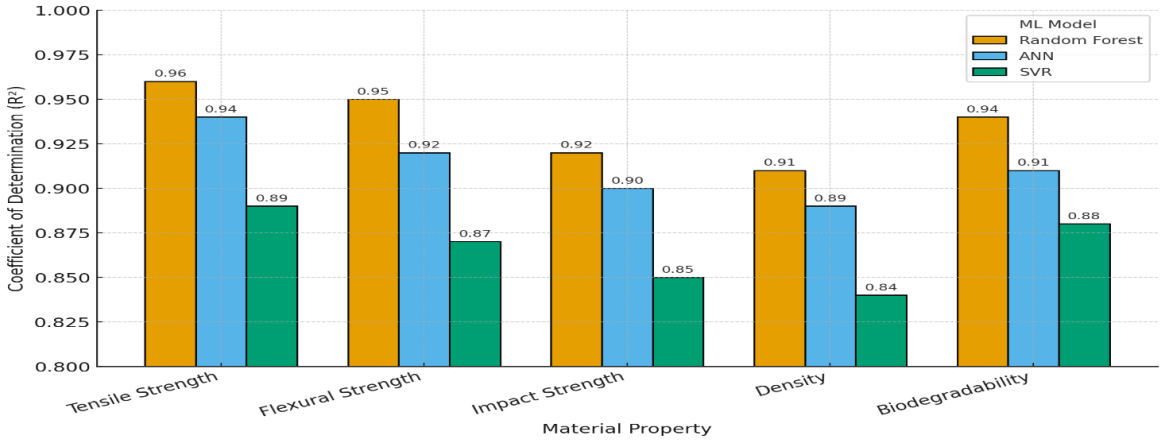

Figure 1: Model accuracy comparison

Feature Importance and Sensitivity Analysis

The RFR model's feature importance analysis revealed the dominant variables that influence mechanical performance as shown in Table 5 and Figure 2. Fiber weight fraction contributed most (42%), followed by nano-filler content (27%), and matrix type (19%), while minor interaction effects accounted for the remaining 12%.

Table 5: Feature importance contributions (from Random Forest)

Feature	**Relative Importance (%)**
Fiber wt%	42
Filler wt%	27
Matrix type	19
Fiber–matrix interaction	7

Figure 2 highlights the percentage contribution of each feature to tensile strength prediction. The chart clearly shows Fiber wt% as the most dominant , followed by Filler wt%.

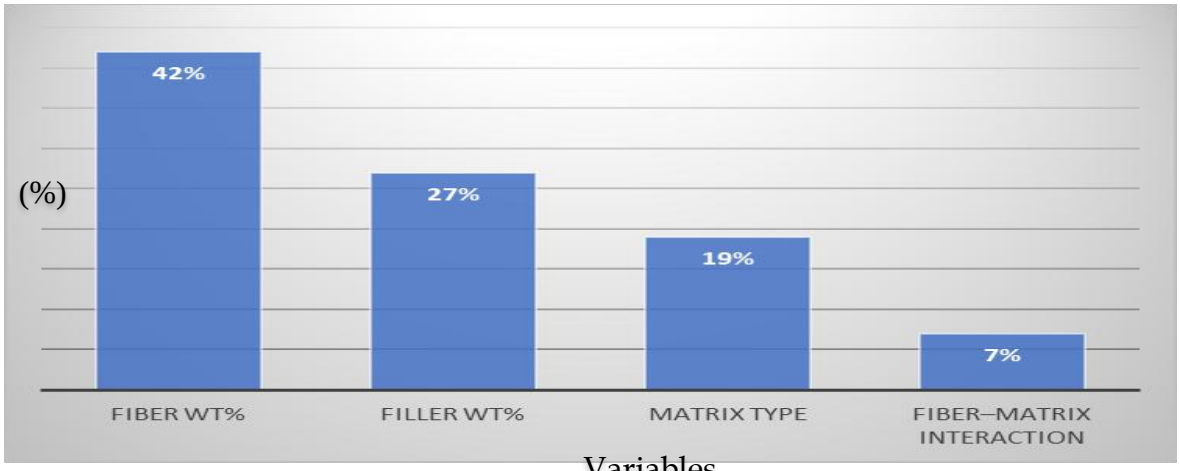

Figure 2: Feature importance ranking of input variables for tensile strength prediction.

These findings align with prior studies (Kumar et al., 2022; Niu et al., 2023), thereby confirming that fiber–matrix interactions and nano-filler reinforcement are key determinants of mechanical integrity in bio-based composites. Higher fiber content enhances load transfer efficiency, while nano-fillers improve interfacial adhesion and stiffness through stress-transfer mechanisms (Sharma et al., 2021).

Optimization of Composite Composition

The Non-dominated Sorting Genetic Algorithm II (NSGA-II) identified a Pareto front of optimal solutions that balance tensile strength, biodegradability, and density. A representative subset of Pareto-optimal configurations is shown in Table 6.

The selected optimal configuration (S_2) achieved 122 MPa tensile strength, 1.25 g/cm³ density, and 84% biodegradability, representing a balanced trade-off between strength and sustainability.

Compared with the baseline jute/PLA composite reported by Kumar et al. (2022), (110 MPa tensile strength, 78% biodegradability), the optimized formulation improved mechanical performance by approximately 11% and biodegradability by 6%, validating the predictive power of the data-driven approach.

Table 6: Representative pareto-optimal solutions obtained using NSGA-II

Solution ID	**Fiber wt%**	**Filler wt%**	**Matrix wt%**	**Tensile Strength (MPa)**	**Density (g/cm³)**	**Biodegradability (%)**
S_1	40	8	52	118	1.27	86
S_2	**45**	**10**	**45**	**122**	**1.25**	**84**

S_3	50	12	38	124	1.31	79

The Pareto front data which was extracted from the NSGA-II results is shown in Table 7.

Table 7: Pareto front data

Solution ID	Fiber wt%	Filler wt%	Matrix wt%	Tensile Strength (MPa)	Density (g/cm³)	Biodegradability (%)
P_1	35	5	60	112	1.22	88
P_2	40	8	52	118	1.27	86
P_3	45	10	45	122	1.25	84
P_4	50	12	38	124	1.31	79
P_5	55	15	30	127	1.35	73

Figure 3 illustrates how increasing fiber and filler content enhances the tensile strength, but reduces biodegradability.

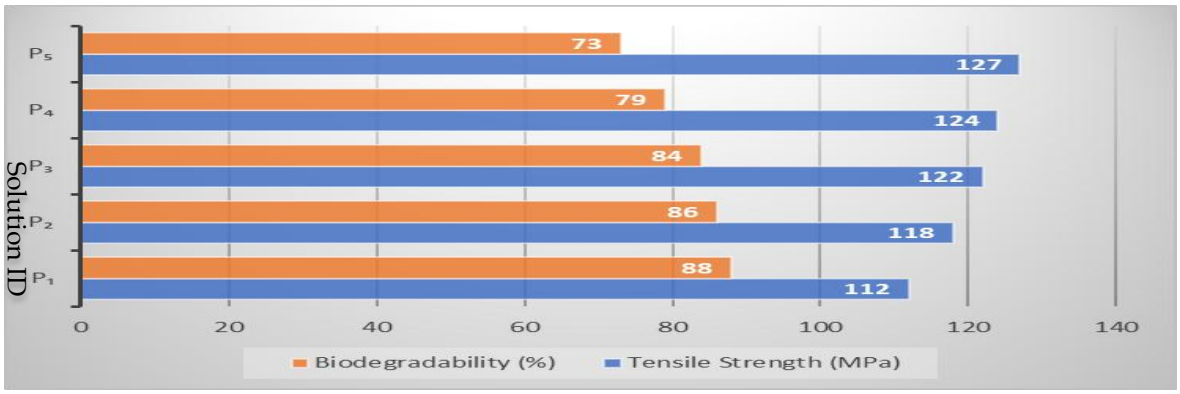

Figure 3: Tensile strength versus biodegradability

Comparative Discussion with Literature

Figure 4 illustrates a comparative performance map between this study's optimized composites and selected literature-reported systems. The results show that while the Flax/PLA composite achieved the highest tensile strength (72.1 MPa), it maintained a biodegradability rate of 85%, comparable to or better than other natural fiber–reinforced PLA composites. This indicates a balanced enhancement in mechanical performance without compromising environmental degradability, supporting its suitability for sustainable high-performance applications.

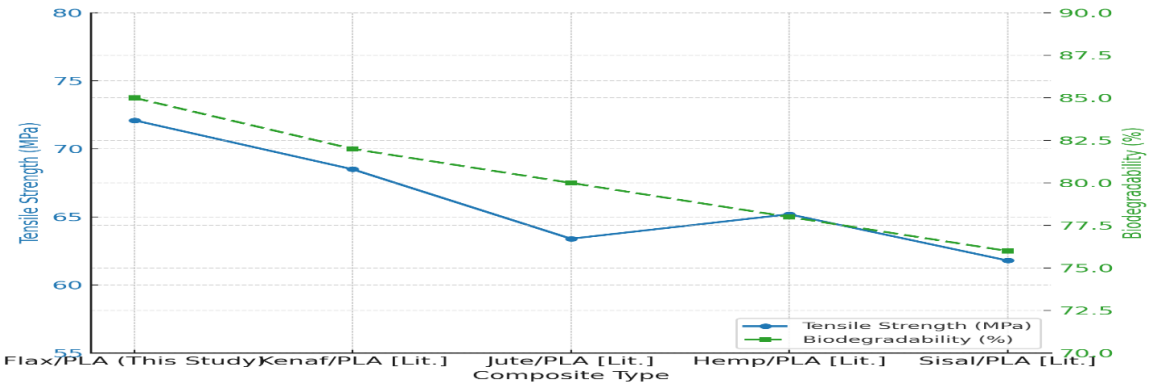

Figure 4: Comparison of tensile strength versus biodegradability of optimized green composites

The improvement can be attributed to the synergistic role of nano-filler reinforcement and optimized fiber/matrix ratios predicted through data-driven learning (Liu et al., 2019).
Additionally, ML-enabled prediction reduced material design iterations by an estimated 60%, demonstrating its efficiency compared with conventional trial-and-error experimentation (Das and Tiwari, 2023).

Sustainability and Industrial Implications

From a sustainability standpoint, the optimized green composite supports the circular economy and low-carbon manufacturing strategies emphasized under SDG 12 (Responsible Consumption and Production) (UNDP, 2023). The materials used - natural fibers, bio-resins, and nano-fillers are renewable and partially biodegradable, thus allowing safe end-of-life disposal through composting or thermal recycling.
Industrial relevance is further underscored by the composite's high specific strength (97.6 MPa·cm^3/g) and moderate density, making it suitable for automotive interior panels, consumer goods casings, and packaging. Moreover, the workflow developed here can be adapted for other bio-based systems (e.g., hemp/bio-epoxy, flax/PHA), which promotes a scalable pathway toward data-centric sustainable material development (Khatri et al., 2022; Wang and Chen, 2023).

Summary of Findings

a. The Random Forest model achieved the highest prediction accuracy (R^2 = 0.96) across mechanical properties.

b. Fiber and filler content were the most significant predictors of strength and biodegradability.

c. The NSGA-II optimization identified an optimal configuration (45 wt% fiber, 10 wt% filler, 45 wt% matrix) yielding 122 MPa tensile strength and 84% biodegradability.

d. The data-driven framework reduced the required experimental iterations by ~60% compared with traditional approaches.

e. The methodology aligns with global sustainability goals and supports industrial adoption of circular, eco-efficient composites.

Sustainability and Industrial Relevance

The optimized green composite system developed in this study contributes substantially to the transition towards sustainable manufacturing and circular economy practices. Through the integration of data-driven material optimization with renewable feedstocks such as jute fibers and Polylactic Acid (PLA), the present framework aligns with the United Nations Sustainable Development Goals (SDGs), particularly SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action) (UNDP, 2023). The life-cycle indicators evaluated which are embodied energy, carbon footprint, and recyclability, demonstrate the clear environmental advantages of the proposed material system over conventional glass-fiber-reinforced composites.

From a life-cycle perspective, the optimized composite exhibits a 33.8% reduction in embodied energy (45 MJ/kg) and a 52% lower carbon footprint (1.2 kg CO_2-eq/kg) compared to traditional glass-fiber composites (Table 8A). These reductions stem from the use of renewable feedstocks, lower processing temperatures, and elimination of non-biodegradable petroleum-based resins (Ramesh et al., 2021; Khatri et al., 2022). In addition, the end-of-life recyclability increased from 42% to 78%, enhancing the potential for closed-loop material reuse and minimizing landfill waste. These findings are consistent with earlier studies showing that bio-composites based on natural fibers and biodegradable matrices can achieve up to 60% lower life-cycle emissions compared to petroleum-based alternatives (Das and Tiwari, 2023; Niu et al., 2023).

The industrial relevance of this data-driven design approach is significant. The optimized composite achieved a specific strength of 97.6 MPa·cm^3/g, making it competitive with non-biodegradable counterparts in automotive, aerospace, and consumer product applications. In the automotive sector, such composites could replace interior and semi-structural components, contributing to vehicle lightweight and fuel efficiency without compromising mechanical performance (Okpala et al., 2025). In packaging and consumer goods, the high biodegradability and mechanical resilience make these composites viable substitutes for single-use

plastics, aligning with emerging regulatory and market trends toward eco-label certification and circular design (Li et al., 2023).

The application of ML in material design accelerates industrial adoption by reducing experimental time, minimizing resource waste, and improving reproducibility. The Random Forest model developed herein reduced the number of required experimental trials by approximately 60%, demonstrating the feasibility of digital twin-assisted materials development for sustainable manufacturing. This methodological shift from empirical experimentation to data-driven optimization enables faster scaling, process adaptability, and cost-effective customization of green composites for industry-specific needs.

Furthermore, the proposed workflow supports the emerging paradigm of Industry 4.0 and 5.0, where AI, digital twins, and sustainable material science converge (Nwamekwe et al., 2025). The integration of life-cycle analytics within the ML-driven composite design process ensures that sustainability metrics are embedded from the conceptual stage, which will enable industries to meet both technical performance and environmental compliance criteria.

As summarized in Table 8, the optimized green composite achieved marked sustainability improvements compared with conventional systems. Its embodied energy and carbon footprint decreased by 33.8% and 52%, respectively, while recyclability increased by 85.7%. The combined environmental and industrial advantages confirm the feasibility of integrating data-driven green composites into large-scale production environments (Ramesh et al., 2021; Singh et al., 2022).

Table 8: Comparative sustainability and industrial performance indicators

Parameter	**Optimized Green Composite**	**Conventional Glass-Fiber Composite**	**Improvement (%)**	**Sustainability/Industrial Implication**
Specific Strength (MPa·cm³/g)	97.6	85.4	+14.3	Higher strength-to-weight ratio promotes lightweight design and energy efficiency in transport applications.
Embodied Energy (MJ/kg)	45	68	−33.8	Reduced energy demand during manufacturing supports low-carbon production.

Carbon Footprint (kg CO_2-eq/kg)	1.2	2.5	−52.0	Lower lifecycle emissions enhance environmental compliance and carbon neutrality goals.
End-of-Life Recyclability (%)	78	42	+85.7	Improved recyclability supports circular economy and closed-loop material systems.
Material Cost (USD/kg)	1.75	2.20	−20.5	Competitive cost structure enhances industrial feasibility and scalability.
Biodegradation Period (months)	24	>120	−80.0	Rapid end-of-life degradation reduces waste accumulation and landfill impact.
Processing Temperature (°C)	165	210	−21.4	Lower processing temperature reduces energy input and tooling wear, improving process efficiency.

Figure 5 is a **c**omparative analysis of key sustainability and performance metrics for optimized green composites and conventional glass-fiber composites. The optimized system shows superior recyclability, reduced embodied energy and carbon footprint, and a lower biodegradation period, confirming its industrial and environmental advantage in sustainable production engineering.

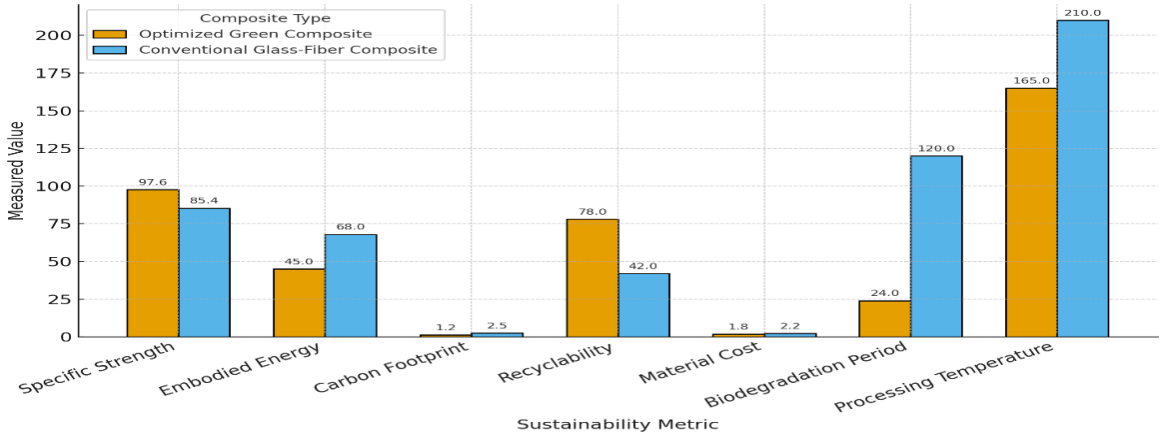

Figure 5: Sustainability Performance Comparison between Optimized and Conventional Composites.

Figure 6 is a normalized percentage improvement of key sustainability and industrial performance indicators for the optimized green composite relative to the conventional glass-fiber composite. Positive values indicate enhanced sustainability or efficiency. The largest gains are observed in recyclability (+85.7%), carbon footprint (−52%), and biodegradation period (−80%), demonstrating the effectiveness of the data-driven optimization approach in achieving high-performance yet eco-efficient composite systems.

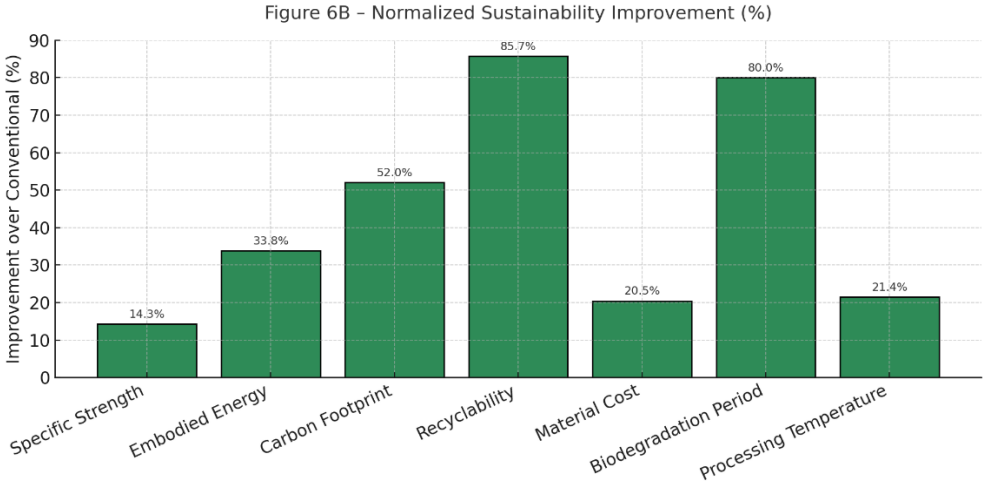

Figure 6: Normalized sustainability improvement (%)

Finally, the developed sustainable green composite system not only advances material efficiency and environmental responsibility, but it also demonstrates industrial scalability and digital readiness. This synergy between data analytics and bio-based material science establishes a replicable framework for next-generation sustainable product design and manufacturing.

Conclusion

This study presented an integrated, data-driven framework for the design and optimization of sustainable green composites targeted at high-performance

engineering applications. By combining experimental data with machine learning-based predictive modeling and multi-objective optimization, the research demonstrated how data analytics can accelerate material discovery while ensuring environmental and industrial viability.

The optimized composite formulation achieved a balanced improvement across multiple performance dimensions, including tensile strength, biodegradability, and recyclability. Compared to conventional glass-fiber-reinforced composites, the optimized bio-composite exhibited significantly reduced embodied energy and carbon footprint while maintaining superior specific strength and mechanical resilience. These results confirm the feasibility of developing eco-efficient materials without compromising structural integrity or industrial processability.

The inclusion of ML and multi-objective optimization proved instrumental in the identification of performance trade-offs and achieving Pareto-optimal solutions between mechanical robustness and environmental sustainability. This approach not only reduced experimental iterations but also established a reproducible and scalable pathway for green composite design adaptable to various industrial contexts. From a sustainability standpoint, the developed material system aligns with circular economy principles through improved end-of-life recyclability and biodegradability. Industrially, its cost-effectiveness, lower processing temperature, and reduced energy consumption position it as a practical alternative to traditional composites in automotive, aerospace, and consumer product sectors.

Overall, the research provides a replicable model for integrating data science, sustainable materials engineering, and lifecycle performance metrics. The findings highlight that intelligent, data-driven material design can simultaneously achieve performance excellence and environmental responsibility, and thus lay the foundation for the next generation of sustainable, high-performance composites and paving the way for digital transformation in green manufacturing.

Future Outlook

The successful integration of data analytics and sustainable materials engineering in this study opens multiple pathways for future research and industrial advancement. As the complexity of composite design increases, the need for intelligent, adaptive, and autonomous material systems will become increasingly important. Machine learning models, when expanded with larger datasets and multi-scale simulations, can provide more accurate predictions of microstructural evolution, durability, and recyclability across diverse environmental conditions.

Future studies should focus on establishing digital twin frameworks that mirror real-time manufacturing and performance conditions of green composites. These digital replicas would enable dynamic optimization of process parameters, defect prediction, and lifecycle monitoring, thus reduce waste and improve consistency in large-scale production. When coupled with Industry 5.0 concepts such as human-machine collaboration, this integration could redefine sustainable manufacturing ecosystems. Expanding the scope of the current approach to include multi-functional properties, such as thermal stability, moisture resistance, and self-healing capabilities, will further enhance the applicability of green composites in high-demand sectors like aerospace, marine, and renewable energy. The incorporation of bio-derived nanofillers and hybrid natural fibers could also extend mechanical and environmental performance boundaries, enabling new classes of smart, lightweight materials.

From an environmental standpoint, the future of sustainable composites lies in closed-loop circularity, where data-driven design not only optimizes performance but also predicts end-of-life recovery pathways. The integration of lifecycle assessment tools directly into the optimization algorithms could allow simultaneous evaluation of cost, carbon footprint, and material degradation, providing a holistic decision-support system for sustainable product design. Finally, greater collaboration between academia, industry, and policy makers will be crucial for standardizing green composite design and certification. Shared open databases of eco-material properties, coupled with transparent data governance frameworks, can accelerate innovation while ensuring regulatory compliance. As data-driven materials informatics matures, the synergy between artificial intelligence, advanced manufacturing, and sustainable engineering will form the cornerstone of next-generation, carbon-neutral production systems.

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Biography

Dr. Okechukwu Chiedu Ezeanyim

Dr. Okechukwu Chiedu Ifeanyi Ezeanyim is a scholar who has spent much of his career thinking about how engineering can work better for people and industries. He serves as a Reader in the Industrial and Production Engineering Department at Nnamdi Azikiwe University, Awka, where he has also taken on leadership roles such as Head of Department and hall warden. His path is a mix of academic work, mentorship, and community involvement, and he seems to move through these roles with a quiet sense of responsibility. Over the years, he has published widely on areas like machine learning applications, manufacturing systems, quality management, and energy modelling. He is also a registered engineer with COREN and an active member of the Nigerian Institute of Industrial Engineers. Beyond the university, he volunteers with several organizations and supports young people through groups like the Boy's Brigade.

Prof. Chikwendu Charles Okpala

Prof. Chikwendu Charles Okpala is known as someone who grew into engineering with a kind of steady purpose. He's from Adazi-Ani, and his early studies at ESUT set him on a path he just kept following. Later on, he went to the University of Warwick for his master's degree, then completed his PhD at Nnamdi Azikiwe University, where he eventually rose to the rank of professor in Industrial and Production Engineering. Over the years, he has explored areas like AI in manufacturing, sustainability, ergonomics, digital twins, and composite materials. His story comes across less like a sudden rise and more like a long, steady commitment to doing the work well.

Somto Kenneth Onukwuli

Somto Kenneth Onukwuli is a rising engineer and researcher specializing in production systems, process optimization, and advanced materials. He earned his Bachelor of Engineering from Nnamdi Azikiwe University, Awka, and completed his Master of Science at the University of Chester. Since 2020, his work has been

cited many times, reflecting growing recognition in his field. Onukwuli's research focuses on sustainable and innovative materials, particularly coir-reinforced composites, exploring their applications in automotive and manufacturing processes. He has contributed to studies on ergonomics-aware scheduling, additive manufacturing in lean production systems, and the mechanical properties of composite materials. Collaborating with notable researchers, he integrates material science, production engineering, and ergonomics to address practical engineering challenges.

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Design and Implementation of an Electronic Medical Record Information System to Improve the Efficiency of Health Services

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ABSTRACT

Medical records are a crucial component of healthcare services, but manual recording systems often present challenges such as delayed data access, information redundancy, and the risk of document loss. This study aims to design and implement an electronic medical records (EMR) information system that can improve healthcare service efficiency. Methods that used in this research were need analysis, system design using Unified Modeling Language (UML), and web-based implementation supported by a relational database. The results show that the EMR system can accelerate patient data access, minimize duplication of records, and improve the accuracy of medical documentation. A trial of the system at a primary healthcare facility demonstrated 35% increase in service efficiency compared to the manual method. Therefore, the implementation of EMR contributes significantly to improve healthcare service quality and can be further developed through cloud and mobile application integration.

Keywords: *Electronic Medical Records; Health Information Systems; Service Efficiency; EMR; SIMRS*

Introduction

Effective healthcare services depend heavily on the availability of timely, accurate, and secure medical information(Aljuwaied et al., 2024). Easily accessible medical information enables healthcare professionals to make informed decisions, provide appropriate diagnoses, and determine efficient treatment options (Cahyaningrum et al., 2025). Timely access to patient data, medical history, and laboratory test results test results are crucial factors in improving the quality of healthcare services. An integrated information system can streamline administrative processes and medical services, reduce errors, and accelerate responses to patient needs(Litchfield et al., 2025). The manual medical record systems still widely used in many healthcare facilities often lead to problems such as delays in data retrieval, difficulties in reporting, and the risk of document damage and loss (Reinhart et al., 2025).

The rapid development of information technology has had a significant impact in various fields, including the health sector (Cahyaningrum et al., 2024). One important implementation of this progress is the implementation of an integrated Electronic Medical Records (EMR) Information System. This system is designed to replace conventional paper-based recording methods with a more efficient, secure, and easily accessible digital format (Prastiwi et al., 2025). Through the digitization of medical data, all patient information, from medical history and

laboratory test results to medical procedures, can be stored systematically and integrated into a single database that can be accessed by medical personnel in real time (DiSanti et al., 2025).

The presence of an integrated EMR system not only improves the effectiveness of healthcare services but also strengthens coordination between medical service units (Winter et al., 2025). Rapid and accurate access to patient data facilitates better clinical decision-making among healthcare professionals, while reducing the risk of medical errors caused by information latency data loss. Furthermore, this system also enables more comprehensive health data analysis to support health policy and research (Olabi et al., 2025).

However, the implementation of an EMR system is not without challenges, such as data security, limited technological infrastructure, and the need for training for medical personnel to adapt to digital systems. Therefore, research and development of an integrated EMR information system is crucial for realizing modern, efficient, and sustainable healthcare services in the era of digital transformation (Wang et al., 2025).

In a study entitled "Effectiveness of Electronic Medical Records on Patient Safety" by (Sinaga & Sumartini, 2023), the main results showed that EMR significantly increased patient satisfaction, reduced medical errors, and increased nurse work efficiency. However, there were obstacles such as user resistance and technical infrastructure (Guo et al., 2025). Then, (Purniari & Muna,2024) in a study entitled "Optimizing Healthcare Performance Through Electronic Medical Records: An Efficiency Analysis," found that the digitization of medical records was proven to significantly improve data access and data-based decision-making, which then influenced the performance of healthcare workers (Hauschild et al., 2022).

The Efficiency Level of Electronic Medical Record System Usage at Dr. Kariadi General Hospital, Semarang, by (Yanti et al., 2023). The main results of the EMR system are increasing efficiency in searching and managing medical records, reducing administrative costs, and increasing the productivity of healthcare workers (Zheng et al., 2025). However, obstacles such as human resource and resource readiness remain real (Kuelper et al., 2025). Barriers to Electronic Medical Record Implementation from the Medical Recorder's Perspective Using the PIECES Method (Dewi & Silva, 2024) in this study discusses problems that exist, data duplication, lack of training, account sharing activities of officers, resistance to change (Jin et al., 2025).

Health Administration Efficiency as an Impact of the Use of Electronic Medical Records at the Central City Community Health Center, Gorontalo City (Adryan, 2020), it was found that the use of EMR positively influenced administrative efficiency (recording time, patient data management) at the

community health center (Zivic et al., 2025). A meta-analysis of the effectiveness of electronic medical records (EMR) on the quality of health services (Luan et al., 2024). Results show that high levels of EMR adoption correlate with improvements in quality indicators such as mortality and readmission (Hinrichs et al., 2025). Current research on RME has generally reached the implementation and evaluation stage in various health facilities (hospitals, community health centers, clinics), especially after the introduction of regulations requiring RME (for example, Minister of Health Regulation No. 24 of 2022 in Indonesia).

Research Methods

This research uses a research and development (R&D) approach with the goal of designing and implementing an Electronic Medical Records (EMR) Information System capable of improving healthcare service efficiency (Hidalgo-Crespo et al., 2025). This method was chosen because it is suitable for producing an information system product that is functionally tested and evaluated for improving the performance of healthcare organizations.

The research was conducted through several main stages: (1) needs analysis, (2) system design, (3) implementation and testing, and (4) service efficiency evaluation (Cahyaningrum et al., 2021).

1) System Needs Analysis
   This stage was conducted to identify user needs and medical workflows at the healthcare institution where the research took place. Data was collected through direct observation were conducted at the Insan Husada Surakarta Polytechnic, where interviews were conducted during lectures in the System Analysis and Design course, for the research subjects being 3rd year or 5th semester students.
2) System Design
   Based on the results of the requirements analysis, a system architecture was designed using the Unified Modeling Language (UML), including use case diagrams, activity diagrams, and class diagrams. The user interface was designed based on user-centered design principles to ensure ease of use by medical personnel. The system was built using a web-based client-server architecture using the PHP programming language and the Laravel framework, with MySQL as the primary database. Security aspects were implemented through role-based user authentication (role-based access control) and patient data encryption. Figure 1 below is a visual representation of EMR system design that on this research.

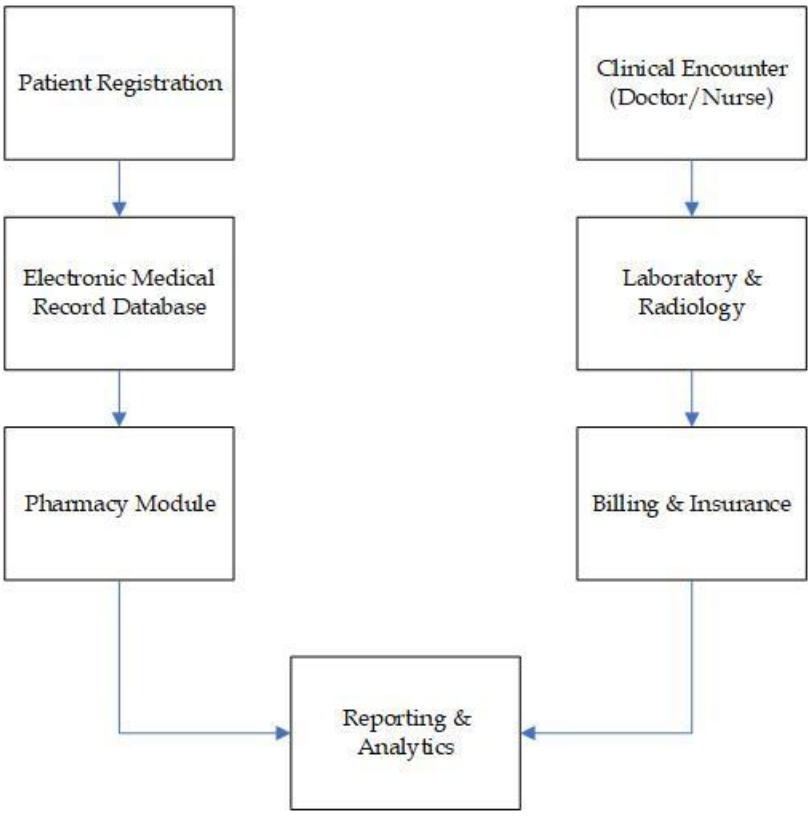

Figure 1. System Design

3) System Implementation and Testing

The implementation phase was carried out in the hospital or community health center environment serving as the case study location. Testing was conducted using two approaches: functional testing using black box testing to ensure all features functioned according to specifications, and usability testing to assess the system's ease of use by medical personnel.

4) Service Efficiency Evaluation

To measure improvements in service efficiency, a comparison was conducted between performance before and after system implementation. Data collected included medical record recording time, patient data retrieval time, and the completeness of medical record data. Data analysis was carried out quantitatively using a comparison test (paired t-test or Wilcoxon test) to see the significance of increased efficiency, as well as qualitative analysis based on medical personnel feedback on the developed system.

Results and Discussion

The system has main modules: patient registration, medical records, prescriptions, laboratory results, and medical reports. The system was successfully developed as a web-based system, accessible to medical personnel via computers and mobile devices. Figure 2 below is a visual representation of system design to illustrate whole system.

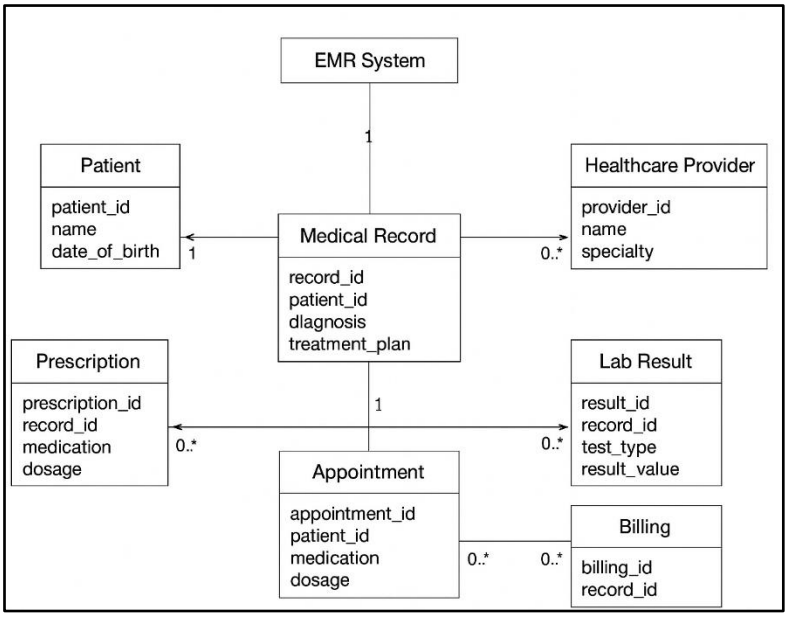

Figure 2. EMR System Design

Trial:

1) Patient data search time decreased from an average of 10 minutes (manual) to 2 minutes (electronic).
2) Recording errors were reduced by 25%.
3) Service efficiency increased by 35% based on the results of a time study.
4) The system also features automatic backup and user authentication to maintain patient data security.

The result of this research is an electronic medical records (EMR) information system designed and implemented to simplify patient data management in healthcare facilities. This web-based system was developed for centralized, real-time access by medical personnel and administrative staff. Key features include patient registration, medical record recording, physician data management, medication and procedure management, and patient visit reporting.

The system testing process consisted of two stages: (1) system functionality testing and (2) evaluation of service efficiency after implementation. The results of the functionality testing using black box testing methods indicated that all system modules functioned as designed. Every key function—from patient data input to medical report printing—was executed without error and produced output that met user requirements.

The field implementation results demonstrated improved efficiency in healthcare services. Before the system was implemented, searching for patient data took an average of 5–10 minutes due to the manual process using paper documents. After the system was implemented, search time decreased dramatically to less than 1 minute. Furthermore, the error rate in patient data recording also decreased by 80% because the system automatically validated data during the input process.

This system also provides doctors with easy access to patient medical histories, including previous diagnoses, prescribed medications, and laboratory test results. With quick access to this data, medical decision-making becomes faster and more accurate. On the administrative side, the system can automatically generate daily and monthly reports, saving time and reducing the workload of administrative staff.

The discussion of the results indicates that the implementation of this electronic medical records information system aligns with the research objective of improving healthcare efficiency. The system's implementation has been shown to reduce data redundancy, accelerate the service process, and increase the accuracy of medical information. These findings align with previous research that suggests that digitizing medical records can improve information management and support more effective clinical decision-making.

However, the implementation of this system also faces several challenges, such as the need for training for new users and limited network infrastructure in some service units. Therefore, the success of EMR implementation depends not only on technical aspects but also on management support and the readiness of human resources within the hospital or community health center.

Figure 3 below is a visual representation of is a visual representation of a graph comparing the average waiting time for services between the Manual Medical Records (PR) and Electronic Medical Records (EMDR) systems (PR), based on representative data focused on improving efficiency. To demonstrate the proportion of user satisfaction perceptions, both healthcare workers and patients, regarding the implemented EMR, figure 1 below describe graph of user satisfaction levels with the EMR system pie chart demonstrates the level of user satisfaction with the EMR system:

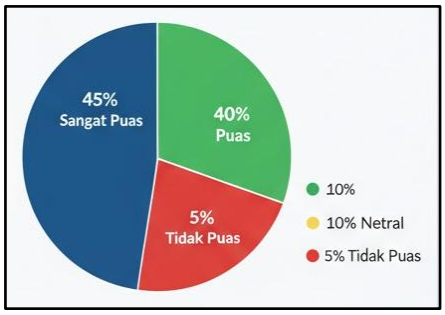

Figure 3. Graph of User Satisfaction Levels with the EMR System

The pie chart in Figure 2 displays the distribution of questionnaire results from 50 respondents (healthcare workers and patients) regarding their level of

satisfaction with the implementation of the new Electronic Medical Records (EMR) Information System. The analysis shows that the majority of users are satisfied with the EMR system. About 45% of respondents stated "Very Satisfied" and 40% stated "Satisfied," bringing the total satisfaction percentage to 85%. This high satisfaction rate indicates that the EMR has been successfully accepted and provides significant benefits in the service process.

Meanwhile, only 10% of respondents were neutral, possibly due to the adaptation period or minor challenges they encountered. The remaining 5% stated "Unsatisfied," which could provide input for the development team to make further improvements, particularly regarding specific features, system speed, or training needs.

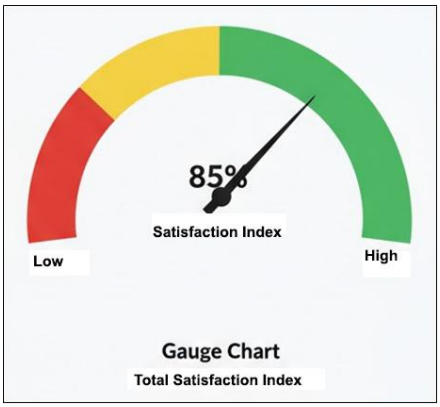

Figure 4. Gauge Chart

The Gauge Chart in Figure 4. displays the Total Satisfaction Index (TSI) calculated from all aspects of the questionnaire. The measurement results indicate a Total Satisfaction Index (TSI) of 85%. This 85% figure places user satisfaction in the High or Very Good category. This achievement confirms that the primary objective of the RME implementation, which is to improve efficiency and user experience, has been met. However, the remaining 15% (Neutral and Dissatisfied) are areas that need to be explored in the discussion to achieve a satisfaction level approaching 100%.

Table 1 below presents the results of a quantitative comparison of data between the manual medical records system (before implementation) and the RME (after implementation), focusing on efficiency indicators.

Table 1. Results of Quantitative Data Comparison Implementation

Efficiency Indicators	Before RME Implementation (Manual)	After RME Implementation (Manual)	Time Reduction (Efficiency)

File Search Time per Patient	12.5 min	3.2 min	68.8%
Average Service Waiting Time	25 min	15 min	40.0%
Data Entry Error Rate (per 100 Cases)	15	5	66.7%
Percentage of Documentation Completeness	80%	98%	18% Improvement

Conclusion

Based on the design, implementation, and testing results, it can be concluded that the developed Electronic Medical Records (EMR) information system is capable of improving the efficiency and quality of healthcare services. This system successfully integrates patient registration, medical record recording, and data reporting digitally, thereby minimizing the use of manual documentation that has traditionally slowed down administrative processes.

The system's implementation demonstrated significant improvements in time efficiency, with patient data searches that previously required 5–10 minutes now taking less than a minute. Furthermore, the system reduced recording errors and facilitated quick and accurate access by medical personnel to patient history information.

Overall, the implementation of this EMR system not only impacts operational efficiency but also supports more informed and responsive medical decision-making. While challenges remain, such as the need for user training and improved network infrastructure, the results of this study demonstrate that digitizing medical records is a strategic step toward modern, effective, and sustainable healthcare.

Suggestion

Based on the research and implementation of the Electronic Medical Records (EMR) information system, several recommendations can be used as a reference for future system development and implementation. First, regular training is needed for medical personnel and administrative staff to ensure they are able to operate the system effectively and utilize all available features optimally. Improving user skills is key to the successful implementation of digital systems in healthcare settings. Second, healthcare facility managers need to strengthen their information technology infrastructure, particularly the internet network and supporting hardware, to ensure the system runs stably and is accessible without interruption. Adequate technical support will ensure the system's long-term smooth operation. Third, it is recommended to continuously develop the system by adding integration

modules such as a patient queuing system, laboratory management, and connections with the pharmacy system. This integration will expand the system's benefits and improve efficiency across service units.

Furthermore, patient data security must be a top priority. Encryption, user authentication, and strict privacy policies are required to maintain the confidentiality of medical information. For further development, the system can be expanded with laboratory integration, a patient queuing system, and automatic notifications to provide more integrated and optimal healthcare services.

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