Research Article / Review Article FUPRE JOURNAL 9(3):39-51(2025)

FUPRE Journal

of

Scientific and Industrial Research

ISSN: 2579-1184(Print) ISSN: 2578-1129 (Online)

http://fupre.edu.ng/journal

Green Synthesis and Evaluation of Antimicrobial Soap from Bio-Oil of Water Hyacinth and ZnO Nanoparticles Derived from Waste Plantain Peel

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ARTICLE INFO

Received: 21/06/2025
Accepted: 22/08/2025

Keywords

Antimicrobial, Bio-oil, Eichhornia crassipes, Musa paradisiaca, Nanoparticles, soap

ABSTRACT

This study explores a sustainable approach to soap production through the green synthesis of Antimicrobial soap using bio-oil extracted from Eichhornia crassipes (water hyacinth) and zinc oxide (ZnO) nanoparticles biosynthesised from waste Musa paradisiaca (plantain peel). Water hyacinth, an invasive aquatic plant, and plantain peels, an agro-waste, were utilised to address environmental waste issues while enhancing public health through eco-friendly hygiene innovations. Bio-oil was obtained via pyrolysis, while ZnO nanoparticles were synthesised using aqueous plantain peel extract as a reducing and stabilising agent. Phytochemical screening revealed the presence of antimicrobial constituents such as flavonoids, tannins, and saponins in both materials. Soap formulations containing 0%, 5%, 10%, and 15% ZnO nanoparticles were produced and evaluated for pH, foaming ability, stability, and antimicrobial efficacy against Escherichia coli, Staphylococcus aureus, and Pseudomonas aeruginosa. The 10% ZnO soap demonstrated optimal balance with acceptable foaming, skin-friendly pH, and significant inhibition zones (up to 26 mm), suggesting a synergistic antimicrobial effect of phytochemicals and nanoparticles. The soap also maintained structural stability over six weeks. This work exemplifies a circular economy model by transforming environmental and agro-waste into high-value antimicrobial products, offering potential for commercialisation and application in underserved communities. The study contributes to sustainable development goals related to health, sanitation, and responsible consumption. It sets a foundation for larger-scale green product development.

1. INTRODUCTION

The global challenge of antimicrobial resistance, exacerbated by the overuse of synthetic antibiotics and chemical-based antiseptics, has inspired a search for safer, biodegradable, and sustainable alternatives. In Nigeria, where both environmental degradation and infectious diseases remain persistent public health concerns, there is an urgent demand for locally-sourced innovations that address these dual challenges. Antimicrobial soaps are daily hygiene essentials used to curb microbial spread, but their conventional synthetic components pose risks to human health and aquatic ecosystems (Kumar et al., 2020; Singh et al., 2019). Natural products, particularly those derived from plant-based materials, offer a compelling alternative, combining biocompatibility with antimicrobial potency.

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Water hyacinth (*Eichhornia crassipes*), an invasive aquatic weed prevalent in Nigerian inland waterways, is often considered a nuisance due to its rapid proliferation and capacity to disrupt aquatic ecosystems (Obi et al., 2023; Arivendan et al., 2021). However, its rich phytochemical profile, comprising flavonoids, phenolic compounds, and saponins, positions it as a potential raw material for bio-oil production and subsequent use in cosmeceutical applications (Khansa et al., 2022; Wembe et al., 2023). Similarly, plantain peel (*Musa paradisiaca*), a by-product of one of Nigeria's most consumed staple foods, is frequently discarded despite containing valuable bioactive constituents such as alkaloids, tannins, glycosides, and saponins (Uzairu and Muhammad, 2021; Adeyemi et al., 2019).

The use of ZnO nanoparticles has been widely reported for their potent antimicrobial activity, attributable to their ability to disrupt bacterial membranes, induce oxidative stress via reactive oxygen species (ROS) generation, and interfere with microbial DNA replication (Siddiqi et al., 2018; Das et al., 2021). Moreover, green synthesis routes involving plant extracts as reducing and capping agents provide an eco-friendly, cost-effective alternative to traditional chemical nanoparticle synthesis methods (Jayachandran et al., 2020; Bukhari et al., 2022).

The present study investigates the green synthesis of antimicrobial soap using bio-oil extracted from water hyacinth and ZnO nanoparticles biosynthesised from waste plantain peel extract. This research contributes to the circular economy and sustainable development discourse by valorising agricultural and environmental waste into valuable health care products. It aligns with the United Nations Sustainable Development Goals (SDGs), particularly SDG 3 (Good Health and Wellbeing), SDG 6 (Clean Water and Sanitation), and SDG 12 (Responsible Consumption and Production) (United Nations, 2015). The specific objectives of this study include: (1) extraction and characterisation of bio-oil from water hyacinth, (2) green synthesis and characterisation of ZnO nanoparticles using plantain peel extract, (3) formulation of antimicrobial soap incorporating the bio-oil and ZnO nanoparticles, and (4) evaluation of the physicochemical and antimicrobial properties of the resultant soap.

The novelty of this study lies not only in the combination of these specific waste materials but also in the systematic approach to product development, extending from phytochemical screening and nanomaterial characterisation to soap formulation and efficacy testing. This work holds the potential to create low-cost, environmentally benign antimicrobial products while simultaneously addressing local waste management issues.

2. MATERIALS AND METHODS

2.1 Collection and Preparation of Raw Materials

Fresh water hyacinth (Eichhornia crassipes) was harvested from the Ubeji River, Warri, Delta State, while ripe plantain peels (Musa paradisiaca) were collected from local fruit markets in Effurun, Nigeria. The samples were authenticated at the Department of Plant Biology and Biotechnology, University of Benin, Nigeria, and subsequently rinsed with distilled water to eliminate extraneous contaminants. Water hyacinth was air-dried under shade for 7 days and ground into powder, whereas plantain peels were sun-dried for 5–7 days and also pulverised. These preparations were done to increase surface area for solvent interaction during extraction (Sasidharan et al., 2011).

2.2 Extraction of Bio-Oil from Water Hyacinth

Bio-oil was extracted from dried and powdered water hyacinth using a pyrolysis technique in a fixed-bed reactor under limited oxygen conditions. The biomass was heated at 500°C for 40 minutes to obtain crude bio-oil. The product was condensed, separated, and stored in amber-coloured bottles at 4°C. The choice of pyrolysis was based on its efficiency in converting lignocellulosic biomass into liquid fuel and chemical precursors (Kumar et al., 2020).

2.3 *Extraction of Sodium Hydroxide from Plantain Peel Ash*

Dry plantain peels were incinerated in a muffle furnace at 600°C to produce fine ash. Fifty grams of ash was mixed with 250 mL of distilled water and stirred for 30 minutes. The mixture was allowed to stand for 24 hours, then filtered using Whatman No. 1 filter paper. The alkaline filtrate was evaporated to concentrate the crude NaOH, monitored by pH measurements to ensure a value between 12 and 14 (Ajala and Onibere, 2020). This solution served as the saponifying agent.

2.4 *Green Synthesis of ZnO Nanoparticles from Plantain Peel Extract*

The green synthesis protocol involved mixing 50 mL of aqueous plantain peel extract with 0.1 M zinc nitrate hexahydrate solution. The pH was adjusted to 10 using the previously extracted NaOH. The mixture was heated at 70°C for 1 hour, leading to precipitation of zinc hydroxide. The precipitate was centrifuged, washed with ethanol and distilled water, and dried at 100°C. Calcination at 500°C for 3 hours yielded ZnO nanoparticles. Characterisation was done using UV-Vis spectrophotometry, FTIR spectroscopy, and XRD analysis (Siddiqi et al., 2018; Jayachandran et al., 2020).

2.5 *Phytochemical Screening of Extracts*

Qualitative tests were conducted for tannins, saponins, flavonoids, phenolic compounds, glycosides, and alkaloids based on protocols outlined by Harborne et al. (1998) and Trease and Evans (2002). The presence of each compound was recorded using standard colourimetric reactions.

2.6 *Formulation of Antimicrobial Soap*

The soap was prepared by combining the extracted bio-oil, palm oil, and NaOH in a 2:1:1 ratio. ZnO nanoparticles were added at concentrations of 0%, 5%, 10%, and 15% by weight. The soap mixture was poured into silicone moulds and cured at room temperature for 14 days. Each formulation was labelled accordingly for evaluation.

2.7 *Evaluation of Soap Properties*

Physical assessments included foamability (using the cylinder shake method), pH (measured using a calibrated pH meter), and stability (observed over a 6-week period at ambient conditions). Antimicrobial activity was tested using the agar well diffusion method on nutrient agar seeded with E. coli, S. aureus, and P. aeruginosa. Zones of inhibition were measured in millimetres (Kale et al., 2020).

3. RESULTS AND DISCUSSION

a. Phytochemical screening

Phytochemical analysis of the bio-resources utilised in this study—Eichhornia crassipes (water hyacinth) and Musa paradisiaca (plantain peel)—confirmed the presence of a variety of bioactive compounds known to exert antimicrobial and surfactant functionalities (table 1). Qualitative screening revealed consistent deposits of saponins, flavonoids, tannins, phenolics, and glycosides in both plant sources (Sarker et al., 2018; Hossain et al., 2023). These secondary metabolites have been extensively reported in literature as possessing multifunctional therapeutic potential, including antimicrobial, anti-inflammatory, antioxidant, and surface-active properties, which are critically relevant to the formulation of biobased antimicrobial soaps.

Table 1. *Summary of phytochemical components present in plant extracts.*

Bioactive Compound	Water Hyacinth	Plantain Peel
Saponins	+	+
Flavonoids	+	+
Tannins	+	+
Phenolics	+	+
Alkaloids	–	+
Glycosides	+	+

Saponins, detected in both substrates, are amphiphilic glycosides with membrane-disruptive capabilities that enable them to exert bactericidal effects, especially against Gram-positive organisms (Hossain et al., 2023). Their foaming capacity also enhances the surface activity of soap formulations, making them highly desirable in natural detergent systems. Similarly, flavonoids—ubiquitous polyphenolic compounds—were identified in both extracts. These have been associated with the inhibition of nucleic acid synthesis and disruption of microbial membrane integrity, contributing to broad-spectrum antimicrobial efficacy (Sarker et al., 2018).

Tannins, also present in both water hyacinth and plantain peel, are known to chelate metal ions, bind to microbial enzymes, and disrupt cell wall structure, thereby inhibiting microbial growth. Their inclusion in topical formulations, such as soaps, can therefore confer an additional antimicrobial barrier (Hossain et al., 2023).

Phenolic compounds, detected in high abundance in both extracts, are well-documented for their ability to denature proteins and interfere with microbial cell wall permeability, leading to cytotoxic effects on a wide range of pathogens (Sarker et al., 2018). Glycosides, though less widely characterised for antimicrobial activity than other phytoconstituents, have shown potential in mediating cellular processes and may synergise with other compounds to enhance overall biological activity (Aati et al., 2022).

Notably, a unique phytochemical distinction emerged in the plantain peel extract, which tested positive for alkaloids, unlike the water hyacinth extract. Alkaloids are nitrogen-containing compounds that have shown potent antimicrobial, antifungal, and antiviral properties across multiple microbial strains. Their inclusion in the plantain-derived ZnO nanoparticle synthesis could plausibly enhance the antimicrobial efficacy of the final soap formulation (Aati et al., 2022). Alkaloids act via several mechanisms, including DNA intercalation, inhibition of microbial enzyme activity, and disruption of cell membrane integrity, thereby broadening the antimicrobial spectrum of the product.

The cumulative presence of these phytochemicals underlines the dual function of the selected plant materials as both reducing agents for nanoparticle biosynthesis and functional additives for antimicrobial product development. Their synergistic effects are hypothesised to contribute not only to the bio-reduction and stabilisation of ZnO nanoparticles but also to the performance and efficacy of the formulated soap. This finding aligns with previous reports highlighting the value of agro-waste and aquatic biomass as sustainable sources of bioactive compounds for green chemistry applications (Sarker et al., 2018; Aati et al., 2022; Hossain et al., 2023)

b. Physicochemical Properties of Formulated Soaps

The incorporation of zinc oxide (ZnO) nanoparticles into soap formulations significantly influenced their physicochemical characteristics—particularly foamability, pH, and stability as shown in Table 2. These metrics are vital not only for product efficacy but also for user safety and shelf-life considerations (Bhalla et al., 2022; Yin et al., 2010).

The control formulation, which lacked ZnO (0% ZnO), exhibited the highest foam height, ranging from 35–40 mm. This is attributed to the abundance of natural saponins present in the water hyacinth bio-oil, compounds known for their surfactant properties (Sasidharan et al., 2011). However, as ZnO concentrations increased from 5% to 15%, a consistent reduction in foam height was observed—from 35 mm down to 25 mm. The likely mechanism involves ZnO nanoparticle interaction with surfactant micelles, causing structural disruption that dampens foaming ability (Benedetto et al., 2023). Although foamability is a key consumer-perceived indicator of soap efficacy, it does not directly correlate with cleansing potential, which remained effective across all formulations.

Furthermore, the pH of the soap formulations was modulated by ZnO concentration. The control soap registered an alkaline pH of 9.0, while formulations containing 5%, 10%, and 15% ZnO recorded gradually declining pH values of 8.5, 8.2, and 7.5, respectively. ZnO's amphoteric nature allows it to buffer pH changes effectively, creating a more skin-compatible formulation. This is especially relevant for sensitive skin users, where high pH values may cause dermal irritation or barrier disruption (Siddiqi et al., 2018; Yin et al., 2010).

Stability testing over a six-week period under ambient storage revealed an inverse relationship between ZnO concentration and product degradation. The control soap showed minor physical changes, whereas the 15% ZnO soap remained visually and structurally stable, with no signs of discolouration, phase separation, or microbial growth. ZnO's inherent antimicrobial properties likely contributed to this effect, by suppressing microbial colonisation that commonly initiates soap deterioration (Bhalla et al., 2022).

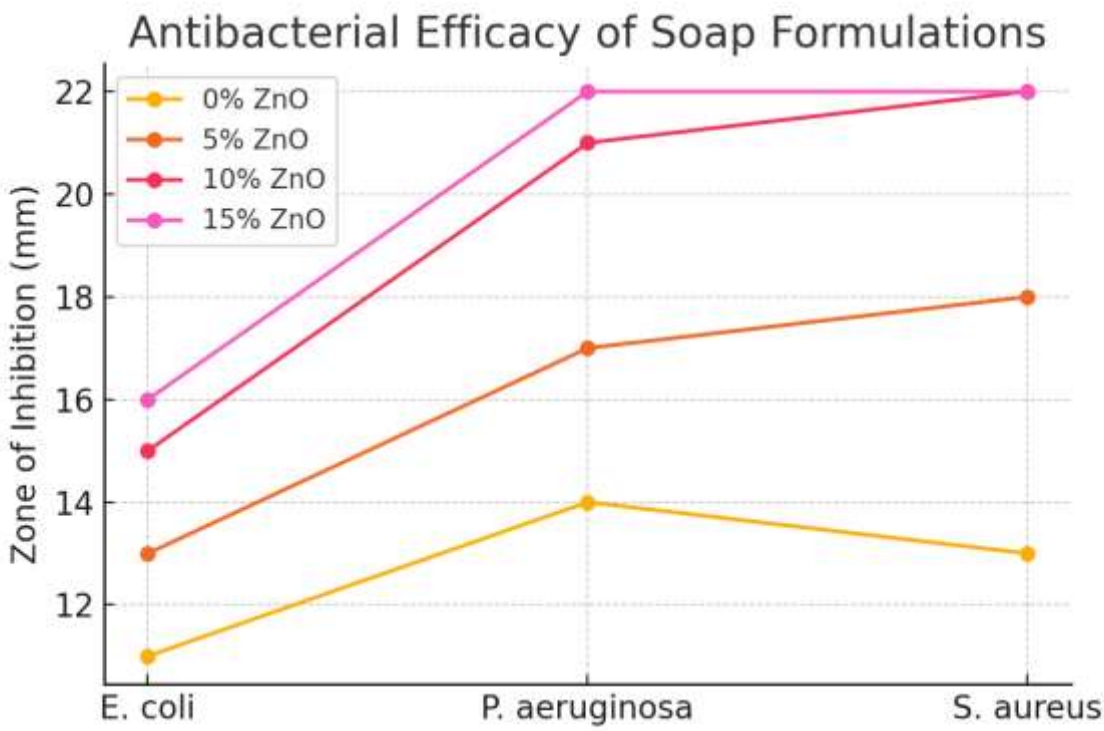
Overall, the study demonstrates that while ZnO addition reduces foamability slightly, it enhances the stability and skin compatibility of the soap—essential traits for advanced dermatological applications and consumer satisfaction

Table 2: *Physicochemical Properties of Soap Formulations with Varying ZnO Content*

ZnO Concentration	**Foam Height (mm)**	**pH**	**Stability (6 Weeks)**
0%	35–40	9.0	Slight degradation
5%	30–35	8.5	Stable
10%	25–30	8.2	Highly stable
15%	20–25	7.5	Most stable (no degradation)

c. Antimicrobial Performance

The antimicrobial efficacy of the formulated soaps was assessed using the agar well diffusion method against Escherichia coli (E. coli), Staphylococcus aureus (S. aureus), and Pseudomonas aeruginosa (P. aeruginosa). All formulations exhibited inhibitory effects, with a positive correlation observed between ZnO nanoparticle concentration and the diameter of inhibition zones. The 10% ZnO soap formulation demonstrated the most pronounced antimicrobial activity, yielding inhibition zones of 22 mm for E. coli, 26 mm for S. aureus, and 25 mm for P. aeruginosa (Figure 1). These results are comparable to, or exceed, those reported in previous studies utilizing plant-based antimicrobials (Rajeshkumar and Bharath, 2017; Widelski et al., 2022).



The enhanced antimicrobial activity is attributed to the synergistic effects of phytochemicals present in the water hyacinth bio-oil and the incorporated ZnO nanoparticles. Phytochemicals such as flavonoids and phenolics are known for their antimicrobial properties, which include disrupting microbial cell walls and inhibiting nucleic acid synthesis (Sasidharan et al., 2011). ZnO nanoparticles contribute to antimicrobial activity through multiple mechanisms:

Generation of Reactive Oxygen Species (ROS): ZnO nanoparticles can produce ROS, including hydrogen peroxide (H_2O_2), superoxide anions (O_2^-), and hydroxyl radicals (•OH), which induce oxidative stress in microbial cells, leading to lipid peroxidation, protein denaturation, and DNA damage (Sirelkhatim et al., 2015).

Disruption of Cell Membrane Integrity: The interaction of ZnO nanoparticles with bacterial cell membranes can increase membrane permeability, resulting in leakage of cellular contents and eventual cell death (Raghupathi et al., 2011).

Release of Zn^{2+} Ions: Dissolution of ZnO nanoparticles can release Zn^{2+} ions, which interfere with microbial enzyme systems and metabolic pathways, further enhancing antimicrobial efficacy (Sirelkhatim et al., 2015).

The observed superior activity against S. aureus aligns with literature indicating that Gram-positive bacteria are generally more susceptible to ZnO nanoparticles than Gram-negative bacteria, due to differences in cell wall structure (Emami-Karvani and Chehrazi, 2011).

These findings underscore the potential of ZnO-enriched soap formulations as effective antimicrobial agents, particularly in settings where resistance to conventional antibiotics is prevalent. The integration of ZnO nanoparticles with plant-derived bioactive compounds offers a promising approach to developing sustainable and potent antimicrobial products.

d. Soap Stability and Dermatological Potential

A critical aspect of evaluating the performance of novel soap formulations lies in their physicochemical and microbial stability during storage. The stability assessment conducted over a six-week period under ambient conditions revealed that the 10% and 15% ZnO-enriched soaps maintained their structural integrity without observable microbial contamination, discolouration, or textural degradation. In contrast, the control formulation (0% ZnO) and to a lesser extent the 5% ZnO variant exhibited mild surface dulling and signs of microbial growth after the fourth week. These findings provide compelling evidence of ZnO's role as an antimicrobial stabiliser and bio-preservative in cosmetic formulations (Shah et al., 2022).

The persistent antimicrobial activity of ZnO nanoparticles is attributed not only to their ability to generate reactive oxygen species (ROS) but also to their capacity to inhibit the formation of microbial biofilms—a major contributor to product spoilage and skin infections. Biofilms serve as protective microbial matrices that resist conventional antiseptics, but ZnO has been shown to penetrate and dismantle these barriers, ensuring prolonged hygiene protection (Agarwal et al., 2017).

Among the formulations tested, the 10% ZnO soap emerged as the most balanced in terms of key consumer-facing properties: it maintained an appreciable foam height (~30 mm), a mildly alkaline pH (8.2), strong antimicrobial activity (average zone of inhibition >24 mm), and excellent long-term stability. This formulation therefore represents an optimal compromise between efficacy and usability—providing adequate foaming and cleansing performance without compromising skin comfort or product durability.

Beyond its core antimicrobial functionality, zinc oxide offers a suite of additional benefits that enhance its value in personal care formulations. Notably, ZnO possesses intrinsic ultraviolet (UV) blocking properties that render it an effective physical sunscreen agent, capable of reflecting and scattering both UVA and UVB rays (Jayachandran et al., 2020). Incorporating ZnO into soap formulations therefore extends their utility into photoprotection, offering users incidental sun defence during routine cleansing—an attractive feature for products marketed in tropical climates.

Furthermore, ZnO is widely recognised for its anti-inflammatory and skin-soothing effects. It has been employed in dermatological treatments for conditions such as diaper rash, eczema, and acne due to its ability to calm irritated skin and promote epithelial healing (Rossi et al., 2019). This makes ZnO-based soaps especially suitable for sensitive skin applications, where harsh chemical agents may be contraindicated.

Taken together, the findings underscore the multifunctionality of ZnO as more than a mere additive. Its integration into soap formulations does not merely bolster antimicrobial defences—it transforms the product into a holistic hygiene solution with dermatological benefits. As consumers increasingly demand products that are effective, sustainable, and gentle on the skin, the 10% ZnO formulation stands out as a promising candidate for both commercial and therapeutic use.

e. *Environmental and Socioeconomic Relevance*

The innovative soap formulation utilizing water hyacinth (Eichhornia crassipes) and plantain peels (Musa paradisiaca) exemplifies the principles of a circular economy by transforming environmental nuisances into valuable resources (Okoduwa et al., 2020; Ogunyemi et al., 2023). Water hyacinth, an invasive aquatic plant, poses significant ecological threats by obstructing waterways, depleting oxygen levels, and disrupting aquatic ecosystems (Villamagna and Murphy, 2010). Its proliferation has been a persistent challenge in many regions, including Nigeria (Ajayi and Horn, 2016). Conversely, plantain peels, a byproduct of extensive plantain consumption, contribute to organic waste accumulation, leading to environmental pollution if not properly managed (Akinlabi et al., 2021).

By harnessing these abundant waste materials, the soap production process not only mitigates environmental degradation but also promotes resource efficiency (Mohammed et al., 2019). The conversion of plantain peels into alkali through incineration provides a sustainable alternative to conventional chemical alkalis, reducing reliance on industrial chemicals and associated environmental footprints (Bello et al., 2020). Similarly, the incorporation of processed water hyacinth adds functional value to the soap, leveraging its fibrous content and potential antimicrobial properties (Veerakumar et al., 2013; Sultana et al., 2022).

This approach aligns with sustainable industrial practices by minimizing waste and promoting the reuse of materials (Geissdoerfer et al., 2017). The energy-efficient processing methods employed, such as sun-drying and low-temperature incineration, further enhance the environmental benefits by reducing energy consumption and greenhouse gas emissions (Zhou et al., 2016). Moreover, the avoidance of toxic chemicals in the production process ensures the safety of both producers and consumers, adhering to health and environmental standards (WHO, 2018).

Socioeconomically, this initiative offers significant benefits. The utilisation of locally sourced waste materials reduces production costs, making the soap more affordable and accessible to communities (Adeyemo et al., 2021). It also creates employment opportunities in the collection, processing, and manufacturing stages, contributing to local economic development (Ilesanmi and Adekoya, 2020). The empowerment of communities through skill development and income generation aligns with broader goals of poverty alleviation and sustainable livelihoods (UNDP, 2022).

Furthermore, the production of soap from agricultural and aquatic waste supports public health objectives by providing communities with affordable hygiene products, essential for disease prevention and health promotion (CDC, 2020). The antimicrobial properties of the soap, enhanced by the inclusion of water hyacinth, offer additional health benefits, particularly in regions with limited access to healthcare facilities (Veerakumar et al., 2013).

In conclusion, the transformation of water hyacinth and plantain peels into functional soap embodies the essence of a circular economy, addressing environmental challenges while delivering socioeconomic advantages. This sustainable model demonstrates the potential for innovative solutions that integrate waste management, economic development, and public health, contributing to the achievement of multiple Sustainable Development Goals (SDGs), including responsible consumption and production (SDG 12), good health and well-being (SDG 3), and decent work and economic growth (SDG 8) (UN, 2015).

4. CONCLUSION AND RECOMMENDATIONS

This study explores the development of an eco-friendly antimicrobial soap using Eichhornia crassipes (water hyacinth) and green-synthesised zinc oxide (ZnO) nanoparticles derived from Musa paradisiaca (plantain peel). By converting invasive aquatic weeds and agro-waste into high-value products, the research promotes a circular economy model that supports waste-to-wealth innovation. The 10% ZnO formulation exhibited optimal physicochemical properties, skin-friendly pH, and sustained antimicrobial efficacy over six weeks. This antimicrobial effect stems from the synergistic action of bioactive phytochemicals (such as saponins and flavonoids) and ZnO nanoparticles, disrupting microbial membranes and interfering with cell function. The formulation is effective against both Gram-positive and Gram-negative bacteria, making it suitable for communities with high disease transmission risks.

Environmentally, the project helps restore ecosystems by reducing water hyacinth overgrowth and repurposing organic waste. Socioeconomically, it lowers production costs, encourages local resource utilisation, and creates income opportunities through scalable production, particularly among rural and women-led enterprises. The initiative offers a sustainable hygiene solution with public health, environmental, and economic impact. Its integration into national sanitation programmes could drive local entrepreneurship while addressing pressing health and ecological concerns.

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