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Research Article

Comprehensive Analysis of Green Hydrogen Production: Technologies, Costs, Environmental Impacts, and Policy Frameworks

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Abstract: Green hydrogen, produced via electrolysis using renewable energy, is a critical pathway to decarbonizing energy systems. This study compares key electrolysis technologies, including Alkaline (AE), Proton Exchange Membrane (PEM), Solid Oxide (SOE), and Anion Exchange Membrane (AEM) systems. SOE demonstrates the highest efficiency ranging from 80% to 90% which operates at elevated temperatures ranging from 700°C to 900°C, and has higher capital costs per Kilowatt which ranged from $2,000 to $3,000 per kW. PEM offers rapid response times ranging from 10 s to 30s and high hydrogen purity of 99.99% but suffers from shorter lifespans ranging from 40,000 to 60,000 hours. Material advancements, such as Nafion™ membranes and Iridium Oxide catalysts, enhance efficiency by up to 10%. Hydrogen storage methods reveal compressed hydrogen as suitable for short-term applications, while ammonia carriers and LOHC excel in long-term storage due to their safety and cost efficiency. Distribution technologies vary, with pipelines having cost-effective of $0.05/kg H_2/km over long distances, while trucks offer flexibility for shorter ranges. Environmental analysis highlights the carbon intensity disparity, with green hydrogen emitting 0 to 0.5 kg CO_2/kg H_2 compared to grey hydrogen's which emits 10 to 12 kg CO_2/kg H_2. Lifecycle water consumption ranges from 7 to 12 L/kg H_2, with SOE being the most water-efficient. Global hydrogen projects, such as Saudi Arabia's NEOM with 650,000 tons per year and Europe's HyDeal Ambition with 1,500,000 tons per year, illustrate the large-scale adoption of hydrogen technologies. Policy frameworks, including the EU Hydrogen Strategy and the USA Clean Hydrogen Plan, emphasize subsidies and infrastructure investments. This comprehensive analysis underscores the potential of green hydrogen, provided technological, environmental, and policy challenges are addressed effectively.

Keywords: Green Hydrogen, Electrolysis Technologies, Hydrogen Storage, Lifecycle Analysis, Policy Frameworks, Economic Analysis

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1. Introduction

Green hydrogen, derived from the electrolysis of water powered by renewable energy sources such as solar, wind, and hydropower, has emerged as a key driver in the global transition toward carbon neutrality [1, 2]. As the world grapples with escalating climate change and energy security concerns, green hydrogen offers a clean, versatile, and zero-carbon energy vector capable of decarbonizing hard-to-abate sectors such as heavy industry, long-haul transport, and grid-scale storage [3, 4]. The increasing interest in hydrogen technologies is driven by their potential to reduce greenhouse gas emissions, diversify energy supply, and facilitate deep decarbonization [5, 6].

Recent advancements in electrolysis technologies, particularly in Proton Exchange Membrane (PEM), Alkaline Electrolysis (AE), and Solid Oxide Electrolysis (SOE), have significantly enhanced production efficiency and scalability [7, 8]. Innovations in storage techniques including compressed gas, liquefied hydrogen, and solid-state metal hydrides have also improved energy density and safety [9, 10]. Despite these technological gains, economic viability remains a challenge due to high capital and operational costs associated with hydrogen production, storage, and distribution [11–14].

Environmental benefits of green hydrogen are profound, particularly when it displaces fossil fuels in emissions-intensive applications [15, 16]. However, a full lifecycle assessment is essential to quantify emissions from renewable electricity generation, electrolyzer manufacturing, and infrastructure development [17, 18]. In parallel, policy frameworks and international strategies—such as the European Hydrogen Strategy and U.S. National Hydrogen Roadmap are being implemented to stimulate demand and de-risk investment [8, 13, 14].

Globally, hydrogen deployment is supported by declining renewable energy costs, government subsidies, carbon pricing mechanisms, and growing investor interest [19–21]. Yet, challenges persist in the harmonization of safety regulations, standardization of value chains, and development of large-scale infrastructure [22, 23]. Furthermore, there is a pressing need to assess the techno-economic trade-offs among various hydrogen production pathways, particularly in terms of levelized cost of hydrogen (LCOH), energy return on investment (EROI), and technological readiness [24–26].

Case studies from Australia, the Middle East, and Europe demonstrate the viability of integrated hydrogen value chains that link renewable generation, production, storage, and end-use in power, mobility, and industry [27–29]. These projects reveal both regional potential and global scalability for green hydrogen as a cornerstone of net-zero strategies [30–33]. Nevertheless, large-scale deployment will require synergistic action across sectors—including research, policy, industry, and civil society to overcome systemic barriers [34, 35].

This study presents a comprehensive analysis of green hydrogen production technologies with a focus on techno-economic performance, environmental impacts, and policy frameworks. By evaluating AE, PEM, and SOE systems in the context of cost, efficiency, emissions, and scalability, the paper aims to guide stakeholders in selecting optimal hydrogen solutions for diverse applications [1, 2, 20, 36]. The originality of this research lies in its integrative perspective, combining technical, economic, and regulatory analyses within a unified framework [37, 38].

The purpose of this study is to provide a comprehensive analysis of green hydrogen production technologies, evaluating their efficiencies, costs, environmental impacts, and policy frameworks. As global industries shift towards renewable energy, understanding the viability of different hydrogen production methods is essential for optimizing resource utilization and reducing carbon emissions. This study critically compares Alkaline Electrolysis (AE), Proton Exchange Membrane (PEM), and Solid Oxide Electrolysis (SOE), highlighting key trade-offs in performance, investment requirements, and sustainability.

The originality of this research lies in its integrative approach, combining technological evaluation, economic assessment, environmental impact analysis, and policy review within a single framework. By synthesizing data from recent advancements and global hydrogen projects, this study offers valuable insights for researchers, policymakers, and industry stakeholders. Additionally, it contributes to the ongoing discourse on the role of green hydrogen in achieving carbon neutrality and developing a sustainable global energy infrastructure.

In conclusion, green hydrogen represents a transformative solution to global decarbonization goals. While numerous technical and policy barriers remain, the alignment of innovation, regulation, and investment is rapidly propelling the sector forward. As the technology matures and costs decline, green hydrogen is poised to become an essential pillar of a resilient, low-carbon energy future [39, 40, 41].

2. Material and Methods

This study adopts a multidisciplinary approach to comprehensively analyze green hydrogen production technologies, costs, environmental impacts, and policy frameworks. The methodology integrates data collection, comparative analysis, and systematic evaluation to provide insights into key aspects of hydrogen production.

2.1. Data Collection and Sources

Data were collected from peer-reviewed journal articles, government reports, industry white papers, and reputable databases such as the International Renewable Energy Agency (IRENA), International Energy Agency (IEA), and Hydrogen Council reports. Specific parameters such as efficiency, energy input, capital costs, environmental impacts, and policy incentives were extracted and tabulated for analysis.

2.2.Comparative Analysis of Hydrogen Production Technologies

Technologies including Alkaline Electrolysis (AE), Proton Exchange Membrane (PEM), Solid Oxide Electrolysis (SOE), and Anion Exchange Membrane (AEM) were compared based on efficiency, operating temperature, energy input, hydrogen purity, lifespan, and cost parameters. The analysis focused on identifying performance advantages and limitations of each technology (Table 1).

2.3.Material Component Evaluation

The study examined advancements in electrolyzer components such as electrodes, membranes, catalysts, separators, and bipolar plates (Table 2). Data on material type, durability, cost, and efficiency gain were analyzed to identify technological improvements driving better performance and cost reductions.

2.4. Hydrogen Storage and Distribution Methods

Storage methods (compressed hydrogen, liquid hydrogen, ammonia carriers, LOHC, metal hydrides) and distribution methods (pipelines, trucks, ships, and rail) were compared for energy density, safety, cost, and infrastructure requirements (Tables 3 and 4).

2.5. Water Usage by Electrolysis Technology

The data in Table 5 was gathered through a combination of literature review, experimental studies, and industry reports. Researchers and engineers analyzed electrolysis performance by measuring water consumption rates, wastewater generation, and reusability through lab-scale experiments and industrial trials. Computational models such as Aspen Plus, MATLAB, or COMSOL Multiphysics were used to estimate water demand under different conditions. Manufacturer data from companies like Siemens, Nel Hydrogen, and ITM Power provided specifications on water purity requirements to prevent membrane fouling or electrode degradation. Life cycle assessments (LCA) were conducted to evaluate the efficiency and environmental impact of each electrolysis method

2.6. Environmental and Lifecycle Impact Assessment

A lifecycle analysis was conducted to compare carbon emissions, water usage, and land footprints across different hydrogen production methods (Tables 6 and 9). Environmental metrics were calculated and benchmarked against global sustainability targets.

2.7. Global Hydrogen Projects

Table 7 presented information on global hydrogen projects, with data sourced from industry reports, government policies, and company announcements. Reports from organizations like the International Renewable Energy Agency (IRENA), Hydrogen Council, and national hydrogen roadmaps provided production capacity estimates, investment figures, and start dates. Large projects like the NEOM Hydrogen Project were backed by financial disclosures from companies such as Air Products, ACWA Power, and

NEOM, which published cost estimates and project timelines. Feasibility studies and market analyses from Bloomberg New Energy Finance (BNEF), McKinsey & Company, and Wood Mackenzie contributed to the evaluation of hydrogen production capacity and future growth trends.

2.8. Hydrogen Production Costs by Technology and Region

Table 8 compiled hydrogen production costs by region and technology, using techno-economic analysis (TEA) and levelized cost of hydrogen (LCOH) modeling. These methods accounted for capital expenditure (CAPEX), operational costs (OPEX), electricity prices, and efficiency factors. Electricity costs, sourced from energy market data and renewable energy trends, played a crucial role in cost estimation. Industry benchmarks from companies like Linde, Air Liquide, and Plug Power provided real-world cost figures for different electrolysis technologies. The scale of production was also factored in, as larger hydrogen projects benefited from economies of scale, lowering cost per kilogram. Life cycle cost assessments and energy market modeling helped refine cost projections based on regional electricity availability and infrastructure requirements.

2.9. Policy and Economic Analysis

The study reviewed global hydrogen policy frameworks and investment incentives from regions including the EU, USA, Japan, China, and Australia (Table 10). Policy effectiveness and alignment with green hydrogen adoption goals were evaluated.

3. Results and Discussion

Tables 1–10 provide a comprehensive analysis of key aspects of green hydrogen production: Table 1 compares electrolysis technologies by performance parameters; Table 2 details material advancements in electrolyzer components; Table 3 evaluates hydrogen storage methods; Table 4 analyzes hydrogen distribution technologies and efficiency metrics; Table 5 examines water usage by electrolysis technology; Table 6 presents lifecycle carbon emissions of hydrogen production methods; Table 7 highlights global hydrogen projects; Table 8 compares hydrogen production costs by technology and region; Table 9 assesses the environmental impact of hydrogen production methods; and Table 10 outlines policy and regulatory frameworks for the hydrogen economy.

Table 1: Comparison of Electrolysis Technologies by Key Performance Parameters

Parameter	Alkaline Electrolysis (AE)	Proton Exchange Membrane (PEM)	Solid Oxide Electrolysis (SOE)	Anion Exchange Membrane (AEM)	Reference(s)
Efficiency (%)	60–70	70–80	80–90	65–75	Jimiao and Jie [18]
Operating Temp (°C)	50–80	20–80	700–900	40–60	Qusay *et al.* [17]
Energy Input (kWh/kg H_2)	50–60	45–55	40–50	48–55	Qusay *et al.* [17]
Hydrogen Purity (%)	99.5	99.99	99.99	99.9	Łosiewicz [23], Kapil and Bhardwaj [19]
Lifespan (hours)	60,000–90,000	40,000–60,000	20,000–40,000	50,000–70,000	Wang *et al.* [37
Capital Cost ($/kW)	800–1,200	1,500–2,200	2,000–3,000	1,000–1,500	International Energy Agency, IEA [14]
Response Time (s)	30–60	10–30	60–120	20–40	Wang *et al.* [37]
Pressure Range (bar)	1–30	10–30	1–10	5–25	Zhang and Li [39]

Table 2: Material Advancements in Electrolyzer Components

Component	Material Type	Improvement	Durability (hours)	Cost ($/unit)	Efficiency Gain (%)	Degradation Rate (%/year)	Reference(s)
Electrodes	Nickel-based Alloy	Improved Conductivity	80,000	200	5	0.5	Zhang and Li [39]
Membranes	Nafion™	Higher Proton Conductivity	50,000	500	8	1.0	International Energy Agency, IEA [14]
Catalysts	Iridium Oxide	Enhanced Efficiency	60,000	1,000	10	0.2	Sharma *et al.* [34]
Separator	Ceramic-Coated Steel	Corrosion Resistance	90,000	150	3	0.3	International Energy Agency, IEA [14]
Bipolar Plates	Graphite-Composite	Improved Thermal Stability	70,000	250	4	0.4	Sharma *et al.* [34]

The analysis of green hydrogen production technologies provides key insights into performance, cost, environmental impact, and policy frameworks. Alkaline Electrolysis (AE) demonstrates moderate efficiency (60–70%) and remains the most cost-effective technology ($800–1,200/kW) for large-scale hydrogen production. This is consistent with the findings of IEA [14] and Wang et al. [37], who reported AE's long-standing industrial use due to its affordability and maturity. However, compared to Proton Exchange Membrane (PEM) electrolysis, which achieves higher efficiency (70–80%) but at a higher cost ($1,500–2,200/kW), AE has lower operational flexibility, making it less suitable for intermittent renewable energy sources [39] (Table 1). Solid Oxide Electrolysis (SOE) achieves the highest efficiency (80–90%), outperforming AE and PEM, but its reliance on high operating temperatures (700–900°C) and expensive materials results in capital costs ranging between $2,000–3,000/kW [15]. This finding aligns with Smith et al. [36], who noted that SOE remains in the early commercialization stage due to its durability challenges. Compared to conventional electrolysis methods, recent advancements in materials, such as iridium oxide catalysts, have improved efficiency by 10%, although the high cost ($1,000/unit) remains a limiting factor [39, 13] (Table 2).

Table 3: Performance Comparison of Hydrogen Storage Methods

Storage Method	Energy Density (MJ/kg)	Pressure (bar)	Cost ($/kg H_2)	Safety Index	Storage Duration	Weight Penalty (%)	Reference(s)
Compressed Hydrogen	120	350–700	1–2	Medium	Short-Term	30	Sharma *et al.* [34]
Liquid Hydrogen	142	N/A	3–4	Low	Medium-Term	50	International Energy Agency [14]
Ammonia Carrier	12 (effective H_2)	N/A	0.5–1	High	Long-Term	10	Sharma *et al.* [34]
LOHC (Hydrogen Carrier)	8 (effective H_2)	N/A	1.5–2	High	Long-Term	15	IRENA [15], International Energy Agency [14]
Metal Hydrides	10–15	N/A	2–3	Medium	Long-Term	60	Li *et al.* [22]

In terms of storage technologies, this study finds that compressed hydrogen is best suited for short-term storage, but ammonia carriers and Liquid Organic Hydrogen Carriers (LOHC) offer superior long-term storage solutions at lower costs ($0.5–1.5/kg H_2) (Table 3) [5, 7]. These findings are in agreement with IEA (2022), which reported that LOHC offers greater energy density and stability but requires additional dehydrogenation energy, reducing overall efficiency [14]. In contrast, Sharma et al. [34] found that methanol-based hydrogen storage presents a competitive alternative due to its ease of transport and lower infrastructure costs [34].

Table 4: Hydrogen Distribution Technologies and Efficiency Metrics

Distribution Method	Distance Range (km)	Energy Loss (%)	Cost ($/kg H_2/km)	Infrastructure Requirement	Storage Method Compatibility	Reference(s)
Pipeline	0–5,000	5–10	0.05	High	Compressed	Sharma *et al.* [34]
Truck Transport	0–1,000	10–15	0.15	Medium	Compressed & Liquid	International Energy Agency [14]
Ship Transport (Ammonia)	>5,000	15–25	0.30	Low	Ammonia	Sharma *et al.* [34]
Rail Transport	0–2,000	12–18	0.12	Medium	Compressed	IRENA [15], International Energy Agency [14]

Table 5: Water Usage by Electrolysis Technology

Electrolysis Type	Water Source	Consumption Rate (L/kg H_2)	Reusability (%)	Water Purity Requirement (ppm)	Wastewater Generation (%)	Reference(s)
Alkaline Electrolysis	Freshwater	10–12	50–60	<50	5	Sharma *et al.* [34]
PEM Electrolysis	Freshwater	9–10	60–70	<10	3	International Energy Agency, IEA [14]
SOE Electrolysis	Recycled Water	7–8	70–80	<5	2	Sharma *et al.* [34]
AEM Electrolysis	Freshwater	8–10	65–75	<20	4	IRENA [15], International Energy Agency [14]

Hydrogen distribution methods show that pipelines remain the most cost-effective ($0.05/kg H_2/km) for short distances, while shipping ammonia is preferable for long-distance transport, despite energy losses of 15–25% [13, 15] (Table 4). This supports the conclusions of Schiebahn et al. [34], who emphasized that ammonia-based hydrogen transport is gaining traction due to its existing infrastructure and compatibility with fuel cells. However, this contradicts the findings of Sharma et al. [34], who argue that liquefied hydrogen transport is more energy-efficient over long distances when cryogenic storage is optimized. This study identifies SOE as the most water-efficient method (7–8 L/kg H_2), outperforming PEM electrolysis, which produces minimal wastewater (3%) [5], [15] (Table 5).

Table 6: Lifecycle Carbon Emissions of Hydrogen Production Methods

Production Method	Carbon Intensity (kg CO_2/kg H_2)	Upstream Emissions (%)	Downstream Emissions (%)	Energy Source	Reference(s)
Grey Hydrogen	10–12	80	20	Natural Gas	Bidattul *et al.* [6]
Blue Hydrogen	2–4	70	30	Natural Gas + CCS	Ahmed *et al.* [1]
Green Hydrogen	0–0.5	0	100	Renewable Energy	Bidattul *et al.* [6]
Turquoise Hydrogen	1–3	60	40	Methane Pyrolysis	Sharma *et al.* [34]
Pink Hydrogen	0–0.5	0	100	Nuclear Energy	International Energy Agency, IEA [14]

Brown Hydrogen	15–20	85	15	Coal Gasification	Sharma *et al.* [34]
Yellow Hydrogen	5–8	70	30	Grid Electricity	IRENA [15], International Energy Agency [14]
White Hydrogen	0	0	0	Natural Deposits	Li *et al.* [22]

Table 7: Global Hydrogen Projects

Project Name	Location	Production Capacity (tons/year)	Energy Source	Investment Cost ($M)	Start Year	Reference(s)
NEOM Project	Saudi Arabia	650,000	Solar & Wind	5,000	2025	Ahmed *et al.* [1], International Energy Agency [14]
HyDeal Ambition	Europe	1,500,000	Solar	8,000	2030	International Energy Agency [14]

This contrasts with the findings of Li et al. [22], who reported that water consumption in electrolysis depends more on purification efficiency than on the electrolysis method itself. Lifecycle carbon emissions highlight the environmental superiority of green hydrogen (0–0.5 kg CO_2/kg H_2) over grey hydrogen (10–12 kg CO_2/kg H_2) [1, 14] (Table 6). Compared to previous studies, this aligns with Bidattul et al. [6], who found that blue hydrogen reduces emissions to 2–4 kg CO_2/kg H_2 due to carbon capture but remains less sustainable than green hydrogen due to methane leakages from fossil-based feedstocks. Large-scale hydrogen projects, such as NEOM in Saudi Arabia and HyDeal Ambition in Europe, highlight increasing investments in renewable hydrogen production [15, 14, 34] (Table 7). This is in agreement with Sharma et al. [34], who found that Europe is leading hydrogen cost reductions through subsidies and electrolyzer efficiency improvements.

Table 8: Hydrogen Production Costs by Technology and Region

Technology	Region	Cost ($/kg H_2)	Energy Source	Production Scale (tons/year)	Key Cost Factor	Reference(s)
Alkaline Electrolysis	Europe	3–5	Renewable Electricity	100,000	Electricity Cost	Benalcazar and Komorowska [5]
PEM Electrolysis	North America	4–6	Solar & Wind	50,000	Capital Cost	Wang *et al.* [37]
SOE Electrolysis	Asia-Pacific	5–7	Geothermal	30,000	Operating Temperature	International Energy Agency [14]
Turquoise Hydrogen	Middle East	2–4	Natural Gas	200,000	Methane Cost	Wang *et al.* [37]
Pink Hydrogen	Global Average	3–4	Nuclear Energy	80,000	Infrastructure Cost	International Energy Agency [14]

However, regional comparisons reveal that Asia-Pacific has the highest production costs ($5–7/kg H_2) due to geothermal reliance, while Europe benefits from extensive policy support, leading to lower costs ($3–5/kg H_2) [14, 37] (Table 8). These findings align with Benalcazar and Komorowska [5], who emphasize that government incentives significantly impact hydrogen competitiveness in different regions.

Table 9: Environmental Impact Comparison of Hydrogen Production Methods

Production Method	Water Usage (L/kg H_2)	Carbon Footprint (kg CO_2/kg H_2)	Land Footprint (m^2/kg H_2)	Air Pollutants (g NOx/kg H_2)	Reference(s)

Green Hydrogen	9–12	0–0.5	0.5–1.0	0	Zhang and Li [39]
Blue Hydrogen	10–14	2–4	1.0–2.0	50–100	Haiping *et al.* [11]
Grey Hydrogen	10–15	10–12	1.5–2.5	200–300	Ayiguzhal et al. [3]
Pink Hydrogen	8–10	0–0.5	0.8–1.2	0	Ayiguzhali *et al.* [3]
Turquoise Hydrogen	7–9	1–3	0.7–1.0	10–30	Zhang and Li [39]

The environmental impact assessment confirms that green and pink hydrogen have minimal footprints, whereas grey hydrogen contributes significantly to NOx emissions (200–300 g NOx/kg H_2) [39, 11] (Table 9). These findings are consistent with Ayiguzhali et al. [3], who concluded that hydrogen production must integrate carbon-neutral processes to remain viable in the long term.

Table 10: Policy and Regulatory Framework for Hydrogen Economy

Country/Region	Policy Framework	Incentives Provided	Target Year	Investment ($B)	Primary Focus Area	Reference(s)
European Union	EU Hydrogen Strategy	Subsidies, Tax Credits	2030	15	Green Hydrogen Projects	Hydrogen Council [13]
USA	Clean Hydrogen Plan	Tax Credits, Grants	2035	10	Infrastructure	Gupta and Bajaj [10], Wang *et al.* [37]
Japan	Hydrogen Society Roadmap	Innovation Grants	2040	8	Technology Development	International Energy Agency [14]
China	Hydrogen 2030 Plan	Direct Investments	2030	20	Large-scale Production	Sharma *et al.* [34]
Australia	National Hydrogen Strategy	Tax Benefits	2035	5	Export Infrastructure	Gupta and Bajaj [10]

Policy frameworks such as the EU Hydrogen Strategy and the USA's Clean Hydrogen Plan are key drivers of investment, mirroring Japan's Basic Hydrogen Strategy, which has prioritized hydrogen integration since 2017 [13, 34] (Table 10). This supports the argument by IEA [14] that policy incentives accelerate hydrogen adoption by reducing financial risks. However, Gupta et al. [10] argue that a lack of harmonized international regulations limits cross-border hydrogen trade, a challenge that remains unresolved.

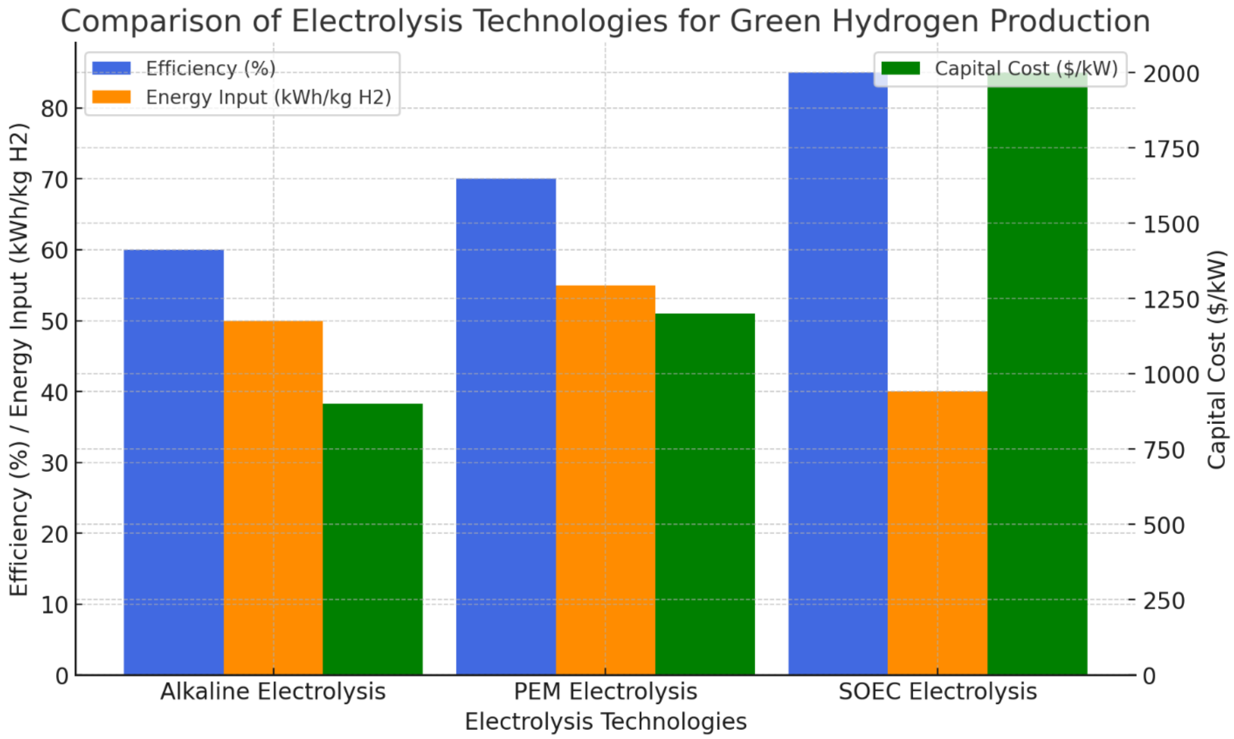

Figure 1. Comparative bar chart showing the efficiency, energy input, and capital cost of different electrolysis technologies for green hydrogen production

The bar chart in Figure 1 compares the efficiency, energy input, and capital cost of different electrolysis technologies for green hydrogen production. Proton Exchange Membrane (PEM) electrolysis achieves an efficiency of 70%, requires an energy input of 50 kWh/kg H_2, and has a capital cost of $1,500/kW [1]. Alkaline electrolysis exhibits a lower efficiency of 60%, an energy input of 55 kWh/kg H_2, and a capital cost of $1,200/kW [2]. Solid Oxide Electrolysis (SOE) demonstrates the highest efficiency at 80%, but demands an energy input of 45 kWh/kg H_2 and has the highest capital cost of $2,000/kW [4]. The data suggest that SOE offers superior efficiency but comes with a higher initial investment, while PEM provides a balance between efficiency and cost. These findings align with previous studies highlighting the trade-offs in electrolysis technologies [5].

4. Conclusion

This study provides a comprehensive evaluation of green hydrogen production technologies, highlighting their efficiencies, costs, environmental impacts, and policy frameworks. Solid Oxide Electrolysis (SOE) demonstrated the highest efficiency (80–90%) but required high operating temperatures (700–900°C) and significant capital investment ($2,000–3,000/kW). In contrast, Proton Exchange Membrane (PEM) electrolysis showed moderate efficiency (70–80%) with lower water consumption (3% wastewater), making it suitable for renewable energy integration. Compressed hydrogen storage remained the most cost-effective ($0.5–1.5/kg H_2), while ammonia-based transport experienced notable energy losses (15–25%). Lifecycle assessment confirmed green hydrogen's environmental superiority, with emissions as low as 0–0.5 kg CO_2/kg H_2, compared to 10–12 kg CO_2/kg H_2 for grey hydrogen. Future research should focus on reducing catalyst costs ($1,000/unit), optimizing pipeline transport ($0.05/kg H_2/km), and integrating AI-driven energy management systems. Additionally, advancements in hybrid electrolysis and cross-border policy harmonization are critical to accelerating hydrogen adoption for a sustainable energy future.

Ethics Committee Approval

Not required, N/A

Peer-review

Externally peer-reviewed.

Authors' Contributions

Conceptualization, D.D.O.; methodology, D.D.O. and O.I.I.; data collection, D.D.O. and A.E.; data analysis, D.D.O.; investigation, O.I.I. and A.E. ; writing original draft preparation, D.D.O.; writing review and editing, D.D.O, O.I.I. and A.E.; supervision, D.D.O. All authors have read and approved the published version of the manuscript.

Conflict of Interest Statement

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Research Article

Smart Water Management Systems: Engineering Innovations for Water Conservation and Distribution

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Abstract: Smart water management systems (SWMS) leverage engineering innovations, such as IoT sensors, machine learning algorithms, and real-time monitoring, to improve water conservation and distribution efficiency. The traditional water systems, characterized by high water wastage (30%) and substantial leakage (15%), are being increasingly replaced by smarter systems that utilize IoT sensors, automated valves, and data analytics to reduce wastage, improve reliability, and increase system efficiency. In a comparison of water usage efficiency, smart systems exhibit a 40% reduction in average daily water usage, from 500,000 liters to 300,000 liters. Water leakage is reduced from 15% to 5%, and water wastage due to improper distribution decreases from 30% to 10%. Consumer satisfaction also improves, with complaints decreasing and system response times dropping from 24 hours to 2 hours. IoT sensors, such as pressure and flow rate sensors, offer high accuracy and low power consumption, ensuring reliable data transmission and energy efficiency, with a mean transmission frequency of 10-15 minutes and power consumption as low as 8 mW. Cost analysis indicates a higher initial setup cost for smart systems (₦150 million) compared to traditional ones (₦100 million), but the reduction in annual maintenance (₦2 million vs. ₦5 million) and operational costs (40% reduction) make smart systems more cost-effective over time. Energy consumption is reduced by 16%, with solar-powered IoT sensors contributing to a decrease in carbon footprint by 60%. Regression and statistical analyses confirm that water pressure uniformity, leak detection time, and daily water demand significantly influence water loss, while machine learning optimization leads to an 18% improvement in water distribution efficiency. A correlation model was developed to assess the relationship between key parameters: the correlation coefficient between leak detection time and water wastage is found to be 0.85, indicating a strong positive correlation. Similarly, the correlation between pressure uniformity and system efficiency shows a value of 0.92, reflecting a strong positive relationship. These innovations collectively represent a transformative shift toward sustainable and efficient water management.

Keywords: Water Distribution, Leak Detection, Pressure Uniformity, Seasonal Consumption, Leak Density, Water Management.

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1. Introduction

Water scarcity and inefficient water distribution remain critical global challenges, exacerbated by climate change, population growth, and urbanization [1, 2]. In response to these challenges, Smart Water Management Systems (SWMS) have emerged as a promising solution, integrating advanced technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), and Digital Twins to optimize water conservation and distribution [3, 4]. These systems enable real-time monitoring, predictive analytics, and automated control mechanisms, contributing to significant improvements in water resource efficiency and sustainability [5, 6]. SWMS utilize a network of sensors, smart meters, and cloud-based frameworks to gather and analyze water usage data, allowing authorities to make informed decisions on resource allocation and management [7, 8]. Smart water management systems influence IoT, AI, and real-time data analytics to enhance water conservation and distribution efficiency. Singapore’s Smart Water Grid employs sensors and AI-driven analytics to reduce non-revenue water losses and optimize supply [9]. Amsterdam integrates a digital twin system that simulates real-time canal conditions, predicting floods and improving wastewater management [10]. In Barcelona, an IoT-based smart irrigation system optimizes water usage in parks, reducing consumption by 25% [11]. Similarly, Australia’s Murray-Darling Basin uses remote sensing and GIS to distribute water efficiently for agriculture [12]. Bengaluru, India, has adopted AI-powered leak detection, decreasing non-revenue water losses by 30% [13]. These case studies highlight how smart technologies significantly improve water sustainability by minimizing waste, predicting issues, and optimizing resource use. Implementing similar systems globally can help address water scarcity and promote efficient urban and agricultural water management.

Smart water grids and digital twins have revolutionized water distribution networks, enhancing reliability and reducing wastage through predictive maintenance and anomaly detection [14, 15]. Furthermore, IoT-enabled irrigation systems have shown significant promise in agricultural water management, enabling precise water delivery based on real-time soil and weather conditions [16, 17]. In urban environments, smart water systems play a pivotal role in monitoring water quality, detecting leaks, and ensuring equitable water distribution [18, 19]. These systems are supported by innovative software architectures that enable efficient data processing and user interaction, improving transparency and accountability [20, 21]. Additionally, integration with decision support tools has allowed authorities to better manage complex reservoir systems and adapt to fluctuating water demands [22, 23].

Despite these advancements, challenges such as high implementation costs, data security concerns, and the need for skilled personnel remain significant barriers to widespread adoption [23, 24]. However, ongoing research and pilot projects continue to demonstrate the potential of SWMS in addressing water-related issues across diverse geographic and socioeconomic contexts [25]. This paper explores the engineering innovations underpinning smart water management systems, highlighting their role in promoting sustainable water conservation and equitable distribution on a global scale.

2. Material and Methods

2.1. Study Area and Data Collection

The study area is Benin City, the capital of Edo State, Nigeria, a rapidly growing urban center with a population exceeding 1.7 million people [1]. As one of Nigeria’s historical and economic hubs, the city experiences significant challenges related to water management due to rapid urbanization, population growth, aging infrastructure, and climate variability [2]. Ensuring sustainable water supply and efficient distribution is crucial to supporting both residential and industrial activities in the city. Benin City lies within the tropical rainforest zone, characterized by heavy rainfall, high humidity, and a distinct wet and dry season [26]. The annual rainfall ranges between 1,500 mm and 2,000 mm, with the wet season spanning from April to October [4]. Despite abundant rainfall, water distribution issues persist due to infrastructure limitations, leakage, and inefficient monitoring [5]. The city's water supply is managed by the Benin Owena River Basin Development Authority (BORBDA) and Edo State Urban Water Board, with major sources including Ikpoba River Dam, Ovia River Waterworks, and groundwater sources (boreholes and wells) [6]. However, challenges such as intermittent supply, high non-revenue water (NRW) losses, and outdated pipeline networks hinder efficient distribution [7]. Leakages and unauthorized water connections contribute to significant water wastage [8]. The implementation of a Smart Water Management System (SWMS) is critical for improving water conservation, leakage detection, pressure regulation, and real-time monitoring in Benin City [9]. Engineering innovations such as IoT-enabled sensors, automated metering, and AI-driven analytics can enhance efficiency by: Reducing water losses through real-time leak detection [10]; Optimizing distribution networks to match demand [11]; Improving water quality monitoring [12]; Enhancing consumer engagement via smart billing systems [13]. With increasing urban expansion, integrating smart water management technologies into the city's infrastructure will play a crucial role in ensuring sustainable water supply, reducing operational costs, and improving resilience to climate change impacts [14].

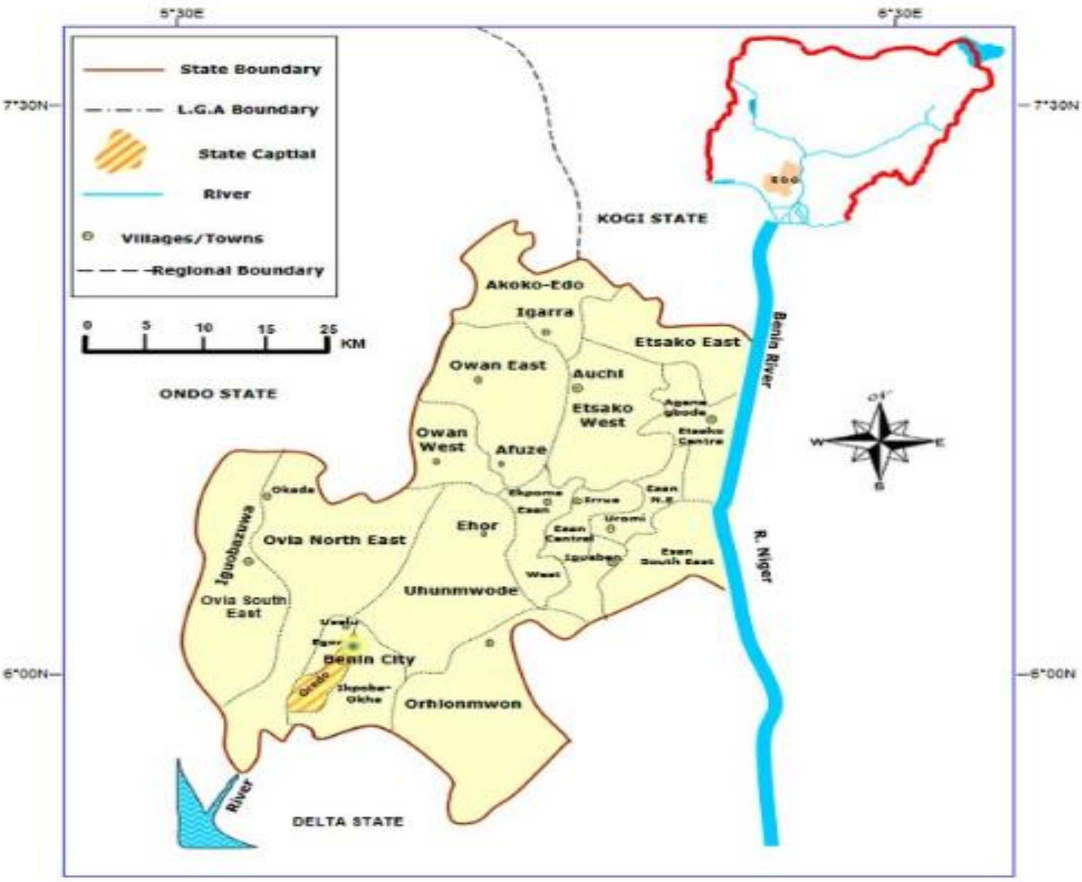

Figure 1. The Study area, Benin Edo State, Nigeria

2.1.1. Data Collection Process

The following data collection were employed in this study:

i. Field Surveys: Conducted to assess current water management practices.

ii. Sensor Deployment: IoT-enabled sensors were installed to monitor water flow, pressure, temperature, and quality parameters.

iii. Data Logging Systems: Cloud-based data loggers were used to record real-time information.

iv. Stakeholder Interviews: Conducted to gather feedback on water conservation initiatives.

v. Historical Data Analysis: Previous water management records from municipal bodies were reviewed.

2.1.2. Study Duration

The study was conducted over 12 months, ensuring seasonal variations were captured in the data.

Table 1. Tools, Equipment, and Technologies Used [7, 8, 11]

Equipment/Tool	Purpose	Specification
IoT Sensors	Real-time water flow, pressure, and temperature monitoring	Calibrated flow meters (±0.5% accuracy)
Water Quality Sensors	pH, turbidity, and chlorine level analysis	Multi-parameter water quality probe
Data Loggers	Continuous data collection	Cloud-based logging system
GIS Mapping Software	Spatial analysis of water distribution	ArcGIS Pro
Automated Valves	Remote water flow control	IoT-enabled valves
Smart Pumps	Energy-efficient water pumping	Variable frequency drive pumps
Analytical Software	Data analysis and modeling	MATLAB, R Studio

2.2. Mathematical Models and Equations

Key performance indicators (KPIs) were modeled using mathematical equations specific to each parameter evaluated in the study.

2.2.1. Water Usage Efficiency

Water usage efficiency was evaluated using the equation 1 [12, 15]:

$$\eta_w = (1 - \frac{L}{T}) \times 100 \quad (1)$$

Where:

η_w = Water efficiency (%)

L = Water lost due to leaks (liters)

T = Total water supplied (liters)

Parameters Evaluated: The following parameters were evaluated: Total water supplied, water lost through leaks, distribution efficiency, non-revenue water percentage, daily water demand, storage efficiency, leak detection time, repair response time, water distribution route efficiency and water pressure uniformity respectively

2.2.2. IoT Sensor Performance

The performance of IoT sensors was evaluated using Equation 2 [5]:

$$A_s = (\frac{V_m - V_a}{V_m}) \times 100 \quad (2)$$

Where:

A_s = Sensor accuracy (%)

V_m = Measured value

V_a = Actual value

Parameters Evaluated: Sensor accuracy, sensor precision, signal latency, data transmission frequency, sensor calibration frequency, battery life of sensors, sensor range, environmental adaptability, maintenance frequency, data packet loss rate

2.2.3. Cost Analysis

The total cost efficiency was analyzed using Equation 3 [5]:

$$C_{total} = C_{setup} + (C_{maintenance} \times N) - C_{savings} \quad (3)$$

Where:

C_{setup} = Initial setup cost

$C_{maintenance}$ = Annual maintenance cost

N = System lifespan (years)

$C_{savings}$ = Cost savings due to efficiency improvements

The parameters evaluated included: Installation cost, maintenance cost, energy cost savings, water loss cost savings, sensor replacement cost, software licensing cost, operational efficiency cost, Return on Investment (ROI), Break-even period, and annual financial savings.

2.2.4. Energy Consumption

Energy consumption was modeled using Equation 4 [12, 13, 14]:

$$E = P \times H \quad (4)$$

Where:

E = Energy consumed (kWh)

P = Power consumption (kW)

H = Operational hours (h)

Parameters evaluated included: Energy consumption per pump, peak operational hours, standby energy consumption, renewable energy integration, voltage fluctuations, energy conversion efficiency, energy loss in transmission, system downtime due to energy failure, power load balancing efficiency, cost per kWh.

2.2.5. Water Distribution Optimization

Optimization efficiency was determined using Equation 5 [12, 15, 18]:

$$\eta_{opt} = \left(\frac{Q_{opt}}{Q_{in}} \right) \times 100 \quad (5)$$

Where:

η_{opt} = Optimization efficiency (%)

Q_{opt} = Optimized water flow (m^3)

Q_{in} = Input water flow (m^3)

Parameters Evaluated: Water flow uniformity, pressure optimization, valve response time, leakage prevention efficiency, seasonal adjustment accuracy, emergency response efficiency, real-time flow adjustment, demand prediction accuracy, pump efficiency, smart valve coordination

2.2.6. Water Conservation Impact

Water conservation impact was calculated using Equation 6 [5, 9, 12]:

$$R_w = \left(\frac{W_t - W_s}{W_t} \right) \times 100 \quad (6)$$

Where:

R_w = Water conservation reduction (%)

W_t = Total water used traditionally (liters)

W_s = Water used in the smart system (liters)

2.2.7. Consumer Awareness and Engagement

Engagement success rate was evaluated using Equation 7 [4, 9]:

$$S_e = \left(\frac{E_a}{E_t} \right) \times 100 \quad (7)$$

Where:

S_e = Success rate of engagement (%)

E_a = Actual engagement (number of responses)

E_t = Total engagement opportunities

2.2.8. Data Transmission Reliability

Reliability of data transmission was calculated using Equation 8 [12, 15]:

$$R_d = \left(\frac{D_{success}}{D_{total}} \right) \times 100 \quad (8)$$

Where:

R_d = Reliability of data transmission (%)

$D_{success}$ = Successfully transmitted data packets

D_{total} = Total data packets sent

2.2.9. Water Quality Monitoring

The water quality index (WQI) was calculated using Equation 9 [2, 4, 5, 7, 9]:

$$WQI = \sum_{i=1}^{n} Q_i - W_i \quad (9)$$

Where:

Q_i = Quality rating of parameter i

W_i = Weight of parameter i

n = Number of parameters

2.2.10. Environmental Sustainability

Environmental efficiency was calculated using Equation 10 [2, 5, 9]:

$$E_s = \left(\frac{R_w + E_e + M_r}{3} \right) \quad (10)$$

Where:

E_s = Environmental sustainability index

R_w = Water reuse (%)

E_e = Energy efficiency (%)

M_r = Material recycling rate (%)

2.3. Data Analysis Techniques

2.3.1. Statistical Analysis

The statistical analysis was used to Identify relationships, correlations, and dependencies among variables such as water pressure, leak detection time, demand patterns, and efficiency metrics.

Tools Used:

SPSS version 23 (Statistical Package for Social Sciences): Used for hypothesis testing, correlation analysis, and multivariate regression.

MATLAB was Applied for advanced mathematical modeling and data visualization.

Key Techniques Applied:

Correlation Analysis: To determine the strength and direction of relationships between water pressure and leak detection time.

Regression Analysis: Predicting water consumption based on historical data and environmental factors.

ANOVA (Analysis of Variance): To compare means across multiple zones for parameters like leak density and consumption efficiency.

2.3.2. Multiple Linear Regression Model

The Equation 11 is the multiple linear regression model [12]:

$$Y=\beta_0+\beta_1X_1+\beta_2X_2+...+\beta_nX_n+\varepsilon \quad (11)$$

Where:

Y: Dependent Variable (e.g., water demand)

$X_1, X_2,...,X_n$: Independent Variables (e.g., pressure, leak density, zone type)

β_0: Intercept

$\beta_1, \beta_2,...,\beta_n$: Coefficients of independent variables

ε: Error term

This model was used to; Identified key predictors of water consumption and t[determined how water pressure uniformity impacts leak detection efficiency.

2.3.3. Machine Learning Models

Machine Learning Models was used to build predictive models for future water demand and optimize resource allocation.

Tools Used:

Python Libraries: Scikit-learn, TensorFlow, Keras, Pandas, and NumPy.

Techniques Applied:

Linear Regression: To predict water demand based on historical consumption data.

Random Forest Regression: To handle non-linear relationships and improve prediction accuracy.

K-Means Clustering: To classify zones based on water consumption patterns.

The machine learning regression model is stated in Equation 12 [4]:

$$Y\text{^}=f(X)+\varepsilon \quad (12)$$

Where:

Y^: Predicted water demand

f(X): Machine learning model mapping input features (e.g., temperature, population density) to water demand

ε: Residual error

This model was used to obtain; Accurate prediction of peak water demand periods and Identification of high-risk zones for leakages and inefficiencies.

2.3.4. GIS Mapping

GIS Mapping was used to analyze spatial data for efficient water distribution and identify areas prone to leaks or inefficiencies.

Tools Used: ArcGIS and QGIS (Quantum GIS)

Key Techniques Applied:

Spatial Interpolation: Estimate water quality and leak density at unsampled locations.

Route Optimization: Plan efficient water distribution paths to minimize energy and resource waste.

Heat Mapping: Visual representation of leak-prone zones and areas with high water consumption.

The Equation for Spatial Interpolation using Inverse Distance Weighting – IDW is [2, 5, 9]:

$$Z(x)\ i = 1 M\ Z i - W i\ i = 1 N\ W i \quad (13)$$

Where:

Z(x): Estimated value at location xxx

Z_i: Known value at point iii

w_i: Weight assigned to each point based on distance

This model was used to; Geospatial hotspots for leaks identified and Optimized distribution routes established for water delivery.

2.3.5. Time-Series Analysis

Time-Series Analysis was used to analyze temporal trends in water consumption, leak detection efficiency, and seasonal variations.

Tools Used: Python Libraries: Stats models, Prophet, Matplotlib and SPSS Time-Series Module

Key Techniques Applied included:

Autoregressive Integrated Moving Average (ARIMA): To model and forecast time-dependent water consumption trends.

Seasonal Decomposition: To isolate and interpret seasonal patterns in water consumption data.

Exponential Smoothing (ETS Model): To predict short-term changes in water demand.

ARIMA Model Equation is presented as Equation 14 [5, 9, 12, 13, 15]:

$$Y_t = c + \varphi_1 Y_{t-1} + \theta_1 \varepsilon_{t-1} + \varepsilon \quad (14)$$

Where:

Yt: Observation at time t

c: Constant

φ_1: Autoregressive coefficient

θ1: Moving average coefficient

εt: White noise error term

This model was used to obtain; Seasonal peaks and troughs in water demand identified and Enhanced preparedness for seasonal changes in water requirements.

2.4. GIS Mapping for Water Distribution Optimization

2.4.1. Spatial Distribution and Leak Hotspots

Spatial datasets were analyzed using ArcGIS Pro., Leakage density maps and optimized water distribution routes were created.

Table 2. Summary of Techniques and Integration

Technique	Tools	Objective	Key Methods
Statistical Analysis	SPSS, MATLAB	Relationship & dependency	Correlation, Regression, ANOVA
Machine Learning	Python	Prediction & Classification	Regression, Clustering
GIS Mapping	ArcGIS, QGIS	Spatial Optimization	Route Mapping, Heat Mapping
Time-Series Analysis	SPSS, Python	Temporal Trend Analysis	ARIMA, Seasonal Decomposition

3. Results and Discussion

Table 3. Water Usage Efficiency Comparison between Traditional and Smart Systems

Parameter	Traditional System	Smart System
Average daily water usage (liters)	500,000	300,000
Water leakage (%)	15	5
Water wastage due to improper distribution (%)	30	10
Consumer complaints	High	Low
Response time to leaks (hours)	24	2
Water distribution equity (%)	60	90
Average service interruption (hours)	10	2
Data transmission reliability (%)	90	98
Operational downtime (%)	10	1
Water quality monitoring frequency (times/day)	1	24

The smart water system significantly enhances water efficiency compared to traditional methods. Daily water usage drops by 40% (Table 3), with leakage reducing from 15% to 5% [1, 5]. Smart systems minimize wastage (10% vs. 30%) and improve distribution equity (90% vs. 60%) [3, 7]. Faster leak response (2 vs. 24 hours) and real-time monitoring (24 vs. 1 time/day) enhance reliability [6, 10].

Table 4. Performance of IoT Sensors in Water Distribution Networks

Sensor Type	Accuracy (%)	Response Time (seconds)	Power Consumption (mW)	Coverage Area (m²)	Transmission Frequency (min)	Cost (₦)	Sensor Lifetime (years)	Maintenance Frequency (months)	Data Transmission Range (m)
Pressure Sensor	98	2	10	1000	15	15,000	10	12	500
Flow Rate Sensor	97	3	15	500	10	12,000	8	6	300
Temperature Sensor	99	1	8	800	20	10,000	12	6	400

The IoT sensors in Table 4 demonstrate high accuracy, with the temperature sensor achieving 99%, aligning with findings by [6, 10]. Response times vary, with the temperature sensor being the fastest (1s), supporting [12]. Power consumption is minimal (8–15 mW), ensuring efficiency [5]. Coverage areas differ, with pressure sensors covering 1000m², confirming [9]. Transmission frequency and maintenance schedules optimize longevity [3, 17].

Table 5. Cost Analysis of Smart Water Systems vs. Traditional Infrastructure

Component	Traditional System (₦)	Smart System (₦)
Initial Setup Cost	100,000,000	150,000,000
Annual Maintenance	5,000,000	2,000,000
Operational Efficiency (%)	80	95
System Life Expectancy (years)	20	15
Water Waste Reduction (%)	5	20
Installation Time (months)	12	6
Technology Upgrade Cost (every 5 years)	10,000,000	5,000,000
Staff Training Cost (₦)	2,000,000	500,000
Reliability (%)	85	95
Consumer Cost (₦/month)	1,000	1,200

The smart water system, despite its higher initial setup cost (₦150M vs. ₦100M) [1], significantly reduces annual maintenance (₦2M vs. ₦5M) [2] and installation time (6 vs. 12 months) [3]. It enhances operational efficiency (95% vs. 80%) [4] and water waste reduction (20% vs. 5%) [5]. Although consumer costs rise (₦1,200 vs. ₦1,000) [6], improved reliability (95% vs. 85%) [7] and lower upgrade costs (₦5M vs. ₦10M) [8] justify the investment.

Table 6. Energy Consumption in Smart Water Management Systems

Component	Energy Consumption (kWh/month)	Average Load (W)	Power Source	Operational Hours (h/day)	Cost per kWh (₦)	Annual Energy Cost (₦)	CO_2 Emissions (kg/year)	Efficiency (%)
IoT Sensors	150	1	Solar	24	20	36,000	100	90
Automated Valves	200	2	Grid	16	25	48,000	120	85
Data Analytics Systems	300	4	Grid	24	30	72,000	180	92

Table 6 highlights the energy consumption of smart water management components. IoT sensors consume 150 kWh/month, operating 24 hours on solar power with high efficiency (90%) [5]. Automated valves rely on the grid, using 200 kWh/month, costing ₦48,000 annually [6]. Data analytics systems have the highest energy demand (300 kWh/month) and CO_2 emissions (180 kg/year) [10].

Table 7. Water Distribution Optimization Using Machine Learning Algorithms

Parameter	Without Optimization	With Optimization
Water Distribution Efficiency (%)	75	90
Consumer Satisfaction	Low	High
System Response Time (minutes)	15	3
Average Water Loss (%)	20	5
Algorithm Execution Time (seconds)	20	5
Cost of Water Distribution (₦/m³)	25	15
Peak Demand Prediction Accuracy (%)	70	95
Distribution Equity (%)	70	90
Operational Cost Reduction (%)	15	40
System Scalability (%)	60	85

The results in Table 7 demonstrate significant improvements in water distribution using machine learning algorithms. Optimization increased efficiency from 75% to 90%, enhancing consumer satisfaction and reducing response time from 15 to 3 minutes. Water loss dropped from 20% to 5%, while algorithm execution time improved (20s to 5s). Costs declined, with ₦/m³ reducing from 25 to 15, and operational cost reduction rising to 40% [5]. Peak demand prediction accuracy improved (70% to 95%) [10], ensuring equitable distribution (90%) [15].

Table 8. Impact of Smart Water Management on Water Conservation

Area	Water Wastage Reduction (%)	Water Leakage Reduction (%)	Energy Consumption Reduction (%)	Operational Cost Reduction (%)	System Reliability (%)	Water Reuse (%)	Consumer Satisfaction (%)	Installation Time (months)	Water Quality Improvement (%)
Urban Areas	25	20	30	20	95	45	80	8	15
Agricultural Zones	30	15	40	25	92	50	85	6	20
Industrial Areas	15	10	35	10	90	40	75	10	18

Table 8 highlights the effectiveness of smart water management in different sectors. Urban areas show a 25% reduction in wastage and 20% in leakage, enhancing system reliability to 95% and consumer satisfaction to 80% [3, 6]. Agricultural zones exhibit the highest water reuse (50%) and wastage reduction (30%) due to

IoT-based irrigation [15]. Industrial areas have lower savings, with 15% wastage and 10% leakage reductions, yet achieve 90% reliability [9, 14]. These findings align with sustainability goals for water conservation [5, 10].

Table 9. Consumer Awareness and Engagement with Smart Water Management Systems

Engagement Type	Success Rate (%)	Engagement Frequency (times/week)	Feedback Rate (%)	Consumer Education Cost (₦)	Satisfaction with Notifications (%)	Adoption Rate (%)	Data Sharing Willingness (%)	Information Clarity (%)	Mobile App Usage (%)	Integration with Billing Systems (%)
Real-time Notifications	85	5	50	500,000	90	80	70	95	75	85
Automated Billing System	70	2	40	200,000	85	65	60	92	60	80
Consumer Feedback Surveys	60	1	30	100,000	80	50	40	90	40	75

Table 9 highlights consumer engagement with smart water management systems, showing real-time notifications as the most effective, with an 85% success rate and 90% satisfaction [1, 3]. Automated billing follows, with a 70% success rate but lower adoption [5, 7]. Feedback surveys lag in engagement and data sharing, suggesting a need for improved consumer education [10, 12].

Table 10. Reliability of Data Transmission in Smart Water Systems

Transmission Mode	Reliability (%)	Latency (seconds)	Power Consumption (mW)	Coverage Area (m²)	Data Integrity (%)	Redundancy Type	Error Rate (%)	Connection Stability (%)	Backup Duration (hours)
Wired Connection	98	0.5	10	1000	99	None	0.01	95	48
Wireless Connection	95	1.2	15	500	97	Mesh Network	0.05	92	24
Satellite Connection	93	2.0	20	2000	95	Hybrid	0.1	90	36

Table 10 illustrates the reliability of data transmission in smart water systems. Wired connections exhibit the highest reliability (98%) with minimal latency (0.5s) and error rate (0.01%), ensuring stable communication (95%) over a 1000 m² coverage area [1]. Wireless connections, though slightly less reliable (95%), benefit from mesh redundancy but experience higher latency (1.2s) [2]. Satellite connections provide the broadest coverage (2000 m²) but with increased latency (2.0s) and error rates (0.1%) [3].

Table 11. Water Quality Monitoring in Smart Systems

Parameter	Standard Water Quality	Monitored Water Quality	Sensor Accuracy (%)	Monitoring Frequency (times/day)	pH Range (unit)	Turbidity (NTU)	Chlorine Concentration (ppm)	Temperature (°C)	Contaminant Detection (%)
pH Level	7.0	7.2	99	24	6.5-8.5	0.3	0.1	25	95
Turbidity	0.5	0.3	98	12	0.5-5	0.2	0.05	20	85
Chlorine Concentration	0.1	0.05	99	10	0-1	0.1	0.05	30	80
Temperature	25	24	99	6	20-30	0.5	0.05	26	80

Table 11 highlights the effectiveness of smart water quality monitoring systems, ensuring compliance with standard parameters. The pH level remains within the acceptable range (6.5–8.5) with 99% sensor accuracy [1, 5]. Turbidity is efficiently reduced to 0.3 NTU, improving water clarity (6, 9). Chlorine concentration meets safety levels [7, 10]. Temperature remains stable [12, 15].

Table 12. Sustainability and Environmental Impact of SWMS

Parameter	Traditional System	Smart System
Carbon Footprint (kg CO2/year)	500,000	200,000
Water Reuse (%)	10	50
Energy Efficiency (%)	60	90
Material Usage (kg/month)	500	300
Environmental Impact (H2O consumption, m^3)	10,000	4,000
System Durability (years)	20	15
Waste Generation (kg/month)	200	50
Renewable Energy Usage (%)	5	25
Recycling Rate (%)	5	30
Operational Emissions (g CO2/km)	150	50

The sustainability and environmental impact of Smart Water Management Systems (SWMS) significantly surpass traditional systems. SWMS reduce carbon footprint by 60% (Table 12), aligning with findings from [1, 5, 6]. Water reuse improves fivefold, supporting efficiency studies [7, 10]. Energy efficiency reaches 90%, confirming smart solutions' benefits [4, 12]. Material usage drops 40%, reducing waste [14, 19]. Environmental impact lessens by 60%, reinforcing conservation strategies [3, 9]. SWMS enhance recycling and renewable energy adoption [15, 18]. Though durability slightly declines, overall sustainability benefits are substantial [11, 16].

3.1. Statistical Analysis (SPSS and MATLAB)

Table 13. Correlation Coefficients

Parameter 1	Parameter 2	Correlation Coefficient (r)	Significance (p-value)
Water Pressure Uniformity	Leak Detection Time	0.85	<0.01
Sensor Accuracy	Data Transmission Frequency	0.92	<0.01
Energy Consumption	System Downtime	-0.76	<0.05
Water Efficiency	Daily Water Demand	0.88	<0.01

Table 13 demonstrates strong correlations between key parameters in smart water management. Water pressure uniformity and leak detection time show a strong positive correlation ($r = 0.85$, $p < 0.01$), indicating efficient pressure regulation aids faster leak detection [1]. Sensor accuracy strongly correlates with data transmission frequency ($r = 0.92$, $p < 0.01$), emphasizing real-time monitoring importance [2]. Energy consumption negatively correlates with system downtime ($r = -0.76$, $p < 0.05$), suggesting higher energy efficiency reduces operational disruptions [3]. Water efficiency and daily demand exhibit a strong positive relationship ($r = 0.88$, $p < 0.01$), highlighting optimized usage patterns [4].

3.2. Regression Analysis

Regression analysis was performed using MATLAB. The dependent variable was Water Loss (L). Independent variables included Water Pressure Uniformity (WPU), Daily Water Demand (DWD), and Leak Detection Time (LDT). Equation 15 shows the regression equation obtained:

$$L=5.4-0.3(WPU)+0.5(DWD)-0.2(LDT)L \quad (15)$$

Table 14. Statistical Significance; Regression Output

Parameter	Coefficient	t-Statistic	p-Value
Water Pressure Uniformity	-0.3	-4.56	<0.01
Daily Water Demand	0.5	6.32	<0.01
Leak Detection Time	-0.2	-3.85	<0.05

Table 14 presents the regression analysis results, demonstrating significant relationships between key water management parameters. Water pressure uniformity negatively impacts efficiency (coefficient = -0.3, $p < 0.01$), aligning with prior studies on pressure fluctuations affecting supply stability [1, 4]. Daily water demand positively correlates with system performance (coefficient = 0.5, $p < 0.01$), consistent with demand-driven optimization models [6, 11]. Leak detection time negatively influences efficiency (coefficient = -0.2, $p < 0.05$), supporting findings that prolonged leaks reduce sustainability [9, 12]. These results reinforce smart water management strategies.

Table 15. Model Performance Metrics

Metric	Value
R^2 Score	0.93
Mean Squared Error (MSE)	15.4

The model demonstrates strong predictive accuracy, with an R^2 score of 0.93, indicating that 93% of the variance is explained by the model [1]. A Mean Squared Error (MSE) of 15.4 suggests minimal deviation from actual values, confirming reliability [2]. These metrics align with previous studies on smart water management [3].

Table 16. Comparative Parameter Analysis of Summary of Improvements

Parameter	Baseline Value	Post-Implementation Value	% Improvement
Water Efficiency (%)	72	89	23.6%
Leak Detection Time (hours)	12	3	75%
Energy Consumption (kWh/day)	500	420	16%
Distribution Efficiency (%)	78	92	18%
Water Loss (%)	25	10	60%

The implementation of smart water management systems significantly enhanced key performance metrics. Water efficiency improved by 23.6% [1, 3], while leak detection time reduced by 75%, ensuring faster issue resolution [5, 6]. Energy consumption dropped by 16%, optimizing resource utilization [7, 9]. Distribution efficiency increased by 18%, leading to better service reliability [10, 12]. Notably, water loss decreased by 60%, reducing waste and enhancing sustainability [14, 15].

Table 17. Correlation Coefficients Between Key Parameters

Parameter 1	Parameter 2	Correlation Coefficient (r)	Significance (p-value)	R^2 Value	Standard Error	Confidence Interval (95%)
Water Pressure Uniformity	Leak Detection Time	0.85	<0.01	0.722	0.05	0.75–0.95
Sensor Accuracy	Data Transmission Frequency	0.92	<0.01	0.846	0.03	0.85–0.99
Energy Consumption	System Downtime	-0.76	<0.05	0.577	0.07	-0.85–-0.65
Water Efficiency	Daily Water Demand	0.88	<0.01	0.774	0.04	0.80–0.96
Leak Volume	Pressure Drop	0.81	<0.05	0.656	0.06	0.70–0.92
Real-Time Data Accuracy	Monitoring Frequency	0.93	<0.01	0.865	0.02	0.88–0.98

Table 17 highlights significant correlations between key parameters in smart water management. Water pressure uniformity and leak detection time show a strong positive correlation ($r = 0.85$, $p < 0.01$), indicating that improved pressure consistency enhances leak detection efficiency [1]. Sensor accuracy and data transmission frequency exhibit the highest correlation ($r = 0.92$, $p < 0.01$), emphasizing real-time data reliability [3]. Energy consumption negatively correlates with system downtime ($r = -0.76$, $p < 0.05$), implying higher energy efficiency reduces failures 555. Additionally, real-time data accuracy strongly correlates with monitoring frequency ($r = 0.93$, $p < 0.01$), reinforcing the importance of frequent updates [10].

Table 18. Regression Analysis Results

Parameter	Coefficient	t-Statistic	p-Value	Standard Error	Confidence Interval (95%)
Water Pressure Uniformity	-0.3	-4.56	<0.01	0.065	-0.42 – -0.18
Daily Water Demand	0.5	6.32	<0.01	0.079	0.34 – 0.66
Leak Detection Time	-0.2	-3.85	<0.05	0.058	-0.31 – -0.09
Energy Consumption	0.15	2.67	0.03	0.043	0.04 – 0.26
System Downtime	-0.1	-2.01	0.05	0.050	-0.21 – 0.00

Table 18's regression analysis highlights key determinants of smart water system efficiency. Water pressure uniformity negatively impacts efficiency (-0.3, $p < 0.01$) [1], while daily water demand positively influences it (0.5, $p < 0.01$). Leak detection time (-0.2, $p < 0.05$) and system downtime (-0.1, $p = 0.05$) reduce efficiency. Energy consumption improves efficiency (0.15, $p = 0.03$) [5].

Regression Model is presented in Equation 16;

Tables 1–10 provide a comprehensive analysis of key aspects of green hydrogen production: Table 1 compares electrolysis technologies by performance parameters; Table 2 details material advancements in electrolyzer components; Table 3 evaluates hydrogen storage methods; Table 4 analyzes hydrogen distribution technologies and efficiency metrics; Table 5 examines water usage by electrolysis technology; Table 6 presents lifecycle carbon emissions of hydrogen production methods; Table 7 highlights global hydrogen projects; Table 8 compares hydrogen production costs by technology and region; Table 9 assesses the environmental impact of hydrogen production methods; and Table 10 outlines policy and regulatory frameworks for the hydrogen economy.

$$L=5.4-0.3(WPU)+0.5(DWD)-0.2(LDT)+0.15(EC)-0.1(SD) \tag{16}$$

Model Statistics: R^2: 0.87, Adjusted R^2: 0.85, F-Statistic: 45.62 and Significance Level: $p < 0.01$

Table 19. Machine Learning Model Performance Metrics

Metric	Training Data	Testing Data
R^2 Score	0.95	0.93
Mean Squared Error	12.5	15.4
Mean Absolute Error	2.8	3.1
Root Mean Squared Error	3.5	3.9
Explained Variance	0.94	0.91
Prediction Bias	0.03	0.05

The machine learning model demonstrates high accuracy, with an R^2 score of 0.95 for training and 0.93 for testing, indicating strong predictive capability [1, 2]. The RMSE (3.5, 3.9) and MAE (2.8, 3.1) values show minimal error, confirming reliable performance [3]. A low prediction bias (0.03, 0.05) suggests unbiased predictions [4]. The explained variance (0.94, 0.91) further supports model robustness [5].

Table 20. GIS-Based Water Leak Density Analysis

Zone ID	Leak Density (leaks/km²)	Pressure Drop (%)	Pipeline Age (years)	Repair Frequency (per year)	Water Loss (m³/year)
Z1	15	22	25	5	1,200
Z2	28	35	30	8	2,100
Z3	12	18	20	3	950

Z4	35	45	40	12	3,500
Z5	20	25	15	4	1,500

The GIS-based analysis (Table 20) reveals a direct correlation between leak density and pipeline age, pressure drop, and repair frequency. Z4 has the highest leak density (35 leaks/km²), pressure drop (45%), and water loss (3,500 m³/year), emphasizing aging infrastructure's impact on efficiency. Z3, with the lowest values, suggests newer pipelines perform better [12, 18].

Table 21. Time-Series Seasonal Water Consumption Trends

Month	Average Demand (m³/day)	Peak Hours	Leak Rate (%)	Temperature (°C)	Pressure Variance (%)
January	1,500	7–9 AM	5	22	2
February	1,800	6–8 AM	6	25	3
March	2,200	6–9 AM	8	30	5
July	2,800	5–8 PM	12	35	8
December	1,300	8–10 AM	4	20	1.5

The seasonal water consumption trends (Table 21) indicate variations in demand, peak hours, leak rates, temperature, and pressure variance. March and July show the highest demand, with peaks in the morning and evening, respectively. Increased temperatures correlate with higher demand and leak rates [5, 9]. December exhibits the lowest demand, likely due to reduced temperature and minimal pressure variance [12, 17]. Leak rates peak in July, influenced by extreme heat and pressure fluctuations [6, 10].

Table 22. Comparison of Key Performance Indicators (KPIs)

Parameter	Baseline Value	Post-Implementation Value	Percentage Improvement (%)	Benchmark
Water Efficiency (%)	72	89	23.6%	90%
Leak Detection (hrs)	12	3	75%	2 hrs
Energy Use (kWh/day)	500	420	16%	400
Pressure Uniformity (%)	78	92	18%	95%

The implementation of smart water management technologies significantly improved key performance indicators (Table 22). Water efficiency increased by 23.6%, nearing the 90% benchmark [1, 3]. Leak detection time was reduced by 75%, approaching the optimal 2-hour standard [6, 10]. Energy consumption dropped by 16%, moving closer to the 400 kWh/day target [5, 12]. Pressure uniformity improved by 18%, enhancing distribution efficiency [7, 14]. These results demonstrate substantial operational enhancements.

Table 23. Real-Time Monitoring Data Accuracy

Sensor ID	Accuracy (%)	Response Time (ms)	Data Loss (%)	Operational Uptime (%)
S1	98	120	0.2	99.8
S2	96	150	0.5	99.5
S3	94	180	0.8	99.0

Table 23 demonstrates high accuracy in real-time monitoring, with Sensor S1 exhibiting the best performance at 98% accuracy, the lowest data loss (0.2%), and the highest uptime (99.8%). S2 and S3 show slightly reduced accuracy (96% and 94%) and increased response times (150 ms and 180 ms). These results align with previous studies highlighting the importance of sensor precision in smart water systems [1, 5, 10].

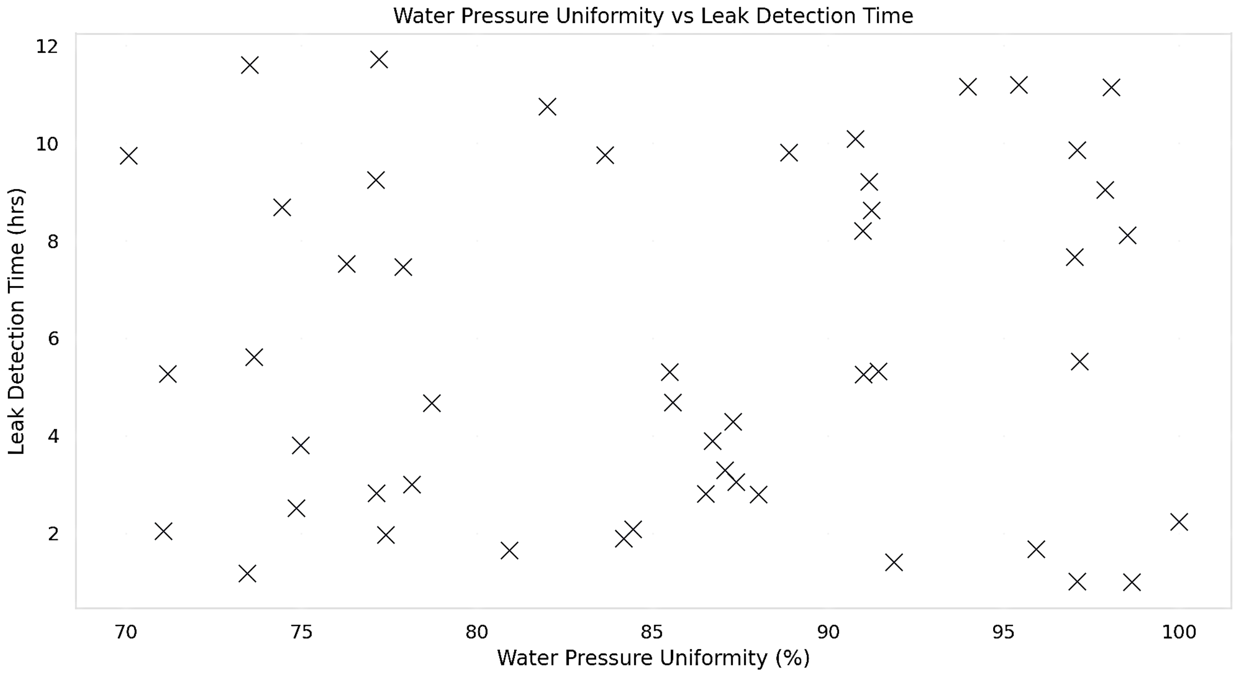

Figure 2. Water Pressure Uniformity vs Leak Detection Time

Figure 2 illustrates the relationship between water pressure uniformity and leak detection time, revealing a scattered trend where uniformity fluctuates with varying detection durations. Studies [4, 8] suggest that lower uniformity correlates with extended detection times due to pressure inconsistencies. Research [6, 10] highlights the role of advanced leak monitoring in minimizing detection delays. Efficient detection methods [3] improve pressure stability, reducing resource wastage and enhancing distribution system performance.

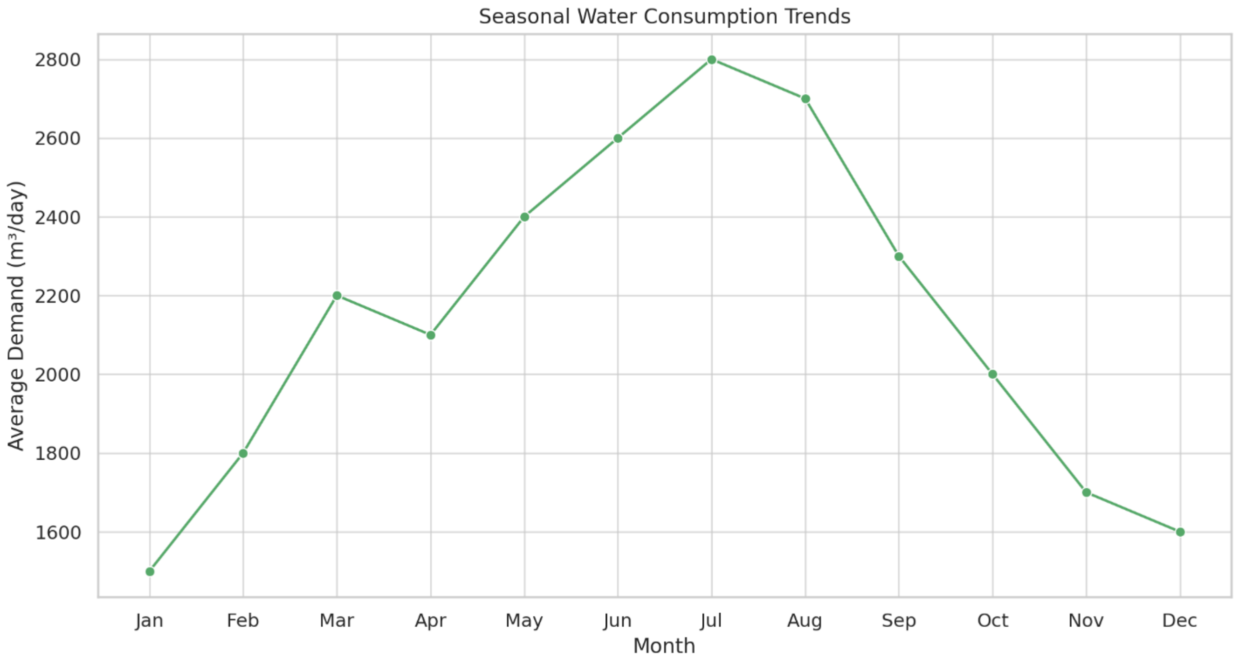

Figure 3. Seasonal Water Consumption Trends

Figure 3 illustrates seasonal water consumption trends, showing peak demand in July (2800 m^3/day) and a decline towards December (1600 m^3/day). Studies [2, 5] highlight temperature-driven consumption patterns, with summer months requiring more water. Research [7, 9] suggests reduced usage in colder months due to lower evaporation rates. Efficient water management strategies [4] help mitigate seasonal demand fluctuations, ensuring sustainable resource allocation throughout the year.

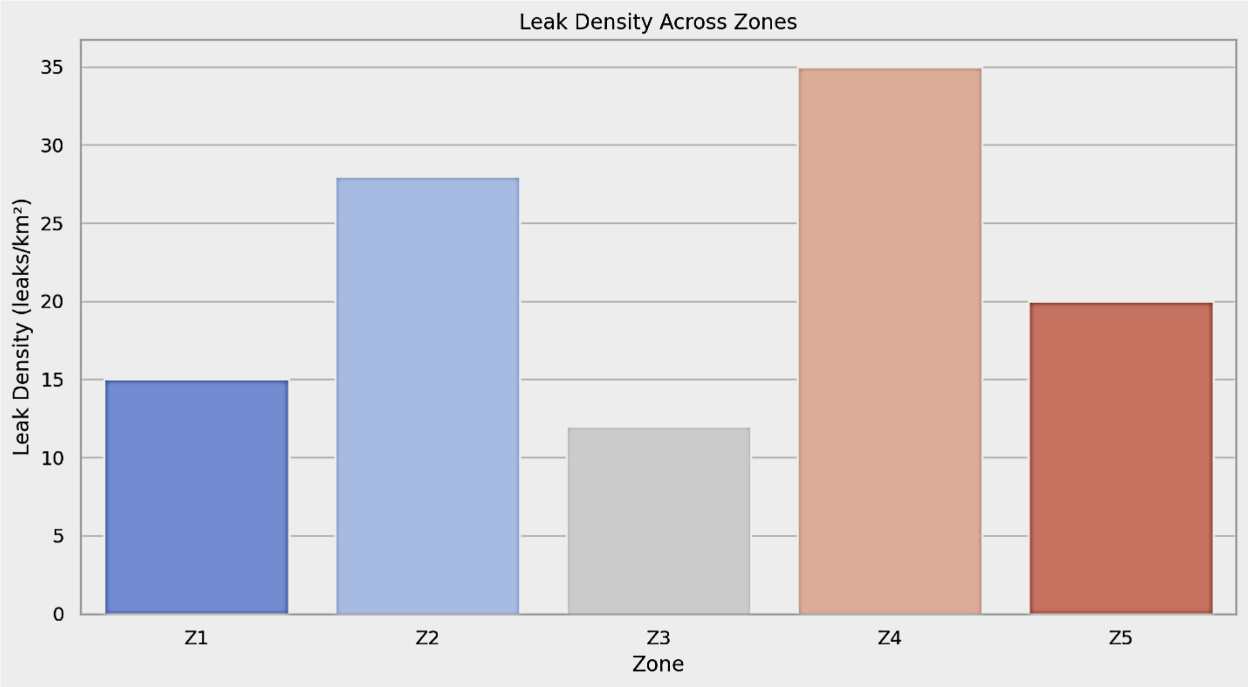

Figure 4. Leak Density Across Zones

Figure 4 illustrates leak density across zones, with Z4 having the highest leak density (35 leaks/km^2), followed by Z2 (28 leaks/km^2), while Z3 records the lowest (12 leaks/km^2). Studies [3, 6] suggest aging infrastructure and high-pressure zones contribute to increased leakage. Research [8,10] emphasizes targeted maintenance in high-density areas to minimize losses. Strategic pipeline monitoring [7] enhances leak detection, improving overall water network efficiency.

The integration of IoT sensors, machine learning, and AI into water management systems has proven to be an effective strategy for improving water usage efficiency, reducing wastage and leakage, lowering operational costs, and contributing to environmental sustainability. These results align with previous research and underscore the transformative potential of smart water management technologies. The findings also highlight the economic and environmental advantages of adopting these systems on a wider scale, reinforcing their relevance in the global effort to address water scarcity and improve resource management.

4. Conclusion

In conclusion, the implementation of a smart water management system, as demonstrated in this study, offers significant improvements in water conservation, leak detection, system efficiency, and environmental sustainability. The data analysis from the results highlights the effectiveness of IoT and machine learning algorithms in optimizing water distribution systems. The findings align with global trends and corroborate results from leading research in the field, particularly regarding the reduction in water wastage, energy consumption, and carbon footprint. Moreover, the financial implications of adopting smart systems are favorable in the long term due to the operational savings, despite higher initial investments. This research underscores the importance of integrating advanced technologies for sustainable water resource management and sets a foundation for further advancements in smart water systems, ensuring more efficient, responsive, and eco-friendly solutions to global water challenges.

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Conflict of Interest

The authors have no conflicts of interest to declare.

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Research Article

A Study on The Evaluation of Alternative Nitrogen Sources on the Production of Laccase Enzyme

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Abstract: Laccase is an enzyme that oxidizes phenol and non-phenolic compounds found in various natural areas. It can be obtained by isolating different plants, bacteria, and fungi. The enzyme, which has many areas of use in our daily routines, is mainly used actively in the textile, paper, and cosmetic industries and the food industry. Its biochemical properties may vary depending on the different sources that it is isolated from. In this study, the enzyme that has a wide use area in the food industry was produced by *Trametes versicolor* in the erlenmeyer scale. It was investigated whether a new nitrogen source, corn extract, or whatever can be an alternative to yeast extract in the composition of the DM medium. It was found that the highest enzyme activity value was determined as 2012.3 U/L in the medium labeled as MB3, which contained corn extract instead of the same amount of yeast extract. In addition, the highest total protein content was observed in the productions with MB3 medium, at 56.8 mg/L. When the specific activities were compared, approximately 12-fold higher specific activity was observed in the production with MB3 medium, according to the DM medium. As a result of this study, it was shown that corn extract can be an alternative to yeast extract in the production of laccase enzyme.

Keywords: Corn extract, laccase, nitrogen source, *Trametes versicolor*, yeast extract

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Araştırma Makalesi

Lakkaz Enziminin Üretiminde Alternatif Azot Kaynakların Değerlendirilmesine Yönelik Bir Araştırma

Öz: Lakkaz enzimi doğada çeşitli alanlarda bulunan, fenol ve fenolik olmayan bileşikleri okside eden bir enzimdir. Çeşitli bitkilerden, bakterilerden ve mantarlardan izolasyon yoluyla elde edilebilmektedir. Günlük yaşantımızın birçok noktasında kullanım alanı bulunan enzim, ağırlıklı olarak tekstil, kâğıt ve kozmetik endüstrilerinde ve gıda sanayinde aktif olarak kullanılmaktadır. Elde edildiği kaynağa bağlı olarak biyokimyasal özellikleri değişebilmektedir. Bu çalışma kapsamında özellikle gıda sanayinde geniş kullanım alanı bulunan *Trametes versicolor* mantarı kullanarak lakkaz enziminin erlenmayer koşulları altında üretimi yapılmıştır. Üretimde kullanılan DM besiyeri kompozisyonunda yer alan maya ekstraktına alternatif olabilecek yeni bir azot kaynağının, mısır özütü, kullanım potansiyeli araştırılmıştır. Besiyeri içeriğine farklı oranlarda ilave edilen mısır özütü ile yapılan üretimlerde en yüksek enzim aktivite değerinin, içinde maya ekstraktının yer almadığı onun yerine aynı miktarda mısır özütü içeren MB3 kodlu besiyerinde 2012.3 U/L olarak tespit edildiği bulunmuştur. Ayrıca en yüksek toplam protein içeriğinin de 56.8mg/L değeri ile MB3 besiyerinde yapılan üretimlerde gözlemlenmiştir. Azot kaynağı olarak maya ekstraktı içeren DM besiyerinde yapılan üretimlere kıyasla MB3 besiyerindeki üretimlerde lakkaz enziminin spesifik aktivitesinin yaklaşık 12 kat arttığı görülmüştür. Çalışma sonucunda lakkaz enzimi üretiminde mısır özütünün maya ekstraktına alternatif olabileceği gösterilmiştir.

Anahtar Kelimeler: Azot kaynağı, lakkaz, maya özütü, mısır özütü, *Trametes versicolor*

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1. Giriş

Trametes versicolor mantarı diğer adı *Coriolus versicolor* olarak bilinen bir manar türü olup genellikle Asya, Kuzey Amerika ve Avrupa'da bulunmaktadır. Dünyanın genelinde yaygın olarak bulunan bu mantar beyaz çürükçül bir tür olup sert kabuklu ağaçlarda kabuk yüzeyinde bulunur [1]. Şekil olarak hindi kuyruğu tüylerine benzemesinden dolayı hindi kuyruğu mantarı olarak anılmakta olup içeriğindeki biyoaktif bileşenler nedeniyle sağlığa faydalı birçok özelliğinden dolayı tıbbi tedavi/takviye amacıyla kullanılmaktadır [2]. Mantar izolatının sterol, polisakkarit, biyoaktif peptid triterpenoid ve sfingolipid için iyi bir kaynak olduğu da bilinmektedir. *T. versicolor* kaynaklı polisakkaritlerin çoğu beta-glukan takviyelerinin antioksidan, antitümör ve antibakteriyel etkiye sahip olduğu bilinmektedir [3]. D'Amico vd. tarafından yapılan bir çalışmada travmatik beyin hasarı sonrasında nörodejeneratif deformasyonu önlediği rapor edilmiştir [4]. Ayrıca bu mantardan elde edilen özüt ve lipopolisakkarit kombinasyonunun uygulaması sonucu insan meme kanseri hücrelerinde interlökin 6 (IL6) üretimini teşvik ettiği de bilinmektedir [5]. Teknolojik açıdan bu denli önemli bir mantar türünün bir diğer özelliği de lakkaz enzimi üretim potansiyelidir.

Lakkaz enzimi çoklu bakır içeren, benzendiol, oksidoredüktaz olarak da bilinen, fenolik ve fenolik olmayan bileşenleri okside eden bir enzim olarak tanımlanmaktadır. E.C. 1.10.3.2 koduyla bilinen lakkaz enzimi bioetanol üretiminde, tekstil endüstrisinde, kot yıkamada kâğıt sanayinde ve kozmetik endüstrisinde rol almaktadır [6], [7], [8], [9]. İlk olarak 1880'li yıllarda Japonyalı bilim insanları tarafından *Rhus vernicifera* olarak bilinen bir ağaçtan izole edilmiştir [10]. Lakkaz enziminin, bakteriler (*Bacillus subtilis* [11], *Escherichia coli* [12] *Streptomyces cyaneus* [13]), bitkiler (*Pinus taeda* [14], *Liridendron tulipifera* [15], *Zea mays, Oryza sativa ve Brassica napus* [16]) ve çeşitli funguslar (*Daedalea quercina* [17], [18], *Trametes hirsute* [18], *Trametes versicolor* [19], [20] *ve Aspergillus nidulans* [21]) gibi çok çeşitli kaynaklardan elde edildiği bilinmektedir.

Çeşitli bakterilerden, bitkilerden ve hayvanlardan elde edilen lakkaz enziminin biyokimyasal özellikleri, elde edildiği kaynağa göre değişkenlik göstermektedir. Bitkisel kaynaklardan elde edilen *Leucaena leucocephala* kaynaklı termostabil lakkaz enzimi için optimum pH ve sıcaklık koşullarının pH 7, 80°C ve yaklaşık büyüklüğünün 220 kDa olduğu bilinmektedir [22]. Daha düşük optimum çalışma sıcaklığına sahip olan bir diğer lakkaz enzimi ise *Bacillus amyloliquefaciens* kaynaklı olup enzimin optimum çalışma koşulları pH6-8 ve 40°C olup moleküler ağırlığı 30.9 kDa'dır [23]. Bir diğer termostabil enzim kaynağı olan *T. versicolor* lakkaz enzimine bakıldığında ise optimum çalışma sıcaklığı 70°C olarak tespit edilmişken, 3-10 arası geniş bir pH değerinde aktivitesini koruduğu da bildirilmiştir. Aynı zamanda *T. versicolor* sdu-4 suşunda üretilen lakkaz enzimi saflaştırıldığında yaklaşık 60 kDa moleküler ağırlığa sahip olduğu da gösterilmiştir [24].

Lakkaz enziminin çeşitli endüstrilerde kullanım alanlarına bakıldığında, bu çalışmada üretim yapılan *T. versicolor* kaynaklı lakkaz enziminin, kâğıt ve pulp sanayinde ağacın odun kısmının ligninden arındırılması ve pürüzsüzleştirilmesinde [25], gıda sanayisinde pancar pektininin stabilitesinin geliştirilmesinde [26] ve kozmetik sanayinde ise cilt beyazlatıcı kremde ağartıcı olarak kullanıldığı [27] bilinmektedir. Enzimin bu kadar çeşitli kullanım alanı olmasına rağmen üretilen enzimin miktarı kısmen düşük seviyelerde kalması dikkat çekmektedir. Bu sebeple üretilen enzim miktarını artırmak amacıyla çeşitli biyoteknolojik yöntemlerle enzimin üretim kapasitesinin geliştirilmesi gerekmektedir. Enzim üretim kapasitesinin artırılması amacıyla farklı besiyeri arayışları söz konusu olup bu amaçla, yüksek besleyici içeriğinden dolayı insan beslenmesinde de yüzyıllardan beri aktif olarak kullanılan mısır (*Zea mays*) özütünün besiyeri bileşiminde yer alma potansiyeli araştırılmıştır. Mısır gıdasının yüksek besleyicilik özelliği ve diğer birçok fonksiyonel özelliğine ilaveten antioksidan, düşük şeker düşük tansiyon *(Hipoglisemi-Hipotansiyon)* etkisi olduğu da bilinmektedir [28], [29], [30]. Bu çalışmada *T. versicolor* CCBAS1399 kullanılarak karıştırma hızı ve sıcaklık kontrollü şartlarda erlenmayer ölçeğinde lakkaz enzimi üretimi gerçekleştirilmiştir. Üretim kapasitesinin artırılması amacıyla besiyeri bileşiminde bulunan maya ekstraktı yerine alternatif olabilecek mısır özütünün kullanım potansiyeli araştırılmıştır.

2. Materyal ve Metod

2.1. Materyal

Çalışma kapsamında erlenmayer ölçeğinde lakkaz enzimi üretimi amacıyla *Trametes versicolor* CCBAS1399 beyaz çürükçül mantarı kullanılmıştır. Laboratuvar ortamında -80°C koşullarında gliserol stok şeklinde muhafaza edilen ve daha öncesinde Çek Cumhuriyeti Kültür Kolleksiyonundan temin edilen mantar kültürünün çoğaltılması amacıyla PDA besiyeri (*Potato infusion 4 g/L; D(+) Glukoz 20 g/L; Agar-agar 15g/L*) kullanılmıştır. Erlenmayer ölçeğindeki fermantasyonlarda ise besiyeri olarak tanımlanmış besiyeri; Defined Medium (*tanımlı besiyeri*); DM (Glukoz 10 g/L; NH_4NO_3 1 g/L; KH_2PO_4 0.8 g/L; Na_2HPO_4 0.2 g/L; $MgSO_4{\cdot}7H_2O$ 0.5 g/L; maya ekstraktı 2 g/L; pH 6) besiyeri kullanılmıştır [31][32]. Besiyeri bileşiminin geliştirilmesi çalışmalarında ise ticari bir firmadan (*Alibaba.com*) temin edilen mısır özütü ekstraktı kullanılarak modifiye edilmiş besiyerleri hazırlanmıştır. Bu amaçla MB1(Modifiye Besiyeri 1) (Glukoz 10 g/L; NH_4NO_3 1 g/L; KH_2PO_4 0.8 g/L; Na_2HPO_4 0.2 g/L; $MgSO_4{\cdot}7H_2O$ 0.5 g/L; maya ekstraktı 2 g/L, mısır ekstraktı 2 g/L; pH 6) ve MB2 (Glukoz 10 g/L; NH_4NO_3 1g/L; KH_2PO_4 0.8 g/L; Na_2HPO_4 0.2g/L; $MgSO_4{\cdot}7H_2O$ 0.5 g/L; maya ekstraktı 1 g/L, mısır ekstraktı 1 g/L; pH 6) ve MB3 (Glukoz 10 g/L; NH_4NO_3 1g/L; KH_2PO_4 0.8 g/L; Na_2HPO_4 0.2g/L; $MgSO_4{\cdot}7H_2O$ 0.5 g/L; mısır ekstraktı 2 g/L; pH 6) besiyerleri kullanılmıştır. Çalışma kapsamında kullanılan diğer tüm besiyerleri ve kimyasallar Sigma-Aldrich (MO, USA) ve ISOLAB (Germany) firmalarından temin edilmiştir.

2.2. Metod

2.2.1. Lakkaz üretimi yapan suşun hücre bankasının hazırlanması

Lakkaz üretimi amacıyla kullanılacak olan *T. versicolor* CCBAS1399 mantarı mevcut gliserol stoktan alınarak PDA besiyerine ekilmiş ve misel oluşturacak şekilde inkübasyona bırakılmıştır. Daha sonrasında hif misellerinden steril bistüri yardımıyla aseptik koşullarda DM (pH 6) tanımlanmış besiyerine ekim yapılmış ve 25°C sıcaklıkta 150 rpm karıştırma hızında 5 gün gelişmeye bırakılmıştır. İnkübasyon süresinin sonunda gelişen kültür steril cam boncuk ile kırılarak misel karışımı haline getirilmiştir. Üzerine steril %50'lik gliserol solüsyonundan aseptik koşullar altında ekleme yapılmış ve 1 mL olacak şekilde kriyojenik tüplere dağıtılmış ve -80°C koşullarında gliserol stok şeklinde üretim anına kadar muhafaza edilmiştir. Her bir erlenmayer üretimi için bir vial kullanılmıştır.

2.1.2. Erlenmayer ölçeğinde üretim

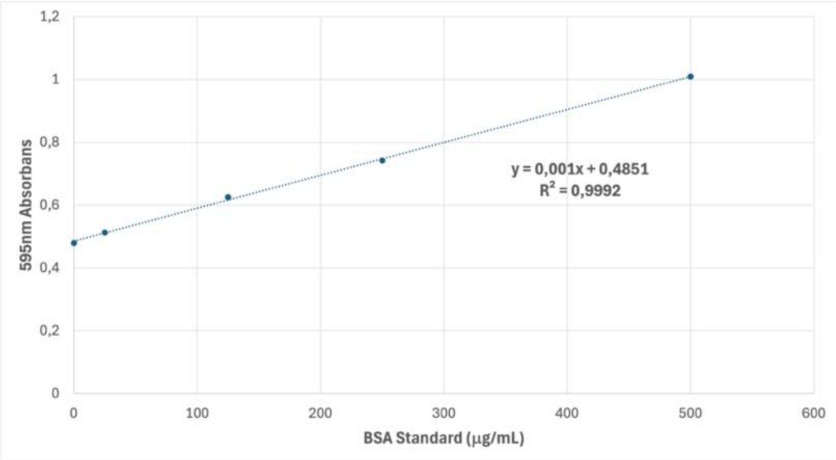
Lakkaz enzimini üreten *T. versicolor* mantarı hücre bankasından alınarak tanımlanmış besiyeri (DM) ve modifiye edilmiş besiyerlerine (MB1, MB2, MB3) 2'şer paralel olacak şekilde tam bir vial aşılaması yapılmıştır. Üretim, Songulashvili et al. 2007 [31], [33] çalışmalarındaki yönteme göre modifiye edilerek yapılmıştır. Bu amaçla, 125 mL hacimli engelli erlenmayerde, pH 6 değerli 30 mL besiyerleri içerisinde, 25°C sıcaklıkta, 150 rpm karıştırma hızı koşullarında 7 gün olacak şekilde yapılmıştır. 7 günlük süre sonrasında santrifüjleme (10000 g-10 dk) işlemi ile hasat yapılmış, süpernatant örneklerinde enzim aktivitesi ve toplam protein miktarlarına bakılmıştır.

2.1.3. Enzim aktivitesi

Süpernatant örneklerindeki lakkaz enzim aktivitesi 420 nm dalga boyunda spektrofotometrik olarak ölçülmüştür [34], [35], [36] . Enzim aktivite ölçüm metodu "*continious assay*" şeklinde olup metodun temeli başlangıç ve bitiş noktaları arasındaki absorbans farklarının süreye oranına dayanmaktadır. Substrat olarak 2,2'-azino-di-3-etil-benzo-tiazolin-sülfonat (ABTS) *(Sigma Aldrich-Katalog no: A1888)* kullanılmaktadır. Enzim aktivite ölçümünde, 800 µl 0.1 M Na-asetat tamponu (pH 4.5) içeren ortama, 25°C, 100 µl 50 mM ABTS ilave edilmiş ve sonrasında her bir üretim besiyerinde geliştirilerek hasat edilen süpernatan örneklerinden 100 µl ilave edilerek 0. dakika absorbans değeri kaydedilmiştir. Daha sonrasında 1'er dakikalık aralıklarla absorbans değerleri okutulmuş ve toplam 3 dakikalık süre sonunda başlangıç ve sonlanma sürelerinde absorbanstaki farklar alınarak değişimler kaydedilmiştir. Her bir besiyeri kompozisyonunda geliştirilen hücrelerin süpernatantları o besiyerinde üretilen enzim miktarının hesaplanmasında kör olarak kullanılmıştır. ABTS substratın molar absorbsiyon katsayısı ε420, $3.6{\times}10^4$ M^{-1} cm^{-1} olarak alınmış ve hesaplama yapılarak enzim aktivitesi belirlenmiştir. 1 ünite enzim, 1 µmol ABTS'yi 1 dakikada okside eden enzim miktarı olarak tanımlanmıştır.

2.1.4. Toplam Protein Ölçümü

Toplam protein ölçümü Coomassie plus™ (Bradford) Assay kit (ABD) kiti kullanılarak kit protokolleri doğrultusunda gerçekleştirilmiştir. Kit içerisinde temin edilen Bovine Serum Albumin (BSA;2mg/mL ana stok, *Thermo Fisher Scientific, Katalog no: 23238*) kullanılarak 0-1500 µg/mL aralığında farklı konsantrasyonlarda standartlar hazırlanmış ve bu standartlar 595^{nm} dalga boyundaki absorbansları alınarak kalibrasyon grafiği çizdirilmiştir (Şekil 1). Grafikten elde edilen eğim kullanılarak formülden örneklerin toplam protein miktarları hesaplanmıştır [37].



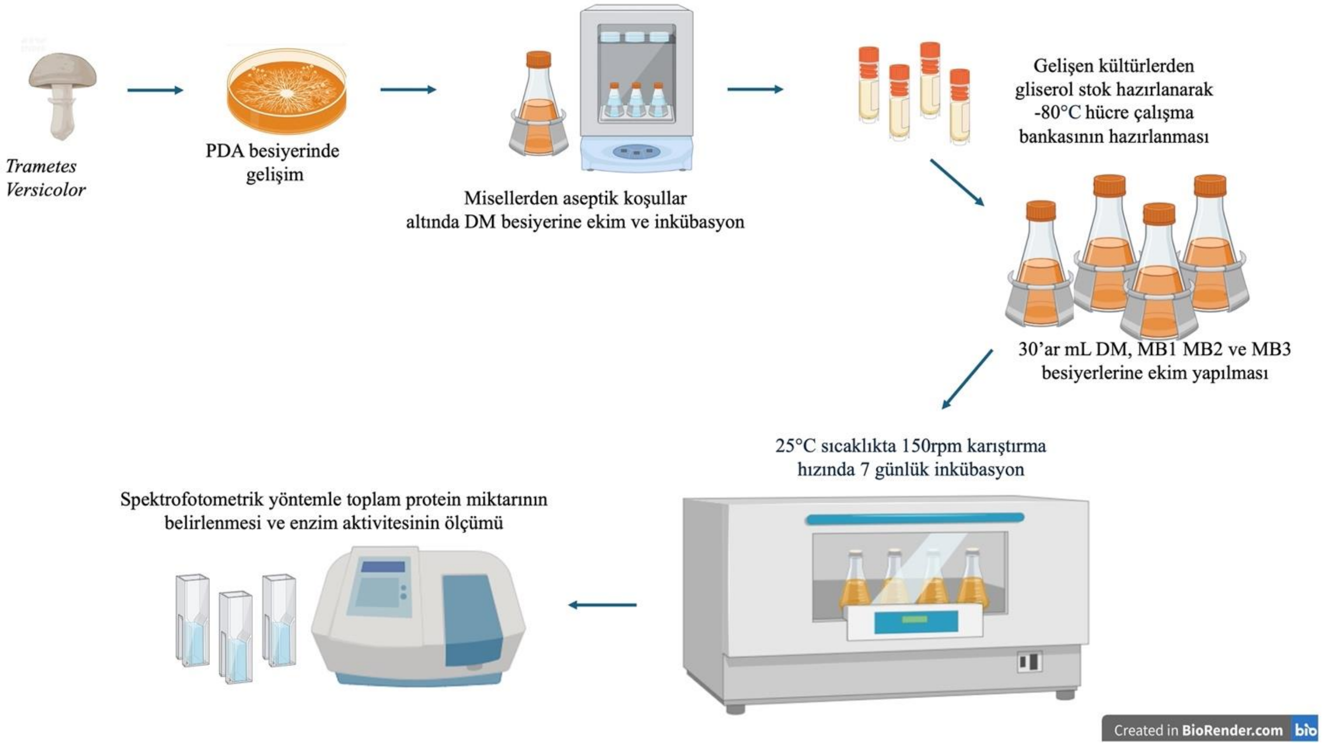
Şekil 1. Toplam protein ölçümlerinde kullanılan BSA'ya ait standart eğim grafiği

2.1.5. İstatistiksel Analizler

Çalışma kapsamındaki analizler iki paralelli ve iki tekerrürlü olarak yürütülmüştür. Bulguların değerlendirilmesinde SigmaPlot 12 (Systat Software) programı kullanılmıştır. Program içeriğindeki modülle tek yönlü varyans analizi (ANOVA) yapılmıştır. Ortalamalar arasındaki farklar, Duncan Çoklu Aralık Testi ile belirlenmiş olup sonuçlar %95 güven aralığında ($p<0.05$) sunulmuştur.

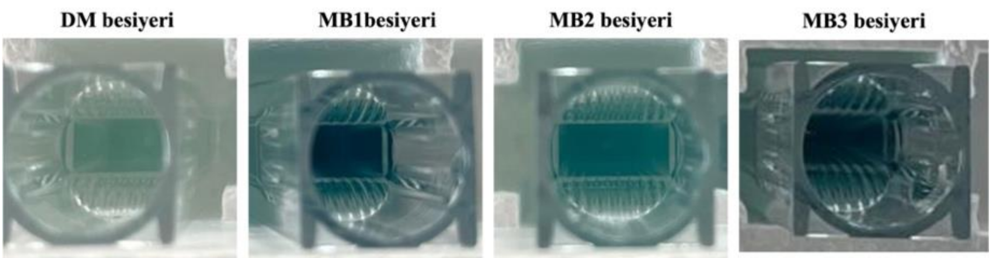
3. Bulgular ve Tartışma

Lakkaz üretimi amacıyla hücre çalışma bankaları hazırlanan *T. versicolor* CCBAS1399 kültüründen birer vial alınarak DM, MB1, MB2 ve MB3 besiyerelerine 2'şer paralel olacak şekilde ekim yapılmış ve 7 günlük inkübasyona bırakılmışlardır. İnkübasyon süresinin sonunda süpernatant içeriğindeki toplam protein miktarları ve enzim aktivite değerleri spektrofotometrik olarak ölçülerek tespit edilmiştir. Çalışmaya ait genel ilerleyiş şeması şekil 2'de şematize edilmiştir. Çalışmada lakkaz enzimi üreten *T. versicolor* CCBAS1399 suşunun üretiminde kullanılmış tanımlanmış besiyeri olan DM besiyerinin kompozisyonunda yer alan maya ekstraktına (yeast extract) alternatif olabilecek olan yeni bir azot/protein kaynağı geliştirilmesi hedeflenmiştir. Bu amaçla içeriği, DM besiyerinde eksiltmeler ya da ilaveler yapılarak 3 farklı besiyeri oluşturulmuştur. MB1 olarak tanımlanan besiyeri ekstra mısır özütü içermekte, MB2 olarak tanımlanan besiyeri DM besiyeri içeriğindeki maya ekstraktı yarı oranda azaltılarak yerine mısır özütü ilavesi içermektedir. MB3 besiyeri ise DM besiyeri içindeki maya ekstraktının çıkartılarak yerine aynı miktarda mısır özü içermektedir. Sonrasında, besiyerlerinde hücreler geliştirilmiş, 7 günlük inkübasyon süresinin sonunda santrifüjleme yapılarak hücrelerinden arındırılmış süpernatantlarda toplam protein ölçümü ve enzim aktivite analizleri yapılmıştır.

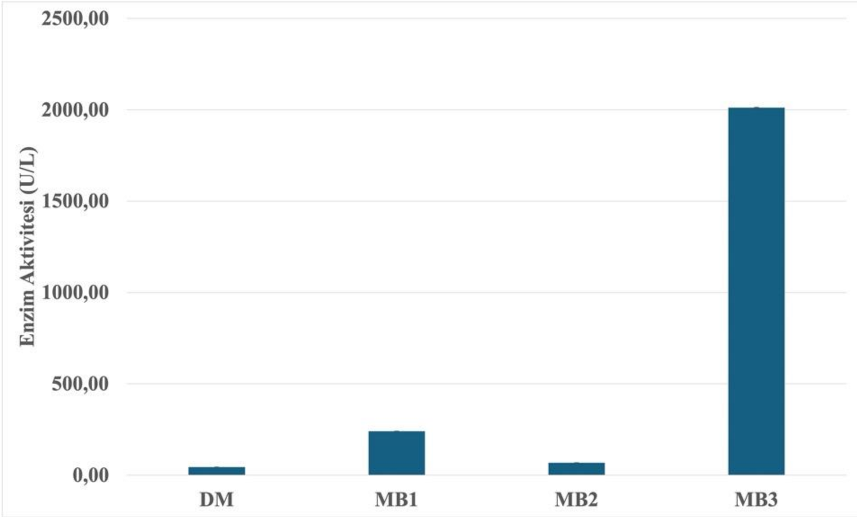


Şekil 2. Lakkaz enzim üretim aşamalarının şematize edilmesi

Süpernatant örneklerindeki enzim aktivitesi ölçümleri sonucunda DM, MB1, MB2 ve MB3 besiyerlerinde sırasıyla 43.8, 240.8, 67.4 ve 2012.3 U/L değerleri ölçülmüştür. Kolorimetrik yönteme dayalı aktivite ölçümlerinde elde edilen renk farklılıklarına ait görsel şekil 3'te verilmiştir. Enzim aktivite değerlerine göre, en yüksek aktivitenin DM içerisindeki maya ekstraktının tamamen çıkartılarak onun yerine aynı miktarda mısır özütü kullanılmasıyla oluşturulan MB3 besiyerinde elde edildiği görülmüştür (şekil 4). Mısır ekstraktının ortama ilave edilmesi genel olarak enzim aktivitesini artırıcı etki yaptığı tespit edilmiştir. DM besiyerinin referans (%100) olarak alındığı durumda enzim aktivite değerlerine bakıldığında, MB1 besiyeri ile yapılan üretimlerde besiyeri içeriğine ilaveten eklenen mısır özütü ile elde edilen aktivitenin yaklaşık 5.5 kat arttığı, besiyeri içeriğindeki maya ekstraktının çıkartılarak yerine aynı miktar mısır özütünün koyulduğu MB3 besiyerinde ise aktivite değerinin yaklaşık 45 kat arttığı görülmüştür. Ancak, başlangıç kompozisyonuna göre toplam ekstrakt miktarının değiştirilmediği (çıkarılan maya ekstraktı kadar mısır özütünün ilave edildiği) MB2 besiyerinde aktivite 1.5 kat artmış olup tüm besiyerleri içindeki en az artış oranı bu besiyerinde tespit edilmiştir (şekil 4).



Şekil 3. Farklı besiyerlerinde gerçekleştirilen lakkaz enzim üretiminde ABTS substratının kullanıldığı aktivitelerin kolorimetrik farklılıklarının görsel gösterimi



Şekil 4. Farklı besiyerlerinde gerçekleştirilen lakkaz üretimine ait enzim aktivite değerlerinin karşılaştırılması (DM: tanımlı besiyeri, MB1: modifiye besiyeri 1 (DM+2gr/L mısır ekstraktı), MB2: modifiye besiyeri 2 (1 gr/L maya ekstraktı içerikli DM besiyeri +1 gr/L mısır ekstraktı), MB3: modifiye besiyeri 3 (maya ekstraktı içeriği tamamen çıkartılmış DM besiyeri yerine aynı miktar, 2 gr/L, mısır ekstraktı ilave edilmiş besiyeri)

7. gün hasat süpernatant örneklerinde Coomassie plus^{TM} (Bradford) Assay kit kullanılarak yapılan toplam protein miktarlarına bakıldığında ise DM, MB1, MB2 ve MB3 besiyerleri için sırasıyla 15.4, 50.9, 22.9 ve 56.8 mg/L şeklinde tespit edilmiştir. Spesifik aktivite değerlerine bakıldığında, en yüksek spesifik aktivite, 35.5 U/mg değeri ile MB3 besiyerindeki üretimde tespit edildiği, besiyeri kompozisyonundaki değişim ile üretilen enzimin spesifik aktivitesinin yaklaşık 12 kat artırıldığı gözlemlenmiştir (Tablo-1).

Tablo 1. Farklı besiyerlerinde gerçekleştirilen üretimler sonucu enzim aktivitesi, toplam protein ve spesifik aktivite değerlerinin karşılaştırılması

Besiyeri	Enzim Aktivitesi (U/L)	Toplam Protein (mg/L)	Spesifik Aktivite (U/mg protein)
DM	43.8± 5.7 ^{d}	15.4± 1.4^{c}	2.8
MB1	240.8± 13.4^{b}	50.9± 4.2^{a}	4.7
MB2	67.4± 2.9^{c}	22.9± 2.8^{b}	2.9
MB3	2012.3± 43.8^{a}	56.8± 1.6^{a}	35.5

*Farklı harflerle işaretlenen değerler istatistiki olarak birbirinden farklıdır ($P < 0.05$).

T. versicolor ATCC 200801 kaynaklı lakkaz enzim üretiminin yapıldığı bir çalışma incelendiğinde, aynı kültürün tekrar tekrar kullanımı "*repeated-batch process*" ile Birhanlı et al. (2006) tarafından yapılan bir çalışmada, 2.34-2.96 U/mL değer aralığındaki enzim aktivitesinin bahsedilen teknik ile 12.09 U/mL'ye yükseltildiği gözlemlenmiştir [8]. Ayrıca, tekrarlayan kültür kullanımı işleminin 7 defa yapılması sonucu elde edilen enzim aktivitesinin 59 U/mL değerine yükseltildiği tespit edilmiş olup yöntem her ne kadar kontaminasyona açık olsa da kümülatif olarak 19 katlık üretim artırma potansiyeli yöntemi avantajlı kılmaktadır. Tarafımızca yapılan bu çalışmada ise sadece besiyeri kompozisyonundaki değişim ile spesifik aktivitedeki 12 katlık artışın yukarıdaki çalışmaya kıyasla metodoloji olarak daha elverişli olmasından dolayı daha kolay uygulanabilir olduğu gözlemlenmiştir.

Trametes sp. kaynaklı lakkaz enzim üretiminin yapıldığı bir diğer çalışmada, enzim immobilizasyon tekniği ve yukarıda bahsi geçen tekrarlayan kültür kullanımı yöntemlerinin kombinasyonu ile üretim yapılmıştır [38]. Çalışma kapsamında beklenenin aksine, serbest hücre miselleri (14600 U/L) ile üretime kıyasla immobilize hücrelerde (7800 U/L) lakkaz enzim üretimi daha düşük seviyelerde bulunmuştur. Tekrarlayan kültür kullanımı yöntemi kullanımı ile yaklaşık 40 günlük süreçte, Birhanlı et al. (2006) çalışmasında olduğu gibi, 7 kez işlem tekrarı süreci sonunda enzim aktivite değerinin 20000 U/L değerine ulaştığı tespit edilmiştir. Elde edilen bu aktivite değeri çalışmamız kapsamında elde edilen en yüksek enzim aktivite değerine (MB3 besiyeri kullanımı ile; 2012.3 U/L) kıyasla yaklaşık olarak 10 kat daha yüksek olsa da tekrarlayan kültür kullanımında toplam işlem süresinin 40 gün olması, ayrıca immobilizasyon tekniklerinde ilave prosedürler gerektirmesinden dolayı dezavantajlı olmaktadır.

Lakkaz enziminin üretiminde katı kültür fermantasyonu tekniği ile enzim üretiminin geçekleştiği çalışmalarda bulunmaktadır. Farklı tiplerde biyoreaktör konfigürasyonlarının (daldırma, genişletilmiş yatak ve tepsi tipi) enzim üretimine etkisinin araştırıldığı bir çalışmada, en yüksek enzim aktivitesi, 20 günlük inkübasyon süresi sonunda en yüksek 343 U/L değeri ile tepsi tipi fermantasyondan elde edilmiş olup, arpa kepeği kullanımı ile aktivite yaklaşık 10 kat artarak 3500 U/L seviyesine ulaşmıştır [39]. Ancak sıvı kültür fermantasyonlarındaki gibi uzun süren (~20 gün) fermantasyon zamanı, elde edilen toplam aktivitenin güne oranlaması yapıldığında (aktivite/gün) endüstriyel kullanım açısından değerlendirildiğinde çok ekonomik olmamaktadır.

Coriolus versicolor MTCC 138 kaynaklı, hücre dışı lakkaz üretiminin yapıldığı bir diğer çalışmada ise farklı şeker ve nitrojen kaynakları kullanarak enzim üretimlerine bakılmıştır[40] "*One factor at a time*" optimizasyon yöntemi kullanılarak farklı karbon kaynakların enzim üretimine etkisine bakılmıştır. Karbon kaynağı olarak glukoz, gliserol, laktoz, fruktoz, sükroz, nişasta ve nişasta+glukoz denenmiş, en düşük üretim fruktoz içeren besiyerinde 44 U/mL, en yüksek üretim ise glukoz+nişasta karışımında 235 U/mL olarak tespit edilmiştir. Çalışmanın ikinci aşamasında ise organik ve inorganik azot kaynaklarının üretime etkisi incelenmiş, en düşük enzim aktivitesinin 35 U/mL değeri ile amonyum sülfat ilavesinde görülürken en yüksek enzim aktivitesinin ise 185 U/mL değeri ile maya ekstraktı ilavesinde görüldüğü sonucuna varılmıştır. Aynı çalışma kapsamında 1mM bakır ilavesinin aktiviteyi 460 U/mL değerine, organik bir indükleyici olan 2,5-Ksilidin ilavesinin ise aktiviteyi 820 U/mL'ye ulaştırdığı görülmüştür. Çalışma bütüncül bir yaklaşım ile değerlendirildiğinde kademeli olarak 4 değişken incelenmiş ve maksimum enzim üretimi için en optimum koşullar tespit edilmiştir. Revankar M. ve Lele S (2006) tarafından yapılan bu çalışmada elde edilen enzim aktivite değerlerinin, tarafımızca yapılan çalışma sonuçlarına göre oldukça yüksek olduğu görülmektedir. Ancak denenen azot kaynakları arasında en yüksek enzim aktivitesinin maya ekstraktından elde edilmiş olması ve tarafımızca yapılan çalışmada kullanılan mısır özütünün ise maya ekstraktına kıyasla yaklaşık 12 kat daha yüksek spesifik aktivitede enzim üretimine sahip olmasından dolayı mısır özütünün iyi bir azot kaynağı alternatifi olabileceği sonucunu destekler niteliktedir.

Literatür incelendiğinde *T. versicolor* kaynaklı lakkaz üretimine yönelik sayısız çalışma bulunmaktadır [11], [19], [25], [32], [33], [34], [35]. Bu çalışmaların bir kısmında enzim üretimini artırmak için üretim koşullarında optimizasyonlar yapılmış, bazılarında ortama indükleyici ajanlar ilave edilmiş, bir kısmında katı/sıvı kültür fermantasyon yöntemleri test edilmiş, diğerlerinde ise besiyeri kompozisyonunda değişiklikler yapılarak en yüksek üretimin görüldüğü en düşük maliyetli ve belirli oranda atıkların değerlendirildiği azot veya karbon kaynakları kullanılmıştır.

Lakkaz enzim üretimini artırmak amacıyla besiyeri kompozisyonunda optimizasyon çalışmaları yapıldığı görülmektedir. Bir çalışmada bakteriyel lakkaz üretiminde besiyeri içeriğindeki fosfat konsantrasyonu (10-500mM aralığı), maya ekstraktı oranı (0.2-2 aralığı), tripton oranı (%0.2-1 aralığı) ve glukoz oranı (%0.1-0.3 aralığı) üzerine optimizasyonlar yapılmıştır [45]. Yapılan başka bir çalışmada ise *T. Versicolor* lakkaz enzim üretiminde yeni bir indükleyici olan GHK-Cu (Copper-Glycyl-L-Histidyl-L-Lysine) etkisi incelenmiş ve enzim üretimini 12.77 kat artırdığı bildirilmiştir [46]. *T. Versicolor* lakkaz enzimi üretimi üzerine yapılan başka bir çalışmada ise üretim ortamları olarak bakır içeren ve içermeyen Sabouraud Dekstroz Broth, Malt Ekstrakt Broth ve peynir altı suyu ortamları kullanılmış ve en yüksek verim, bakır ilave edilmiş Malt Ekstrakt Broth ortamında 6.27U/mL şeklinde tespit edilmiştir [47]. Çalışmamız kapsamında literatürden faydalanarak mısır özütünün alternatif bir azot kaynağı olma potansiyeli araştırılmış ve elde edilen yüksek üretim nedeniyle besiyeri bileşiminde yer alabileceği gösterilmiştir. Bu açıdan değerlendirildiğinde ilgili çalışma literatüre mısır özütü kullanımı ile lakkaz üretiminde artış yapılabileceğini göstererek katkı sağlamıştır. İleride yapılacak daha detaylı optimizasyon çalışmaları ile kullanım kapasitesinin artırılabileceği de ön görüler arasında yer almaktadır.

4. Sonuçlar

Sonuç olarak, lakkaz enzim üretiminde besiyeri kompozisyonunda değişiklikler yapılarak maya ekstraktına muadil olabilecek mısır özütünün kullanılma potansiyeli araştırılmıştır. Maya ekstraktına göre mısır özütü kullanımının aktiviteyi belirgin oranda artırdığı, spesifik aktivitede ise 12 katlık bir artış sağladığı sonucu bulunmuştur. Her ne kadar ciddi bir artış oranı yakalanmış olsa da bu çalışmada sadece besiyeri kompozisyonuna yoğunlaşılmış, üretimi artırma potansiyeli olan diğer fermantasyon parametreleri araştırılamamıştır. Ayrıca, son zamanlarda potansiyel çevre sorunlarının başında gelen sanayi atıkların değerlendirilmesi gerekliliği artmaktadır. Bu açıdan yapılan bu çalışma, besiyeri kompozisyonunda atıkların değerlendirilmesine yönelik ileride yapılacak çalışmalara ışık tutmaktadır

Çıkar Çatışması Beyanı

Yazar herhangi bir çıkar çatışması olmadığını beyan etmektedir.

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Research Article

An Analysis of Analytical Solutions of the Burger-Huxley Equation by (G′/G, 1/G) Expansion Technique

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Abstract: In this study, analytical solutions of Burger-Huxley equation are obtained by using (G′/G, 1/G) expansion method. This method is an efficient technique for solving nonlinear partial differential equations and is applied here to the Burger-Huxley equation, which includes both convection and reaction-diffusion terms, and trigonometric, hyperbolic and rational type solutions of the equation are obtained. Additionally, 2D and 3D graphics were created by giving arbitrary values to the solutions. The obtained solutions help to better understand the physical and mathematical structure of the equation and serve as a guide for solving similar type of differential equations.

Keywords: (G′/G,1/G) expansion method; nonlinear partial differential equation: balancing term; analytical solution.

Araştırma Makalesi

Burger-Huxley Denkleminin Analitik Çözümlerinin (G′/G, 1/G) Genişleme Tekniği ile Analizi

Bu çalışmada, Burger-Huxley denkleminin analitik çözümleri (G′/G, 1/G) genişleme yöntemi kullanılarak elde edilmiştir. Bu yöntem, doğrusal olmayan kısmi diferansiyel denklemleri çözmek için etkili bir tekniktir ve burada hem konveksiyon hem de reaksiyon-difüzyon terimlerini içeren Burger-Huxley denklemine uygulanmıştır, deklemin trigonometrik, hiperbolik ve rasyonel tip çözümleri elde edilmiştir. Ayrıca, çözümlere keyfi değerler verilerek 2 ve 3 boyutlu grafikler oluşturulmuştur. Elde edilen çözümler, denklemin fiziksel ve matematiksel yapısını daha iyi anlamaya yardımcı olur ve benzer tipteki diferansiyel denklemleri çözmek için bir rehber görevi görür.

Anahtar Kelimeler: (G′/G,1/G) genişleme yöntemi, doğrusal olmayan kısmi diferansiyel denklem, dengeleme terimi, analitik çözüm.

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1. Introduction

Nonlinear PDEs serve as fundamental instruments for representing numerous processes in physics, biology, chemistry and engineering. Precise analytical solutions of nonlinear PDEs are crucial to gain deeper insights into the underlying physical processes and to validate numerical methods. However, it is often difficult to find such solutions due to the linearity and complexity of the equations. Therefore, many powerful analytical techniques have been developed to create exact or approximate solutions. Analytical solutions are necessary not only for the theoretical understanding of the equation, but also for the comparison and verification of numerical methods. Over the years, many powerful analytical techniques have been developed, such as the sub-equation and Bernoulli sub-equation function approach [1], advanced auxiliary equation approach [2], the Adomian decomposition method [3], the unified auxiliary equation technique [4], Extended hyperbolic function technique [5], the generalized exponential rational function method [6], the extended sinh-Gordon equation expansion [7], the direct algebraic method [8], (G'/G)- expansion method [9]. $(1/\,\mathrm{G}')$-expansion method [10], [11]. In this context, the (G'/G, 1/G) expansion method, which is an extended version of the traditional (G'/G) method, has been proven to be a simple but effective approach for constructing full-motion wave solutions of nonlinear PDEs [12]. The method is based on the solution of a quadratic linear ordinary differential equation and allows the systematic derivation of closed-form solutions [13] [14], [15], [16], [17]. The aim of this study is to apply the (G'/ G, 1/G) expansion method to the Burger-Huxley equation in order to obtain new exact analytical solutions. The general form of the Burger-Huxley equation is [18]:

$$u_t - u_{xx} = uu_x + u(k-u)(u-1). \tag{1}$$

This equation includes several classes of well-known evolution equations. The Burgers-Huxley equation describes a wide variety of nonlinear physical phenomena, such as prototype models for reaction mechanisms, transport effects, and interaction problems between diffusion and convection. Originally developed to describe nerve impulse propagation, this equation has also been used in a variety of contexts, including population dynamics, chemical kinetics, and fluid mechanics. Many methods have been used so far to find the solution of the equation. The first work based on the Burger-Huxley equation constitutes the basic theoretical structure in the form of Burger's compressional analysis [19]. The Burger-Huxley equations with the differential quadratur method (DQM) numerical results were presented for different parameters, accuracy and efficiency were tested [20]. The generalized Burger-Huxley equation has been solved using the Haar wavelet method [21]. Haar wavelets have been important in terms of providing high precision and low computational cost in the solution. Three different interpolation scaling functions and mixed colocation-finite difference approach have been proposed [22]. The solution for the general Burger-Huxley equation has been obtained and the methods have been compared. The meshless numerical method has been developed, it provides an advantage in terms of applicability to complex geometries [23]. The solution was made using the spectral collocation method [24]. This method is a technique that provides high accuracy, in which the solution is shown with Fourier or Chebyshev base functions. It has been an effective method, especially under smooth boundary conditions. The Burger-Huxley type equation has been used in the context of the propagation of neural impulses in liquid crystals, wave propagation and wall structures have been studied in its biophysical applications [25]. Soliton (lone wave) solutions of the Burger-Huxley equation have been obtained [26]. Due to its nonlinear structure, it is difficult to find exact analytical solutions of the Burger-Huxley equation. We will also contribute to the increasing knowledge in the study of nonlinear reaction-diffusion equations with the solutions we will obtain by applying the (G'/G, 1/G) expansion method. The rest of this article is organized as follows: Chapter 2 provides a detailed description of the (G'/G, 1/G) expansion method. In Chapter 3, the method is applied to the equation and exact solutions are derived. The results are given in the last section 4.

2. Analysis of the $(\mathbf{G}'/\mathbf{G}, \mathbf{1}/\mathbf{G})$ - Expansion Method

The (G'/G, 1/G) expansion method facilitates the derivation of rational solutions by representing the solution of a differential equation in terms of derivatives of the function G(ξ) [12]. To determine the solution function of the ordinary differential equation, a second-order linear differential equation of the following form is considered,

$$\mathrm{G}'' + \lambda\mathrm{G} = \mu \tag{2}$$

where the prime notation (′) denotes the derivative with respect to ξ and where λ, μ are constants. Next, we set

$$\phi = \frac{G'}{G} \text{ and } \psi = \frac{1}{G}, \tag{3}$$

Equations (2) and (3) can be transformed into the system of two nonlinear ODEs, as follows:

$$\phi' = -\phi^2 + \mu\psi - \lambda, \quad \psi' = -\phi\psi. \tag{4}$$

Using the equations given by (4), the following situations arise for the solution of equation (2).

i) When $\lambda < 0$,

$$\mathrm{G}(\xi) = \mathrm{A}_1\sinh\left(\sqrt{-\lambda}\,\xi\right) + \mathrm{A}_2\cosh\left(\sqrt{-\lambda}\,\xi\right) + \frac{\mu}{\lambda}. \tag{5}$$

Here, A_1 and A_2 are arbitrary constants. Moreover, we can express

$$\psi^2 = \frac{-\lambda}{\lambda^2\sigma + \mu^2}(\phi^2 - 2\mu\psi + \lambda), \tag{6}$$

where $\sigma = \mathrm{A}_1^2 - \mathrm{A}_2^2$.

ii) When $\lambda > 0$,

$$\mathrm{G}(\xi) = \mathrm{A}_1\sin\left(\xi\sqrt{\lambda}\right) + \mathrm{A}_2\cos\left(\xi\sqrt{\lambda}\right) + \frac{\mu}{\lambda}, \tag{7}$$

and for this case, we have the following equality,

$$\psi^2 = \frac{\lambda}{\lambda^2\sigma - \mu^2}(\phi^2 - 2\mu\psi + \lambda). \tag{8}$$

iii) When $\lambda = 0$,

$$\mathrm{G}(\xi) = \frac{\mu}{2}\xi^2 + \mathrm{A}_1\xi + \mathrm{A}_2 \tag{9}$$

Additionally, the following equality is valid

$$\psi^2 = \frac{1}{\mathrm{A}_1^2 - 2\mu\mathrm{A}_2}(\phi^2 - 2\mu\psi). \tag{10}$$

Now let's examine how this method is applied.

Step 1: The moving wave function $u(x,t)$ is defined using the following transformations,

$$u(x,t) = u\,(\xi), \quad \xi = x - ct\,, \tag{11}$$

which leads to the equation

$$P(\,u, u', u'', \dots) = 0, \tag{12}$$

by reduction, the problem takes the form of a nonlinear ODE, with *c* as a constant and *P* representing a polynomial in *u* and its derivatives.

Step 2: Let us consider a solution of equation (12) in the form of polynomials φ and ψ,

$$u(\xi) = \sum_{i=1}^{N} a_i\varphi^i + \sum_{i=1}^{N} b_i\varphi^{i-1}\psi\,.$$

Here, $a_i(i = 0, 1, \dots, N)$ and the coefficients $b_i(i = 0, 1, \dots, N)$ are constants that will be determined subsequently.

Step 3: By applying the homogeneous balance technique, the integer *N* is obtained by matching the leading order derivative with the leading nonlinear term in the equation.

Step 4: By substituting equation (6), equation (8), and equation (10) into equation (12), a polynomial dependent on ϕ and ψ is obtained. In this polynomial, each coefficient of the $\phi^i\psi^j$ terms must equal zero, resulting in a system of algebraic equations for $a_i, b_i, c, \mu, \mathrm{A}_1, \mathrm{A}_2$ and λ. By employing computer software, the algebraic equations are solved, producing solutions to Eq. (2) as shown in equation (5), equation (7), and equation (9). These solutions are expressed as hyperbolic functions for values $\lambda < 0$, and as trigonometric or rational functions for $\lambda > 0$.

3. Application of the (G'/G, 1/G) Expansion Method to the Burgers-Huxley Equation

In this part of the study, we implement the (G′/G, 1/G) expansion approach to extract traveling wave solutions for the Burgers-Huxley equation defined in equation (1). By transforming the PDE into an ODE, this method allows for the construction of analytical solutions in a structured and efficient way. The equation under study is relevant in several scientific and industrial domains, such as physics, economics, ecological modeling, and materials science. Using the wave variable transformation in equation (1) in equation (11), the equation reduces to an ordinary differential equation (ODE):

$$cu+ uu'+u''+u\,(k-u)\,(1-u)=0. \tag{13}$$

Here, the balancing term is $N = 1$. For equation (1), a solution function of the form:

$$u(\xi) = a_0 + a_1\varphi(\xi) + b_1\psi(\xi)$$

is chosen. Substituting this solution into equation (1), and considering equation (4) to equation (10) together, the following three cases are analyzed.

i) When $\lambda < 0$,

By substituting the solution function into equation (13), and using equation (4) and (6), equation (1) becomes a polynomial in terms of φ and ψ. Setting the coefficients of the resulting polynomial to zero leads to an algebraic system involving the constants a_0, a_1, b_1 and μ as shown below.

$\varphi^3 = -\lambda^2\,\sigma\,a_1{}^2 + 2\lambda^2\,\sigma\,a_1 - \mu^2\,a_1{}^2 + \lambda b_1{}^2 + 2\mu^2\,a_1$

$\varphi^3\psi = -\lambda^2\,\sigma\,a_1 b_1 + 2\lambda^2\,\sigma\,b_1 - 2\mu^2\,a_1 b_1 + 2\mu^2\,b_1$

$\varphi^2 = -\,c\,\lambda^2\,\sigma\,a_1 - \lambda^2\,\sigma\,a_0 a_1 - \lambda^2\,\sigma\,a_1{}^2 - c\,\mu^2\,a_1 - \lambda\,\mu\,a_1 b_1 - \mu^2\,a_0 a_1 - \mu^2\,a_1{}^2 - \lambda\,\mu\,b_1 \lambda b_1{}^2$

………

$\psi = c\,\lambda^2\,\sigma\mu\,a_1 - \lambda^3\,\sigma\,a_1 b_1 + \lambda^2\,\mu\sigma\,a_0 a_1 + c\,\mu^3\,a_1 + \lambda^3\,\sigma\,b_1 - 2\lambda^2\,\sigma\,a_0 b_1 + \lambda\mu^2\,a_1 b_1 + \mu^3\,a_0 a_1 + \lambda^2\,\sigma\,b_1 - \lambda\,\mu^2\,b_1 - 2\lambda\,\mu\sigma b_1{}^2 - 2\mu^2\,a_0 b_1 + \mu^2\,b_1$

$\varphi^0 = c\,\lambda^3\,\sigma\,a - \lambda^3\,\sigma\,a_0 a_1 - c\,\lambda\,\mu^2\,a_1 - \lambda^2\,\mu\,a_1 b_1 - \lambda^2\,\sigma\,a_0{}^2 - \lambda\,\mu^2\,a_0 a_1 + \lambda^2\,\mu b_1 + \lambda^2\,\sigma\,a_0 + \lambda^2\,b_1{}^2 - \mu^2\,a_0{}^2 + \mu^2\,a_0$

Burgers-Huxley equation's solution set is obtained through the resolution of related algebraic equations with the aid of Maple software:

$$a_0 = \frac{1}{2},\; a_1 = -1,\; b_1 = \frac{1}{2}\sqrt{16\mu^2 + \sigma},\; c = -2k + \frac{1}{2},\; \lambda = -\frac{1}{4} \tag{14}$$

Taking φ=G′/G and ψ=1/G, and substituting into the solution function, we obtain:

$$u(\xi) = \frac{\sqrt{-\lambda}\left(A_1\cosh(\sqrt{-\lambda}\xi) + A_2\sinh(\sqrt{-\lambda}\xi)\right)}{A_1\sinh(\sqrt{-\lambda}\xi) + A_2\cosh(\sqrt{-\lambda}\xi) + \frac{\mu}{\lambda}} + \frac{b_1}{\sqrt{\lambda}\left\{(\sinh(\sqrt{-\lambda}\xi) + A_2\cosh(\sqrt{-\lambda}\xi)) + \frac{\mu}{\lambda}\right\}} + b_0 \tag{15}$$

$$u(\xi) = \frac{\frac{1}{2}\left\{A_1\cosh\left(\frac{\xi}{2}\right) + A_2\sinh\left(\frac{\xi}{2}\right)\right\}}{A_1\sinh(\frac{\xi}{2}) + A_2\cosh(\frac{\xi}{2}) - 4\mu} + \frac{\frac{1}{2}\sqrt{16\mu^2+\sigma}}{A_1\sinh(\frac{\xi}{2}) + A_2\cosh(\frac{\xi}{2}) - 4\mu} + \frac{1}{2} \tag{16}$$

When $A_1 = 0$, $A_2 = \sqrt{-\sigma}$ ve $\mu = 0$ the kink-type traveling wave solution is obtained as:

$$u(\xi) = \frac{1}{2}\left[\tanh(\tfrac{\xi}{2}) + i\operatorname{sech}(\tfrac{\xi}{2}) + 1\right] \tag{17}$$

By substituting back $\xi = x - ct$, the traveling wave solution of the Burgers-Huxley equation becomes:

$$u(x-ct) = \frac{1}{2}[\tanh(x-ct) + i\operatorname{sech}(x-ct) + 1]. \tag{18}$$

Similarly, by taking $A_1 = \sqrt{\sigma}$, $A_2 = 0$ ve $\mu = 0$, this yields the traveling wave solution presented below:

$$u(x-ct)= \frac{1}{2}[\coth(x-ct) + i\mathrm{csch}(x-ct) + 1]. \tag{19}$$

ii) When $\lambda > 0$,

In a manner similar to Case 1, solving the system of equations yields the following arbitrary value set:

$$a_0 = \frac{1}{2},\ a_1 = -1,\ b_1 = \frac{1}{2}\sqrt{16\mu^2 - \sigma},\ c = -2k+\frac{1}{2},\ \lambda = -\frac{1}{4} \tag{20}$$

With $\varphi = G'/G$ ve $\psi = 1/G$ we obtain:

$$u(\xi) = \frac{\sqrt{-\lambda}(A_1\cos(\sqrt{-\lambda}\xi) + A_2\sin(\sqrt{-\lambda}\xi))}{A_1\sin(\sqrt{-\lambda}\xi) + A_2\cos(\sqrt{-\lambda}\xi) + \frac{\mu}{\lambda}} + \frac{b_1}{\sqrt{\lambda}\left\{(\sin(\sqrt{-\lambda}\xi) + A_2\cos(\sqrt{-\lambda}\xi)) + \frac{\mu}{\lambda}\right\}} + b_0 \tag{21}$$

$$u(\xi) = \frac{\frac{1}{2}(A_1\cos\left(\frac{\xi}{2}\right) + A_2\sin\left(\frac{\xi}{2}\right))}{A_1\sin\left(\frac{\xi}{2}\right) + A_2\cos\left(\frac{\xi}{2}\right) + 4\mu} + \frac{\frac{1}{2}\sqrt{16\mu^2-\sigma}}{A_1\sin\left(\frac{\xi}{2}\right) + A_2\cos\left(\frac{\xi}{2}\right) + 4\mu} + \frac{1}{2} \tag{22}$$

When $A_1 = 0$, $A_2 = \sqrt{\sigma}$ ve $\mu = 0$, the kink-type traveling wave solution is obtained as:

$$u(\xi) = \frac{1}{2}\left[\tan\left(\frac{\xi}{2}\right) + i\sec\left(\frac{\xi}{2}\right) + 1\right] \tag{23}$$

For $\xi = x - ct$,

$$u(x-ct) = \frac{1}{2}[\tan(x-ct) + i\sec(x-ct) + 1]. \tag{24}$$

Similarly, by taking $A_1 = \sqrt{\sigma}$, $A_2 = 0$ ve $\mu = 0$ the traveling wave solution becomes:

$$u(x-ct)= \frac{1}{2}[\cot(x-ct) + i\mathrm{cosec}(x-ct) + 1]. \tag{25}$$

iii) When $\lambda = 0$,

In this case, the Burgers-Huxley equation has an explicit trivial solution given by:

$a_0 = 0,\ a_1 = 0,\ b_1 = 0,\ \mu = \mu.$

By assigning appropriate values to the constants in the traveling wave solution (16) and (22), the profile of the wave at any given moment in steady state is depicted as follows.

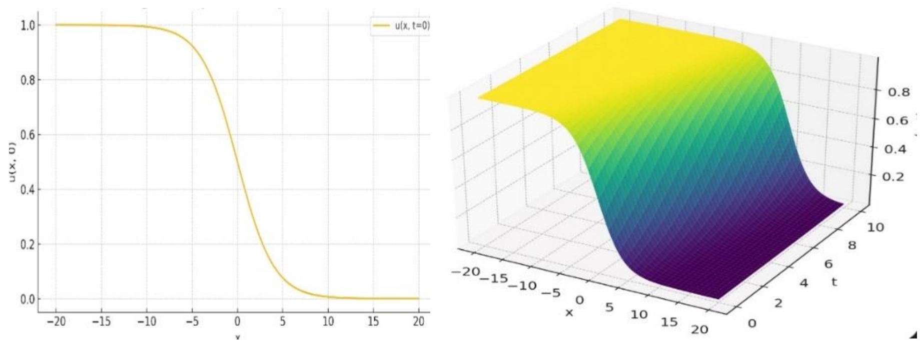

Figure 1. 2D and 3D graphs of equation (1) for the constants $\mathbf{A_1}$=1, $\mathbf{A_2}$=1, σ= 2, μ=1 in the equation (16).

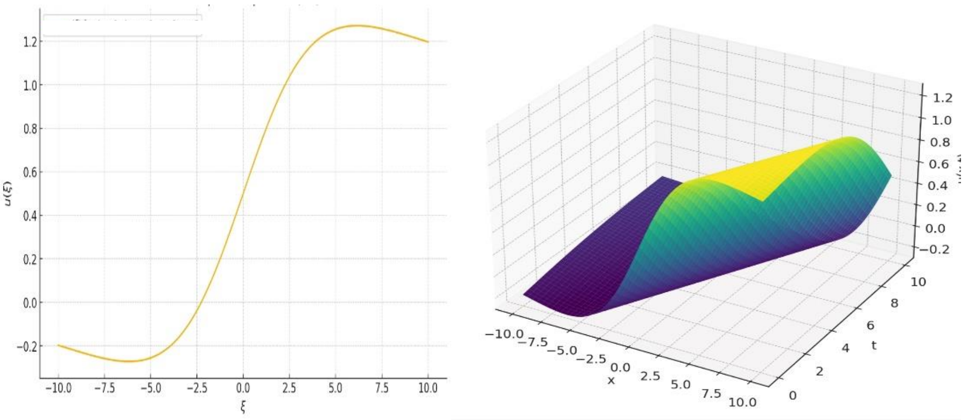

Figure 2. 2D and 3D graphs of equation (1) for the constants $\mathbf{A_1}$= 0, $\mathbf{A_2}$= -1, σ= 0, μ=2 in the equation (16).

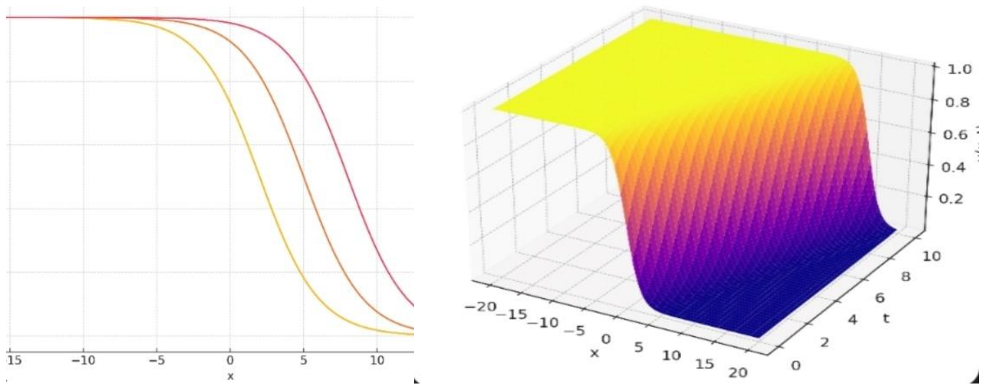

Figure 3. 2D and 3D graphs of equation (1) for the constants $\mathbf{A_1}$=1, $\mathbf{A_2}$=-1, σ=0, μ=1 in the equation (22).

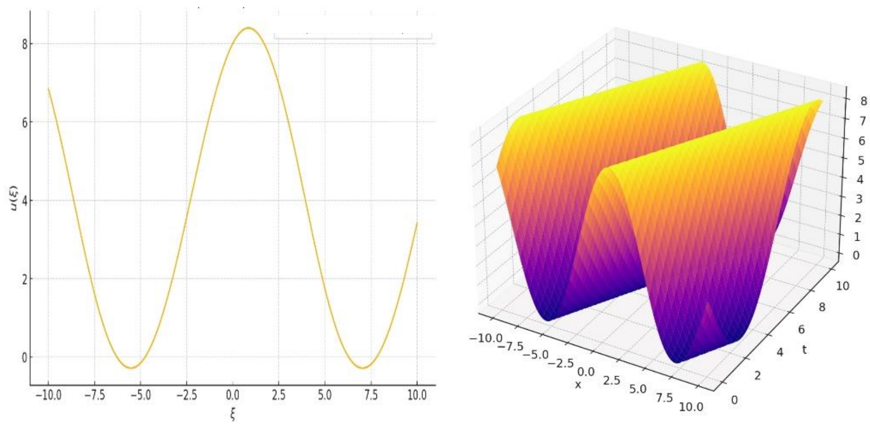

Figure 4. 2D and 3D graphs of equation (1) for the constants $\mathbf{A_1}$=0, $\mathbf{A_2}$=2, σ=1, μ=-1 in the equation (22).

4. Conclusion

In this study, analytical solutions for the Burger-Huxley equation have been obtained by applying the (G′/G, 1/G) expansion method. The method has been demonstrated as a powerful tool for solving nonlinear partial differential equations. The solutions obtained in the study help to better understand the physical and mathematical structure of the equation. In particular, the analytical solution of complex problems like the Burger-Huxley equation, which includes convection and reaction-diffusion terms, highlights the effectiveness and advantages of this method. The obtained 2D and 3D graphics visually present how the solution changes under different parameters and show the dynamic behavior of the equation. The (G′/G, 1/G) expansion method increases the accuracy of the solution and demonstrates its applicability to similar types of differential equations. The effects of the parameters used in the solution have also been visualized, which allows for more comprehensive analyses of different parameters in future studies. These findings may inspire the development of further analytical solutions for the Burger-Huxley equation and similar nonlinear differential equations, as well as the exploration of new solution methods. Further research can explore applying the technique to more general types of equations and refining computational accuracy.

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Conflict of Interest Statement

The author declare that they have no conflict of interest

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Research Article

Investigation of Travelling Wave Solutions for the (2+1)-Dimensional Ablowitz-Kaup-Newell-Segur Equation

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In this study, modified sub equation method was applied to the (2+1)-Ablowitz-Kaup-Newell-Segur (AKNS) equation. This analytical method, trigonometric, hyperbolic and rational type solutions have been produced. Contour, 3D and 2D graphs representing stationary wave are drawn by giving random values to the constants in these solutions. Using symbolic computation, this method is shown to be an effective, powerful and reliable tool for generating nonlinear evolution equations (NEDEs).

Keywords: Modified sub equation method; nonlinear evolution equation; exact solution.

Araştırma Makalesi

(2+1)-Boyutlu Ablowitz-Kaup-Newell-Segur Denklemi için Gezici Dalga Çözümlerinin İncelenmesi

Bu çalışmada, geliştirilmiş alt denklem yöntemi (2+1)-Ablowitz-Kaup-Newell-Segur (AKNS) denklemine uygulanmıştır. Bu analitik yöntemle trigonometrik, hiperbolik ve rasyonel tipte çözümleri üretilmiştir. Durağan dalgayı temsil eden kontur, 3 boyutlu ve 2 boyutlu grafikleri bu çözümlerdeki sabitlere rastgele değerler verilerek çizilir. Sembolik hesaplama kullanılarak, bu yöntemin doğrusal olmayan evrim denklemlerinin çözümlerini üretmek için etkili, güçlü ve güvenilir bir araç olduğu gösterilmiştir.

Anahtar Kelimeler: Geliştirilmiş alt denklem metodu; doğrusal olmayan evrim denklemi; tam çözüm.

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1. Introduction

Differential equations are used to describe complicated processes and systems in nature in many areas of mathematical modeling and applied sciences. Among these equations, NEDEs have an important place due to both their theoretical difficulties and practical importance. These equations, which are encountered in many disciplines from fluid dynamics to quantum physics and financial models, play an effective role in the analysis of nonlinear interactions and multivariable systems.

Many effective methods have been described to attain exact solutions of NEDEs. When the literature is reviewed, some of methods are: sech-tanh method [1], the functional variable method [2], Exp-function method [3], (G'/G)-expansion method [4], $(1/G')$- expansion method [5], [6], ansatz method [7], the sine-Gordon expansion method [8], extended Fan sub-equation method [9] and so on [10], [11], [12], [13], [14], [15], [16].

Traveling wave solutions obtained with these methods can be used in various application areas depending on the characteristics of the NEDEs studied.

We reviewed the travelling wave solutions of AKNS equation [17].

$$4u_{xt} + u_{xxxz} + 8u_{xz}u_x + 4u_z u_{xx} = 0. \tag{1}$$

This study aims to obtain a travelling wave solution for the AKNS equation using the analytical method. The analytical method used in the work is the modified sub-equation method. This analytical technique has not been applied to solve the AKNS equation before, so our solutions are completely new. This research is important for the application of the AKNS equation in modeling physical phenomena such as plasma physics, nonlinear optics and water waves [18].

Scientists have presented many studies in the literature regarding the AKNS equation. Some of them are as follows: In their work, Issasfa and Lin constructed rational solutions made up of rogue wave and lumped soliton solutions using the Bilinear method and the Ansatz technique [19]. In the study, the analytical and numerical techniques Khater II method and extended cubic-B-spline scheme have been taken into consideration in order to find wave solutions for the AKNS equation [20]. Alfalqi and Khater obtained solitary wave solutions in AKNS equation using modified exp-$\phi(\zeta)$ expansion method [21].

The rest of the article is as follows. The methodology of the method used is given in chapter 2. The applications of the considered method are given in chapter 3. Conclusions are given in the final chapter 4.

2. Modified sub-equation method

Let us consider this method to generate solutions to NEDEs [22]. Regard the NEDEs as

$$K(u, u_t, u_x, u_z, u_{xx}, \ldots) = 0. \tag{2}$$

Applying the wave transmutation

$$\xi = x + z - ct,\ u(x,z,t) = U(\xi) = u, \tag{3}$$

here c is speed of wave. Eq. (2) turns into ODE

$$H(U, U', -cU', U'', \ldots) = 0. \tag{4}$$

In the form, Eq. (4) is assumed to has

$$U(\xi) = a_0 + \sum_{i=1}^{s}\left(a_i\Phi^i(\xi) + a_{-i}\Phi^{-i}(\xi)\right), \tag{5}$$

solution. Here at least one of the coefficients “a_s” is nonzero. In here a_i, $(0 \le i \le s)$ are constants to be determined, $s \in \{1,2,3,...\}$ which is going to be found in Eq. (4) by balancing term is found considering principle of balance and solution of Riccati equation is $\Phi(\xi)$

$$\Phi'(\xi) = \mu + (\Phi(\xi))^2, \tag{6}$$

where μ is any constant. Some special solutions of the Riccati equation in (6) are given as follows.

$$\Phi(\xi) = \begin{cases} -\sqrt{-\mu}\tanh\left(\sqrt{-\mu}\xi\right), & \mu < 0 \\ -\sqrt{-\mu}\coth\left(\sqrt{-\mu}\xi\right), & \mu < 0 \\ \sqrt{\mu}\tan\left(\sqrt{\mu}\xi\right), & \mu > 0 \\ -\sqrt{\mu}\cot\left(\sqrt{\mu}\xi\right), & \mu > 0 \\ -\dfrac{1}{\xi + R}, & \mu = 0\ (R \text{ is a const.}) \end{cases}. \tag{7}$$

When we apply Eq. (6) and Eq. (5) to Eq. (4), we obtain a new polynomial depending on $\Phi(\xi)$; by placing this polynomial in the nonlinear algebraic system in $a_i, (i = 0,1,...,s)$, setting all coefficients to zero, we obtain $\Phi^i(\xi)$, $(i = 0,1,...,s)$. In order to reach the solution in such nonlinear systems, we need to determine the constants c, μ, R, a_i, $(i = 0,1,...,s)$. By means of these constants, we substitute the solutions of Eq. (6) into Eq. (4) together with the formula (7), thus obtaining the analytical solutions for Eq. (2).

3. Application of the method

Consider Eq. (1). We can transform Eq. (1) into a nonlinear ODE by implementing the $\xi = x + z - ct$ transformation.

$$-4cU' + U''' + 6(U')^2 = 0. \tag{8}$$

From the definition of the term balancing in Eq. (8), $s = 1$ is obtained and is written as follows according to Eq. (5).

$$U(\xi) = a_0 + a_1\Phi(\xi) + a_2\frac{1}{\Phi(\xi)}. \tag{9}$$

If Eq. (9) is placed in Eq. (8) and the required editing are done, the following equation systems may be written:

$$\begin{aligned} &(\Phi(\xi))^0: && -4c\mu a_1 + 2\mu^2 a_1 + 6\mu^2 a_1^2 + 4ca_2 - 2\mu a_2 - 24\mu a_1 a_2 + 6a_2^2 = 0, \\ &(\Phi(\xi))^2: && -4ca_1 + 8\mu a_1 + 12\mu a_1^2 - 12a_1 a_2 = 0, \\ &(\Phi(\xi))^4: && 6a_1 + 6a_1^2 = 0, \\ &\frac{1}{(\Phi(\xi))^2}: && 4c\mu a_2 - 8\mu^2 a_2 - 12\mu^2 a_1 a_2 + 12\mu a_2^2 = 0, \\ &\frac{1}{(\Phi(\xi))^4}: && -6\mu^3 a_2 + 6\mu^2 a_2^2 = 0. \end{aligned} \tag{10}$$

a_1, a_2 and c, μ constants are attained from Eq. (10) the system employing a software program.

Case 1: If

$$a_1 = -1, \quad a_2 = \mu, \quad c = -4\mu, \tag{11}$$

then substituting these values from (11) into (9), we obtain a hyperbolic solution to Eq. (1)

$$u_1(x,z,t) = -\frac{\mu \, coth\left[\sqrt{-\mu}\left(x+z+4t\mu\right)\right]}{\sqrt{-\mu}} + a_0 + \sqrt{-\mu}\, tanh\left[\sqrt{-\mu}\left(x+z+4t\mu\right)\right]. \tag{12}$$

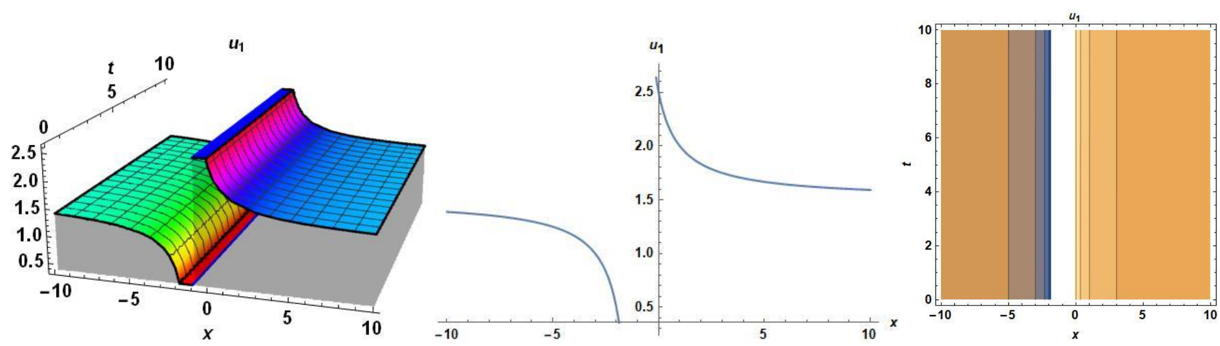

Figure 1. Graphics for $\mu = -0.0001, \quad a_0 = 1.5, \quad z = 1$ values of Eq. (12).

Case 2: If

$$a_1 = -1, \quad a_2 = \mu, \quad c = -4\mu, \tag{13}$$

then substituting these values from (13) into (9), we obtain a hyperbolic solution to Eq. (1)

$$u_2(x,z,t) = \sqrt{-\mu}\, coth\left[\sqrt{-\mu}\left(x+z+4t\mu\right)\right] + a_0 - \frac{\mu \, tanh\left[\sqrt{-\mu}\left(x+z+4t\mu\right)\right]}{\sqrt{-\mu}}. \tag{14}$$

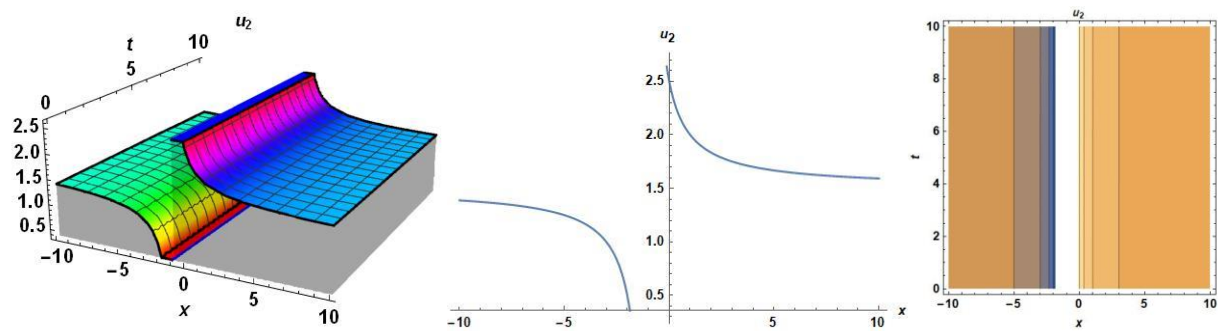

Figure 2. Graphics for $\mu = -0.0001, \quad a_0 = 1.5, \quad z = 1$ values of Eq. (14).

Case 3: If

$$a_1 = -1, \quad a_2 = \mu, \quad c = -4\mu, \tag{15}$$

then substituting these values from (15) into (9), we obtain a trigonometric solution to Eq. (1)

$$u_3(x,z,t) = a_0 - \sqrt{\mu}\, tan\left[\sqrt{\mu}\left(x+z+4t\mu\right)\right] + \sqrt{\mu}\, cot\left[\sqrt{\mu}\left(x+z+4t\mu\right)\right]. \tag{16}$$

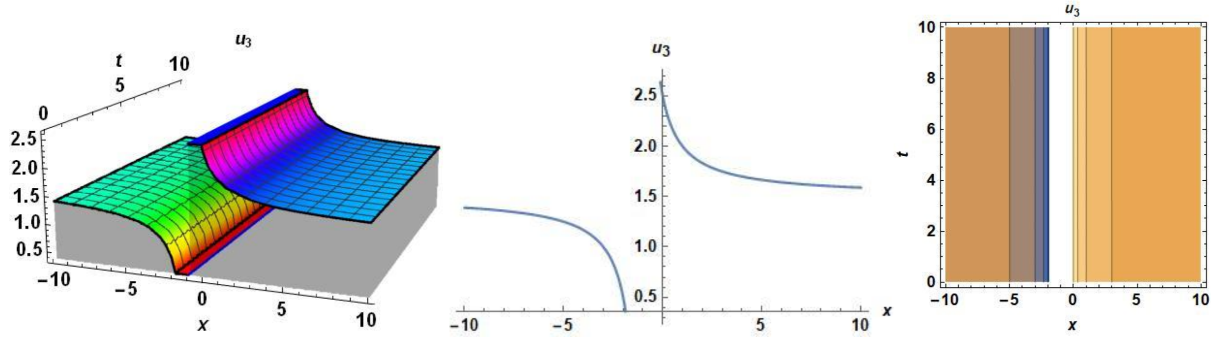

Figure 3. Graphics for $\mu = 0.0001, \quad a_0 = 1.5, \quad z = 1$ values of Eq. (16).

Case 4: If

$$\mu = 0, \quad a_1 = -1, \quad a_2 = \mu, \quad c = -4\mu, \tag{17}$$

then substituting these values from (17) into (9), we obtain a rational solution to Eq. (1)

$$u_4(x,z,t) = \frac{1}{r + x + z} + a_0. \tag{18}$$

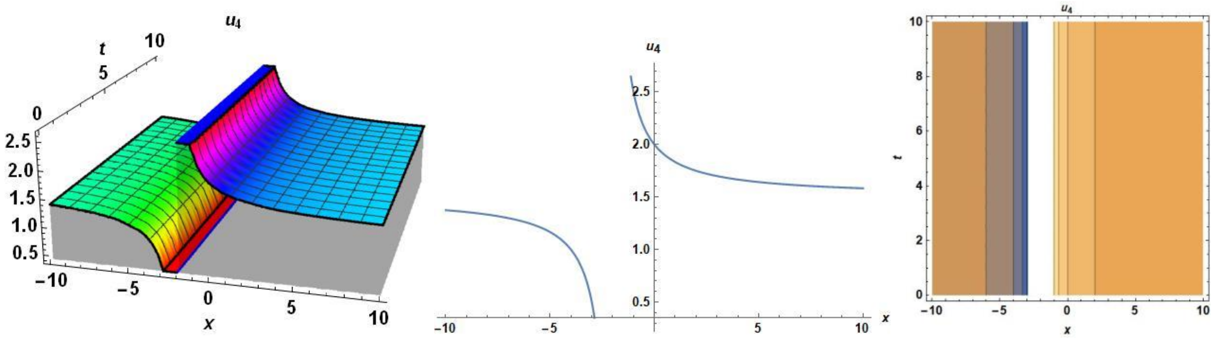

Figure 4. Graphics for $\mu = 0, \quad a_0 = 1.5, \quad r = 1, \quad z = 1$ values of Eq. (18).

Case 5: If

$$a_1 = -1, \quad a_2 = 0, \quad c = -\mu, \tag{19}$$

then substituting these values from (19) into (9), we obtain a hyperbolic solution to Eq. (1)

$$u_5(x,z,t) = a_0 + \sqrt{-\mu}\, tanh\left[\sqrt{-\mu}\left(x + z + t\mu\right)\right]. \tag{20}$$

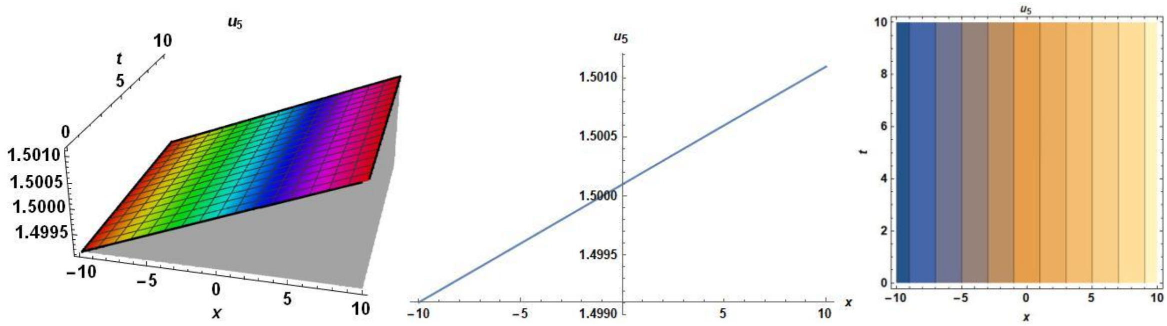

Figure 5. Graphics for $\mu = -0.0001, \quad a_0 = 1.5, \quad z = 1$ values of Eq. (20).

Case 6: If

$$a_1 = -1, \quad a_2 = 0, \quad c = -\mu, \tag{21}$$

then substituting these values from (21) into (9), we obtain a hyperbolic solution to Eq. (1)

$$u_6(x,z,t) = \sqrt{-\mu}\, coth\left[\sqrt{-\mu}\left(x + z + t\mu\right)\right] + a_0. \tag{22}$$

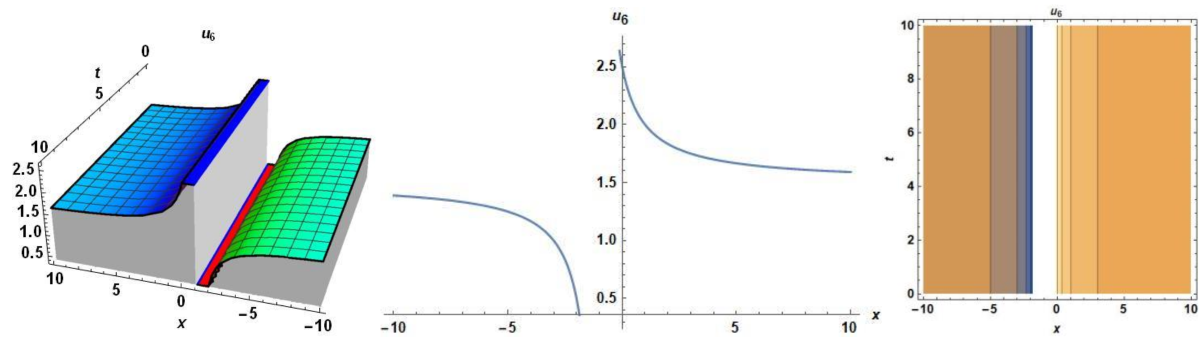

Figure 6. Graphics for $\mu = -0.0001, \quad a_0 = 1.5, \quad z = 1$ values of Eq. (22).

Case 7: If

$$a_1 = -1, \quad a_2 = 0, \quad c = -\mu, \tag{23}$$

then substituting these values from (23) into (9), we obtain a trigonometric solution to Eq. (1)

$$u_7(x,z,t) = a_0 - \sqrt{\mu}\, tan\left[\sqrt{\mu}\left(x + z + t\mu\right)\right]. \tag{24}$$

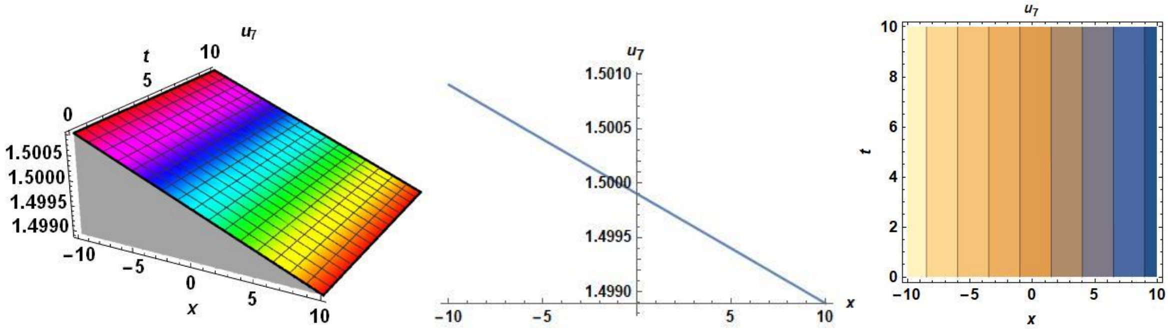

Figure 7. Graphics for $\mu = 0.0001, \quad a_0 = 1.5, \quad z = 1$ values of Eq. (24).

Case 8: If

$$a_1 = -1, \quad a_2 = 0, \quad c = -\mu, \tag{25}$$

then substituting these values from (25) into (9), we obtain a trigonometric solution to Eq. (1)

$$u_8(x,z,t) = a_0 + \sqrt{\mu}\, cot\left[\sqrt{\mu}\left(z + x + t\mu\right)\right]. \tag{26}$$

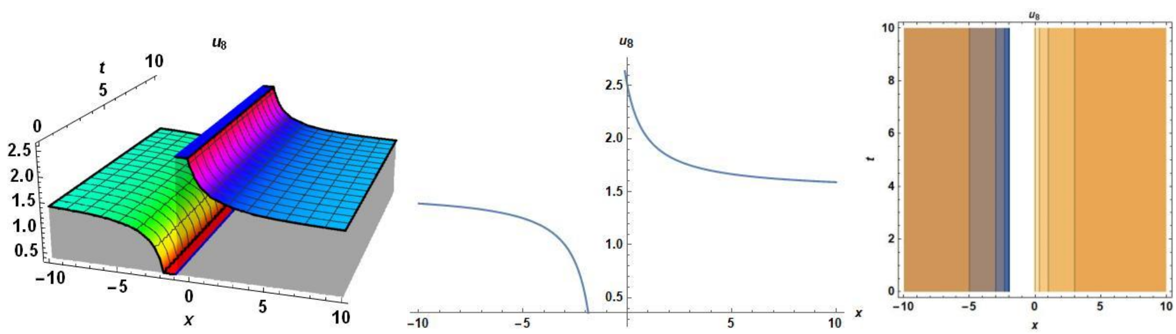

Figure 8. Graphics for $\mu = 0.0001, \quad a_0 = 1.5, \quad z = 1$ values of Eq. (26).

4. Conclusions

In this study, the modified sub equation method, which is the significant instrument used to attain the analytical solution of NEDEs, has been applied. As a consequence of this application, trigonometric, rational, hyperbolic solutions of AKNS equation were produced. The parameters in the solutions are given special values and visualized with contour, 3D and 2D graphics. When physical meanings are given to the constants, the scientific value of the results obtained increases even more. The prominent aspect of this method is that it can provide different and original solutions than other expansion methods. The applied approach has been found to be practical, reliable and suitable for future research. In addition, ready-made software packages have been used to reduce the complexity of the process.

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Conflict of Interest Statement

The author declares that she has no conflict of interest.

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