



## COMPARATIVE ANTIBACTERIAL EFFICACY OF AGRICULTURAL WASTE-DERIVED PHYTOCHEMICAL EXTRACTS FROM *Musa paradisiaca*, *Manihot esculenta* Peels, and *Acacia nilotica* SEEDS AGAINST MULTIDRUG-RESISTANT ENVIRONMENTAL BACTERIAL ISOLATES

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### ABSTRACT

Antimicrobial resistance poses a severe global health threat, with projections indicating 39 million deaths between 2025 and 2050. Waste water systems are major reservoirs for resistant bacteria promoting their spread. Agricultural waste offers a promising, sustainable source for developing antimicrobial agents. This study examined the antibacterial activity of ethanolic and methanolic extracts from *Musa paradisiaca* (banana) peel, *Manihot esculenta* (cassava) peel, and *Acacia nilotica* seeds against bacterial isolates from industrial and domestic waste water in Oyo State, Nigeria. Fifty-six bacterial isolates were obtained using standard microbiological methods. Plant materials underwent cold maceration extraction with ethanol and methanol (1:4 w/v) for 48 hours. Antibacterial effectiveness was evaluated through agar well diffusion assay, minimum inhibitory concentration testing, and antibiotic susceptibility profiling following CLSI M100-34 guidelines. Recovered isolates included *Bacillus* spp. (42.9%), *Pseudomonas* spp. (28.6%), *Proteus* spp. (14.3%), *Enterobacter* spp. (10.7%), and *Salmonella* spp. (3.6%). Methanolic *M. paradisiaca* extract showed superior antibacterial activity with mean inhibition zones of  $18.6 \pm 2.8$  to  $22.4 \pm 3.2$  mm, compared to *M. esculenta* ( $16.2 \pm 2.0$  to  $18.2 \pm 2.4$  mm) and *A. nilotica* ( $14.2 \pm 1.8$  to  $16.4 \pm 2.1$  mm). The lowest MIC value (0.0625 g/mL) was achieved with methanolic *M. paradisiaca* extract. Strong positive correlations between extract activity and quinolone susceptibility ( $r = 0.78-0.82$ ,  $p < 0.01$ ) suggest DNA gyrase-targeting mechanisms. These findings demonstrate that agricultural waste-derived phytochemicals, especially methanolic banana peel extract, possess substantial antibacterial potential against multidrug-resistant environmental bacteria, supporting agricultural waste valorisation for sustainable antimicrobial development and waste water treatment.

**Keywords:** Multidrug-Resistant Bacteria, Waste Water

### INTRODUCTION

Antimicrobial resistance (AMR) is still one of the greatest critical threats to universal public health in the current century. According to the Global Antimicrobial Resistance and Use Surveillance System (GLASS) Account, antimicrobial resistance continues to threaten global health security (WHO, 2024). A comprehensive systematic analysis published in *The Lancet* projected that AMR-instigated deaths could climb to 39 million between 2025 and 2050 without significant intervention, with the greatest weight falling on low- and middle-income countries (Naghavi *et al.*, 2024). In sub-Saharan Africa, the weightiness of AMR is particularly severe, reflecting healthcare infrastructure limitations and the need for innovative containment strategies (Anyaeibunam *et al.*, 2024).

Waste water systems, particularly those receiving industrial and domestic effluents, have been recognised as critical ecological pools for antimicrobial-resistant bacteria (ARB) and antimicrobial resistance genes (ARGs). A systematic review of hospital waste water in West Africa revealed alarming prevalence rates of extended-spectrum  $\beta$ -lactamase (ESBL)-producing organisms and carbapenemase producers (Hotor *et al.*, 2025). Studies from Ethiopia have similarly documented high rates of multidrug-resistant bacteria in waste water treatment facilities (Adugna & Sivalingam, 2022). In Nigeria, a high prevalence of carbapenem-producing *Pseudomonas aeruginosa* has been reported from tertiary healthcare facilities (Olaniran *et al.*, 2021; Olalekan *et al.*, 2023). A systematic appraisal and meta-analysis of

carbapenem-resistant Enteric organisms in West Africa further underscores the regional AMR burden (Somda *et al.*, 2024).

The limitations of conventional antibiotics, including increasing resistance rates, adverse effects, and high costs, have catalysed research interest in plant-derived antimicrobials as complementary or alternative therapeutic agents. Medicinal plants have always served as primary sources of bioactive compounds, with an estimated 25-50% of pharmacological drugs derived indirectly or directly from botanical sources (Hikal *et al.*, 2022). Phytochemicals generally, including alkaloids flavonoids, tannins, saponins, and phenolic compounds, have proven significant antimicrobial potential through multiple mechanisms, including membrane disruption, enzyme inhibition, and interference with nucleic acid synthesis (Mohidin *et al.*, 2023). *Musa paradisiaca* L. (banana) is among the most commonly cultivated and consumed fruits universally, with yearly production exceeding 150 million metric tons. The peel, constituting approximately 30-40% of fruit weight, is typically discarded as agricultural waste despite containing substantial concentrations of bioactive compounds, including gallic acid, catechin, dopamine, and various flavonoid glycosides. A comprehensive appraisal by Hikal *et al.* (2022) documented the extensive pharmacological potential of banana peels, while HPLC analysis has identified specific phenolic and flavonoid constituents responsible for antimicrobial activity (Behiri *et al.*, 2019). Previous studies have demonstrated antibacterial action of banana peel extracts against both

Gram-positive and Gram-negative bacteria (Sirajudin *et al.*, 2014; Kapadia *et al.*, 2015). Recent research has shown enhanced antibacterial activity following purification of *M. paradisiaca* methanolic peel extracts (Jastria *et al.*, 2024). Jaleel *et al.* (2024) provided an all-inclusive review of the nutrient profile and medicinal benefits of this species.

*Manihot esculenta* Crantz (cassava) represents a staple food crop for over eight hundred million people worldwide, particularly in sub-Saharan Africa. The peel, comprising 10-20% of tuber weight, contains cyanogenic glucosides alongside pharmacologically relevant mixtures including flavonoids, saponins, and tannins with documented antimicrobial and antioxidant properties. A systematic review by Mohidin *et al.* (2023) comprehensively documented the pharmacological activities, traditional uses, and phytochemistry of cassava. Mustarichie *et al.* (2020) demonstrated antibacterial activity of cassava leaf extracts against clinical isolates of *Staphylococcus epidermidis* and *Propionibacterium acnes*. Lima *et al.* (2017) reported the efficacy of cassava extracts against antibiotic-resistant bacteria. More recently, Mulia *et al.* (2023) evaluated the antibacterial activity of cassava peel ethanol extract against the fish pathogen *Aeromonas hydrophila*, while Fariska *et al.* (2024) investigated antibacterial activities of endophytic bacteria from cassava leaves.

*Acacia nilotica* (L.) Delile, known locally as "bagaruwa" in Nigeria, has extensive ethnomedicinal applications across Africa and Asia for treating infectious diseases, gastrointestinal disorders, and inflammatory conditions. The seeds and pods are particularly rich in tannins (18-28%), including gallotannins and condensed tannins, which exhibit potent antimicrobial activity through protein precipitation and membrane disruption mechanisms (Jodi *et al.*, 2020). Sadiq *et al.* (2017) investigated the antibacterial activities and possible modes of action of *A. nilotica* against multidrug-resistant *Escherichia coli* and *Salmonella*. Aliero *et al.* (2024) reported antimicrobial activities of bioactive compounds isolated from *A. nilotica* against multidrug-resistant bacteria. Idrees *et al.* (2024) conducted *in vivo* and *in silico* evaluations of *A. nilotica* pods for antimicrobial properties, while Ahmed *et al.* (2024) assessed antimicrobial activity against Gram-positive bacteria in Sudan. Abdel-Tawab *et al.* (2023) demonstrated antimicrobial activities of dietary bioactive lipid compounds from *A. nilotica* bark.

Despite the documented antimicrobial potential of these plant materials individually, comparative studies evaluating their efficacy against environmental bacterial isolates from waste water sources remain limited, particularly within the Nigerian context. This study aimed to systematically compare the antibacterial efficacy of ethanolic and methanolic extracts from *M. paradisiaca* peel, *M. esculenta* peel, and *A. nilotica* seeds against bacterial isolates recovered from industrial and domestic waste water in Oyo State, Nigeria. The results help to comprehend the potential of agricultural waste valorisation for sustainable antimicrobial development and waste water bioremediation in countries or areas with limited resources. It was hypothesised that ethanolic and methanolic extracts from *M. paradisiaca* peel, *M. esculenta* peel, and *A. nilotica* seeds would demonstrate significant and differential antibacterial activity against multidrug-resistant environmental bacterial isolates recovered from waste water, with methanolic extracts exhibiting greater efficacy due to their superior polarity and extraction of bioactive compounds.

## MATERIALS AND METHODS

### Study Design and Ethical Considerations

This laboratory-based experimental study was carried out at the Microbiology and Biotechnology Laboratory, Ajayi Crowther University, Oyo, Nigeria, between January and June 2025. As the study involved environmental samples and did not include human subjects, institutional ethical approval was not required. However, all laboratory procedures adhered to established biosafety guidelines for handling potentially pathogenic microorganisms.

### Collection and Preparation of Plant Materials

Fresh *Musa paradisiaca* (banana) peels were collected from fruit vendors at Ajegunle Market, Oyo. *Manihot esculenta* (cassava) peels were obtained from cassava processing facilities in Apitipiti, Oyo. *Acacia nilotica* seeds were purchased from traditional medicine vendors at Akesan Market, Oyo. All plant materials were authenticated by a taxonomist at the Department of Botany, University of Ibadan, with voucher specimens deposited in the university herbarium (UIH/2025/001-003). The plant parts were washed thoroughly using distilled water to eliminate surface contaminants, air-dried at ambient room temperature (25-30°C) for 14 days, and subsequently ground to powder using an electrical blender (Waring Commercial, USA). The powdered materials were stored in airtight containers at 4°C until extraction.

### Extraction Protocol

Crude extracts were prepared using the cold maceration technique as described by Sadiq *et al.* (2017) with modifications. For each plant material, 100 g of powdered sample was macerated in 400 mL (1:4 w/v ratio) of analytical-grade ethanol (96%) or methanol (99.8%) (Sigma-Aldrich, Germany) in separate conical flasks. The mixtures were agitated on an orbital shaker (150 rpm) for 48 hours at room temperature (25 ± 2°C) and subsequently filtered through Whatman No. 1 filter paper. The filtrates were concentrated under reduced pressure using a rotary evaporator (Büchi R-210, Switzerland) at 40°C, and the resulting crude extracts were stored at -20°C in amber glass vials until use. Extraction yields were calculated and expressed as the percentage weight of dried extract relative to initial powder weight.

### Waste Water Sample Collection

Waste water samples were collected from an industrial facility (7°50'45"N 3°57'9"E) and a domestic source (7°51'3" N 3°56'56" E) in Oyo, Oyo State, Nigeria. Samples were collected in sterile 500 mL Schott bottles and transported to the laboratory in ice-cooled containers within 4 hours of collection. Physicochemical parameters, including pH, temperature, and turbidity, were recorded at the point of collection.

### Isolation and Identification of Bacterial Isolates

Bacterial isolation was performed using standard microbiological protocols. Serial dilutions (10<sup>-1</sup> to 10<sup>-6</sup>) of waste water samples were prepared in sterile normal saline, and 0.1 mL aliquots were spread-plated onto Nutrient Agar (Oxoid, UK), MacConkey Agar, and Cetrinide Agar for selective isolation. Plates were incubated aerobically at 37°C for 24-48 hours. Morphologically distinct colonies were subcultured to obtain pure isolates, which were subsequently characterised using colonial morphology, Gram staining, and standard biochemical tests, including catalase, oxidase, indole, coagulase, methyl red, citrate utilisation, Voges-Proskauer, urease, and triple sugar iron reactions. Isolates

were identified to the genus level based on standard bacteriological methods. Toxicogenic potential and antimicrobial susceptibility patterns of *Bacillus* isolates were evaluated following the methods described by Gdoura-Ben Amor *et al.* (2019).

### Preparation of Extract Concentrations and Inoculum Standardisation

Stock solutions of crude extracts were prepared at a 500 mg/mL concentration in 10% dimethyl sulfoxide (DMSO) (Sigma-Aldrich, Germany). Working concentrations were prepared through serial two-fold dilutions. Bacterial inocula were standardised by adjusting overnight broth cultures to match a 0.5 McFarland turbidity standard (approximately  $1.5 \times 10^8$  CFU/mL) using sterile normal saline, as recommended by CLSI guidelines (CLSI, 2024).

### Antibacterial Activity Assay

Antibacterial activity was evaluated using the agar well diffusion method as described by Mustarichie *et al.* (2020). Plates of Mueller-Hinton Agar (MHA) were seeded with standardised bacterial suspensions using sterile cotton swabs to achieve confluent growth. Wells (8 mm diameter) were aseptically bored into the agar using a sterile cork borer. Each well was filled with 100  $\mu$ L of extract at concentrations of 500, 250, 125, 62.5, and 31.25 mg/mL. DMSO (10%) served as a negative control, while ciprofloxacin (5  $\mu$ g/mL) served as a positive control. Plates were incubated at 37°C for 24 hours, and zones of inhibition (ZOI) were measured in millimetres using a calibrated ruler. All experiments were performed in triplicate.

### Minimum Inhibitory Concentration (MIC) Determination

MIC values were determined using the broth microdilution method in 96-well microplates following CLSI guidelines (CLSI, 2024). Two-fold serial dilutions of extracts were prepared in Mueller-Hinton Broth to achieve final concentrations ranging from 0.0313 to 16 g/mL. Each well received 100  $\mu$ L of extract dilution and 100  $\mu$ L of standardised bacterial inoculum (approximately  $5 \times 10^5$  CFU/mL final concentration). Plates were incubated at 37°C for 18-24 hours.

MIC was defined as the lowest concentration showing no visible turbidity. Resazurin (0.015%) was added as a colourimetric indicator, with blue/purple colour indicating inhibition and pink/red indicating bacterial growth.

### Antibiotic Susceptibility Testing

Antibiotic susceptibility patterns of bacterial isolates were determined using the Kirby-Bauer disk diffusion method following CLSI M100-34 guidelines (CLSI, 2024). Standardised inocula were spread on MHA plates, and antibiotic disks (Oxoid, UK) were applied. The panel included: augmentin (AUG, 30  $\mu$ g), ceftazidime (CTX, 30  $\mu$ g), ceftriaxone (CRO, 30  $\mu$ g), imipenem (IMP, 10  $\mu$ g), ciprofloxacin (CIP, 5  $\mu$ g), gentamicin (GN, 10  $\mu$ g), ofloxacin (OFX, 5  $\mu$ g), levofloxacin (LBC, 5  $\mu$ g), aztreonam (ZEM, 30  $\mu$ g), and nalidixic acid (NA, 30  $\mu$ g). After incubation at 37°C for 18-24 hours, zone diameters were measured and interpreted as susceptible, intermediate, or resistant according to CLSI breakpoints. AMR surveillance methodology followed established protocols (Tsalidou *et al.*, 2023).

### Statistical Analysis

Results are expressed as mean  $\pm$  standard deviation. Statistical analyses were performed using IBM SPSS Statistics version 26.0 (IBM Corp., Armonk, NY, USA). One-way analysis of variance (ANOVA) with post-hoc Tukey's HSD test was used for multiple comparisons between extract types. Pearson's correlation coefficient was calculated to assess relationships between plant extract activity and antibiotic susceptibility. Statistical significance was set at  $p < 0.05$ .

## RESULTS AND DISCUSSION

### Extraction Yields

The percentage yields of crude extracts obtained from the three plant materials using ethanol and methanol solvents are presented in Table 1. *Musa paradisiaca* peel yielded the highest extract quantities with both solvents, followed by *Manihot esculenta* peel and *Acacia nilotica* seeds. Ethanolic extraction generally produced higher yields compared to methanolic extraction for *M. paradisiaca* and *M. esculenta*, while the reverse was observed for *A. nilotica*.

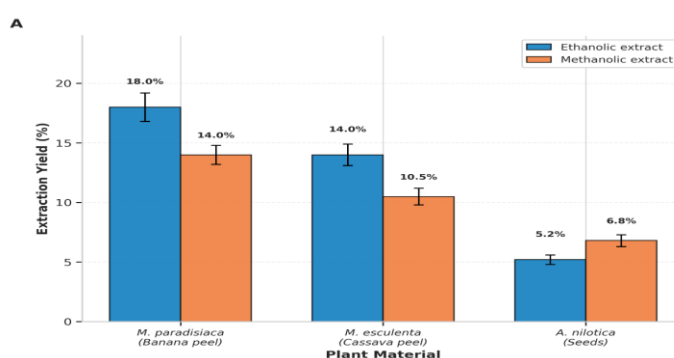


Figure 1: Percentage Yield of Crude Extracts from *Musa paradisiaca* Peel, *Manihot esculenta* Peel, and *Acacia nilotica* Seeds using Ethanolic and Methanolic Extraction. Error Bars Represent Standard Deviation

Table 1: Percentage Yield of Crude Extracts from Plant Materials

Plant Material	Ethanolic Extract (%)	Methanolic Extract (%)
<i>Musa paradisiaca</i> peel	18.0 $\pm$ 1.2	14.0 $\pm$ 0.8
<i>Manihot esculenta</i> peel	14.0 $\pm$ 0.9	10.5 $\pm$ 0.7
<i>Acacia nilotica</i> seeds	5.2 $\pm$ 0.4	6.8 $\pm$ 0.5

**Bacterial Isolate Distribution**

A total of 56 bacterial isolates were recovered from industrial and domestic waste water samples. The distribution of isolates by genus is presented in Table 2. *Bacillus* spp. were the most frequently isolated organisms (42.9%), followed by

*Pseudomonas* spp. (28.6%), *Proteus* spp. (14.3%), *Enterobacter* spp. (10.7%), and *Salmonella* spp. (3.6%). Industrial waste water sources yielded a higher proportion of Gram-negative isolates compared to domestic sources.

**Table 2: Distribution of Bacterial Isolates from Waste Water Sources**

Bacterial Genus	Number (n)	Percentage (%)	Primary Source
<i>Bacillus</i> spp.	24	42.9	Domestic/Industrial
<i>Pseudomonas</i> spp.	16	28.6	Industrial
<i>Proteus</i> spp.	8	14.3	Domestic
<i>Enterobacter</i> spp.	6	10.7	Industrial
<i>Salmonella</i> spp.	2	3.6	Domestic
Total	56	100.0	-

**Antibiotic Susceptibility Patterns**

The antibiotic susceptibility patterns of bacterial isolates revealed high rates of resistance to  $\beta$ -lactam antibiotics (Figure 2). All Gram-negative isolates (100%) exhibited resistance to augmentin, ceftazidime, ceftriaxone, and imipenem, indicating the presence of extended-spectrum  $\beta$ -lactamase (ESBL) and carbapenemase production. Resistance

to fluoroquinolones was comparatively lower, with 35% of Gram-negative isolates resistant to ciprofloxacin and 25% resistant to ofloxacin. Gram-positive isolates (primarily *Bacillus* spp.) demonstrated variable susceptibility, with the lowest resistance rates observed for gentamicin (5%) and ciprofloxacin (12%).

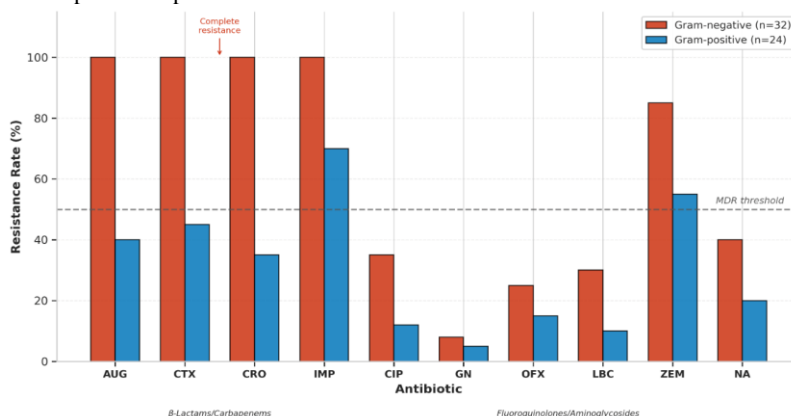


Figure 2: Antibiotic Resistance Patterns among Bacterial Isolates from Waste Water. Gram-negative Isolates showed 100% Resistance to  $\beta$ -lactam Antibiotics and Carbapenems

**Antibacterial Activity of Plant Extracts**

The antibacterial activity of plant extracts, expressed as zones of inhibition (ZOI), is presented in Table 3 and Figures 4-5. Methanolic extracts consistently demonstrated greater antibacterial activity compared to ethanolic extracts across all plant materials and test organisms ( $F = 24.67, p < 0.001$ ). Among methanolic extracts, *M. paradisiaca* peel exhibited the highest mean ZOI values, ranging from  $18.6 \pm 2.8$  mm

against *Pseudomonas* spp. to  $22.4 \pm 3.2$  mm against *Bacillus* spp. *M. esculenta* peel extract showed intermediate activity ( $16.2 \pm 2.0$  to  $18.2 \pm 2.4$  mm), while *A. nilotica* seed extract demonstrated the lowest but still significant activity ( $14.2 \pm 1.8$  to  $16.4 \pm 2.1$  mm). All ZOI values exceeded the susceptibility threshold of 10 mm, indicating clinically relevant antibacterial activity.

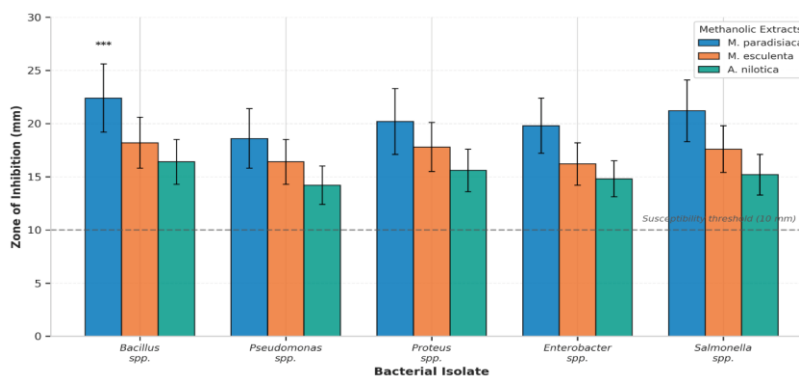


Figure 3: Antibacterial Activity of Methanolic Plant Extracts was Measured as the Zone of Inhibition (mm) against Bacterial ISOLATES. *M. paradisiaca* Extract showed Significantly Higher Activity ( $p < 0.001$ , ANOVA)

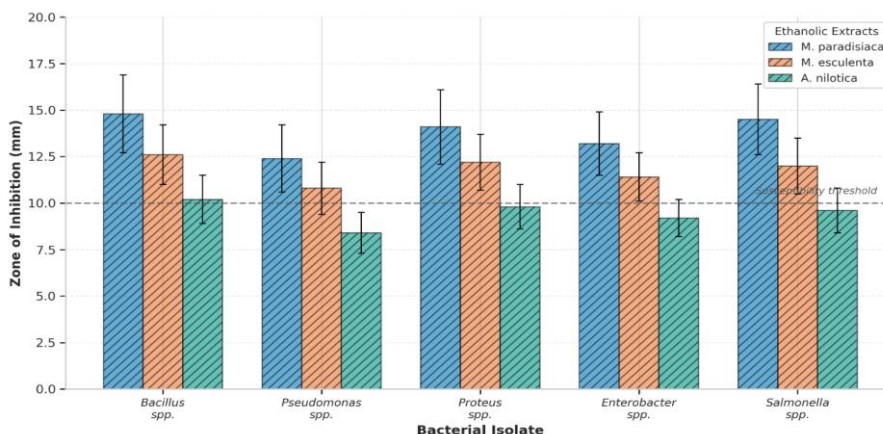


Figure 4: Antibacterial Activity of Ethanolic Plant Extracts Measured as Zone of Inhibition (mm). Ethanolic Extracts Consistently Showed Lower Activity Compared to Methanolic Extracts

**Minimum Inhibitory Concentration (MIC)**

The MIC values of methanolic plant extracts against bacterial isolates are presented in Table 4 and Figure 6. Methanolic *M. paradisiaca* extract exhibited the lowest MIC values across all tested organisms, ranging from 0.0625 g/mL against *Bacillus* spp., *Proteus* spp., and *Salmonella* spp. to 0.125

g/mL against *Pseudomonas* spp. and *Enterobacter* spp. *M. esculenta* and *A. nilotica* extracts demonstrated similar MIC ranges (0.125-0.25 g/mL), with slightly higher values against *Pseudomonas* spp. and *Enterobacter* spp., indicating greater inherent resistance in these organisms.

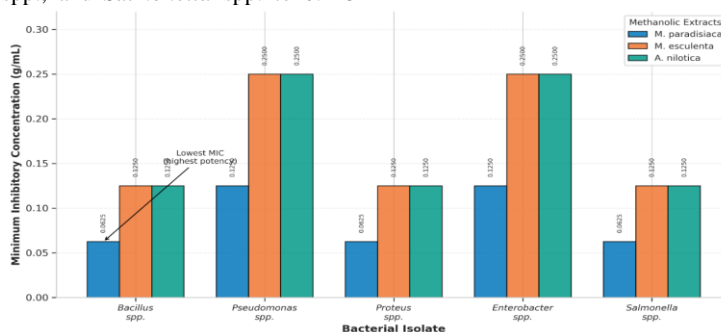


Figure 5: Minimum Inhibitory Concentration (MIC) of Methanolic PLANT Extracts against Bacterial Isolates. *M. paradisiaca* Extract Demonstrated the Lowest MIC Values (0.0625-0.125 g/mL)

**Correlation Analysis**

Pearson correlation analysis revealed significant positive correlations between plant extract antibacterial activity and susceptibility to quinolone antibiotics (Table 5, Figure 6). The strongest correlation was observed between methanolic *M. paradisiaca* extract activity and ofloxacin susceptibility ( $r = 0.82, p < 0.01$ ), followed by ciprofloxacin ( $r = 0.78, p < 0.01$ )

and nalidixic acid ( $r = 0.71, p < 0.05$ ). Moderate correlations were observed for *M. esculenta* extract ( $r = 0.55-0.65$ ), while *A. nilotica* extract showed weak to moderate correlations ( $r = 0.38-0.48$ ). Correlations with aminoglycoside (gentamicin) susceptibility were notably weaker across all extracts ( $r = 0.38-0.52$ ).

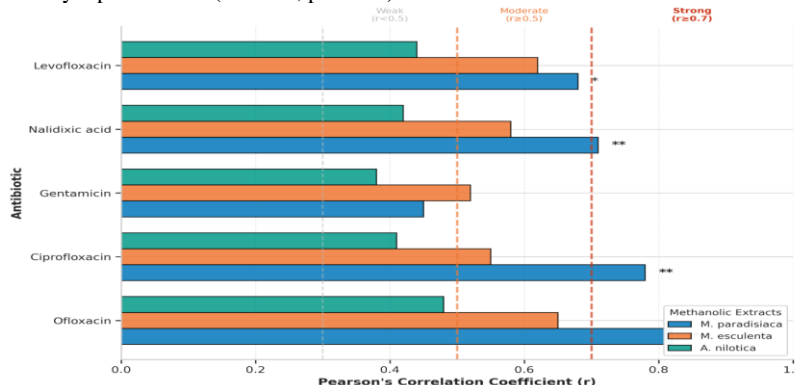


Figure 6: Pearson Correlation Coefficients between the Methanolic Plant Extract Antibacterial activity and Antibiotic Susceptibility Patterns. *M. paradisiaca* Extract showed Strong Positive Correlations with Quinolone Susceptibility

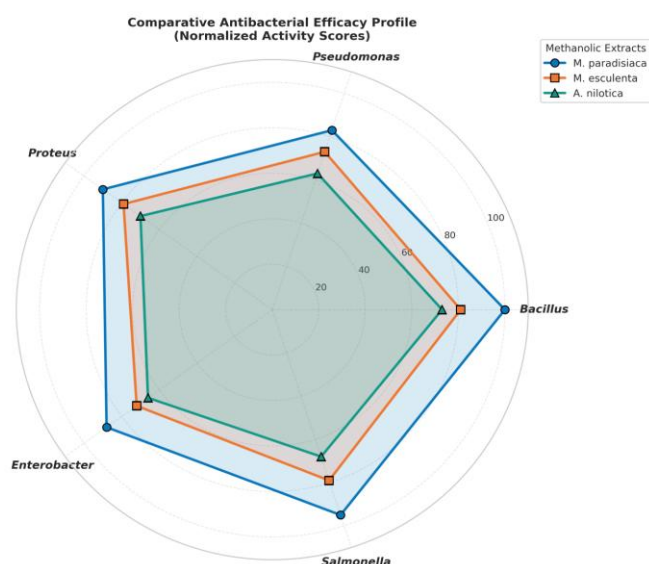


Figure 7: Multidimensional Antibacterial Efficacy Profile (Radar Plot) Showing Normalised Activity Scores (0-100 scale) for Methanolic Extracts against Different Bacterial Genera

## Discussion

This study provides comprehensive comparative data on the antibacterial efficacy of agricultural waste-derived plant extracts against multidrug-resistant environmental bacterial isolates from waste water sources in Nigeria. The findings demonstrate significant antibacterial potential, particularly for methanolic *M. paradisiaca* peel extract, and offer insights into mechanisms of action relevant to sustainable antimicrobial development.

The bacterial isolates recovered from waste water samples exhibited alarming rates of antimicrobial resistance, consistent with recent systematic reviews of West African waste water systems (Hotor *et al.*, 2025). The 100% resistance to  $\beta$ -lactam antibiotics (augmentin, ceftazidime, ceftriaxone) and carbapenems (imipenem) among Gram-negative isolates suggests widespread ESBL and carbapenemase production, reflecting the global AMR crisis. Naghavi *et al.* (2024) projected significant increases in AMR-related mortality, with estimates suggesting 39 million deaths attributable to AMR between 2025 and 2050 without urgent intervention. These findings emphasise the pressing need for alternative antimicrobial strategies, particularly in areas with limited resources where second-line antibiotics may be unavailable or unaffordable (Anyaeibunam *et al.*, 2024). Similar patterns of resistance have been documented in hospital waste water in Ethiopia (Adugna & Sivalingam, 2022) and among *Pseudomonas aeruginosa* clinical isolates in Nigeria (Olalekan *et al.*, 2023).

The superior antibacterial activity of methanolic extracts compared to ethanolic extracts can be credited to the differential solubility of bioactive compounds. Methanol's higher polarity enables efficient extraction of polar phenolic compounds, flavonoids, and tannins, which are primary contributors to antimicrobial activity (Hikal *et al.*, 2022). This observation is consistent with previous studies demonstrating enhanced antibacterial activity following purification of *M. paradisiaca* methanolic extracts (Jastria *et al.*, 2024). The phytochemical profile of banana peel, including gallicocatechin, epicatechin, and other flavonoid glycosides identified through HPLC analysis (Behiry *et al.*, 2019), provides a mechanistic basis for the observed activity.

The zones of inhibition recorded for methanolic *M. paradisiaca* extract (18.6-22.4 mm) in this study are

consistent with values reported by Sirajudin *et al.* (2014) and Kapadia *et al.* (2015), that documented significant antibacterial activity of banana peel extracts against various pathogenic bacteria. The activity against *Pseudomonas* spp., a resistant organism, is particularly noteworthy given the limited therapeutic options for multidrug-resistant *P. aeruginosa* infections, as documented by Olalekan *et al.* (2023) in Lagos, Nigeria. Lima *et al.* (2017) similarly reported efficacy of *M. esculenta* extracts against antibiotic-resistant bacteria, supporting the potential utility of agricultural waste extracts against clinically challenging pathogens.

The MIC values obtained for methanolic *M. paradisiaca* extract indicate moderate potency requiring further optimisation for therapeutic applications. These values are consistent with crude extract evaluations in the literature. Sadiq *et al.* (2017) investigated the antibacterial activities and possible modes of action of *A. nilotica* against multidrug-resistant *E. coli* and *Salmonella*, documenting MIC ranges that provide context for our findings. Mulia *et al.* (2023) reported the efficacy of cassava peel extracts against *Aeromonas hydrophila*, while Aliero *et al.* (2024) documented antimicrobial activities of bioactive compounds isolated from *A. nilotica* against multidrug-resistant bacteria. The significant positive correlations between plant extract activity and quinolone antibiotic susceptibility suggest potential mechanistic overlap, possibly involving DNA gyrase inhibition. Flavonoids and related polyphenols have been demonstrated to inhibit bacterial type II topoisomerases through mechanisms similar to fluoroquinolones (Mohidin *et al.*, 2023). The weaker correlations observed for *A. nilotica* extract may indicate a predominant membrane-disruption mechanism mediated by its high tannin content, which acts through protein precipitation and cell wall damage rather than intracellular target inhibition (Sadiq *et al.*, 2017; Idrees *et al.*, 2024).

From a sustainability perspective, the Utilisation of agricultural waste materials (banana and cassava peels) for antimicrobial development aligns with circular economy principles and addresses dual challenges of waste management and antimicrobial resistance (Hikal *et al.*, 2022). Nigeria is a major producer of both banana and cassava, generating substantial quantities of peel waste with limited current utilisation (Mohidin *et al.*, 2023). Valorisation of

these waste streams for antimicrobial production could provide economic benefits while contributing to environmental sustainability.

## CONCLUSION

This study demonstrates that agricultural waste-derived phytochemical extracts, particularly methanolic *Musa paradisiaca* peel extract, exhibit significant antibacterial activity against multidrug-resistant environmental bacterial isolates from waste water sources. The observed correlations with quinolone antibiotic susceptibility suggest potential DNA gyrase-targeting mechanisms worthy of further investigation. These findings support the valorisation of agricultural waste for sustainable antimicrobial development and waste water bioremediation in resource-limited settings. The study had several limitations worth acknowledging. Bacterial identification was performed to genus level only; molecular characterisation and resistance gene profiling would provide more precise epidemiological data. The study evaluated crude extracts without fractionation or compound isolation, limiting mechanistic interpretation. The in vitro nature of the study precludes direct extrapolation to in vivo efficacy or clinical applications. Furthermore, synergistic or antagonistic interactions between plant extracts and conventional antibiotics were not evaluated. Based on these findings, bio-guided fractionation and compound isolation from *M. paradisiaca* peel extract should be pursued to identify the specific active compounds and elucidate their mechanisms of action. Synergy studies combining plant extracts with subinhibitory concentrations of conventional antibiotics are recommended to explore potential combination therapy approaches. Pilot-scale studies should be conducted to evaluate the feasibility of integrating plant extract application into waste water treatment systems. Molecular characterisation of bacterial isolates, including resistance gene profiling, would enhance understanding of the local AMR epidemiology. Finally, thorough toxicological and pharmacokinetic studies are necessary prior to any consideration of clinical applications of these extracts.

## Data Availability

All data generated or analysed during this study are included in this manuscript.

## Author Contributions

O.A.A. conceived the study and designed the methodology. OAA and FAO performed the microbiological experiments and data collection. OAA, FAO, OTT, JIO and OJS performed data analysis, drafted and reviewed the manuscript. All authors read and approved the final manuscript.

## AI use

The authors acknowledge the use of Grammarly–2.8.263 to assist with grammar checking. The authors reviewed and edited the outcome and take full responsibility for the final content.

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