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Microbiological Evaluation of Microbes Associated with the Deterioration of Banana Sold at Rumuokoro Market Port Harcourt, Rivers State

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Abstract **Review Article**

Banana (*Musa spp.*), a nutritionally valuable staple fruit, is highly perishable and vulnerable to postharvest microbial deterioration, particularly in informal markets lacking cold chains and hygienic handling. This study investigated the microbial profile and contamination dynamics of deteriorated bananas sold at Rumuokoro Market, Port Harcourt, Rivers State, Nigeria. Twenty banana samples were purchased from four different points at the market and subjected to standard microbiological assays. Total Heterotrophic Bacterial Counts (THBC) ranged from 3.5×10^6 to 9.8×10^6 CFU/g, while Total Fungal Counts (TFC) varied from 2.5×10^4 to 4.2×10^4 CFU/g both exceeding international safety thresholds established by the ICMSF. The most prevalent bacterial species were *Staphylococcus* spp. (53.3%), *Streptococcus* spp. (26.7%), and *Escherichia coli* (20.0%), reflecting contamination via human handling and possible fecal exposure. Fungal isolates included *Fusarium* spp. (38.4%), *Aspergillus fumigatus*, *A. flavus*, *Mucor*, *Candida*, and *Rhizopus*, with several known mycotoxin producers posing significant food safety risks. Spatial analysis revealed variable microbial burdens, with Point B exhibiting the highest contamination levels and Point A showing the greatest fungal diversity. These findings underscore the dual-pathway contamination model in open-air markets comprising both anthropogenic and environmental routes and highlight systemic lapses in postharvest handling, storage, and vendor hygiene. The presence of toxigenic fungi such as *Fusarium* and *Aspergillus* raises public health concerns due to the risk of chronic mycotoxin exposure. This study advocates for urgent implementation of Good Agricultural Practices (GAP), Good Hygiene Practices (GHP), and Hazard Analysis and Critical Control Points (HACCP) protocols. Additionally, the integration of microbial surveillance and targeted mycotoxin mitigation strategies is imperative to ensure food safety and consumer protection in resource-constrained urban produce markets.

Keywords: Banana, postharvest deterioration, microbial contamination, Rumuokoro Market, Nigeria, *Staphylococcus* spp., *Fusarium* spp., mycotoxins, food safety, hygiene practices, informal markets, microbial surveillance.

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1. INTRODUCTION

Banana (*Musa spp.*), one of the most widely consumed fruits in the world, plays a pivotal role in the diet and economy of many developing nations, including Nigeria. Its global significance stems not only from its affordability and availability but also from its high nutritional value, particularly as a source of carbohydrates, potassium, dietary fiber, and vitamins such as B6 and C (Aurore et al., 2009; Simmonds, 1966). However, bananas are climacteric fruits that exhibit rapid physiological ripening and senescence postharvest, rendering them highly susceptible to microbial deterioration during storage, transportation, and marketing (Dadzie & Orchard, 1997; Hailu, et al., 2013). Postharvest deterioration of bananas is largely attributed to a consortium of pathogenic microorganisms, primarily fungi and bacteria, which invade the fruit either during

growth or after harvest through mechanical injuries, bruises, or natural openings (Ranasinghe, et al., 2003). Fungal genera such as *Colletotrichum*, *Aspergillus*, *Penicillium*, *Fusarium*, and *Rhizopus* are commonly implicated in the decay of stored bananas, often causing soft rot, black rot, or anthracnose lesions (Al-Hindi et al., 2011; Ibe & Ogbulie, 2005). In addition, bacterial species such as *Erwinia spp.* and *Pseudomonas spp.* contribute to tissue maceration and offensive odor production, accelerating fruit spoilage and rendering the produce unmarketable (Lescot, 2009; FAO, 2011).

Market environments in sub-Saharan Africa, particularly in urban centers such as Port Harcourt, Nigeria, often lack adequate postharvest infrastructure and hygiene practices. Rumuokoro Market, a major produce hub in Port Harcourt, typifies the open-air markets in the region where poor handling, high ambient humidity, inadequate sanitation, and crowding of overripe and spoiled fruits facilitate microbial cross-contamination and accelerate postharvest losses (Nwachukwu et al., 2008). These conditions not only compromise fruit quality and shelf life but also pose significant public health concerns due to the potential production of mycotoxins and other microbial metabolites (Pitt & Hocking, 2009).

Despite the evident implications of microbial spoilage on banana postharvest quality and food security, limited empirical data exists on the specific microorganisms involved in banana deterioration in local Nigerian markets. A comprehensive microbiological profiling of bananas sold in Rumuokoro Market is crucial for identifying the predominant spoilage organisms and understanding their patterns of occurrence. Moreover, a comparative assessment of microbial isolates from visibly spoiled and apparently fresh bananas could offer insights into latent infections, contamination routes, and effective mitigation strategies.

Therefore, this study seeks to conduct a comparative analysis of the microorganisms associated with the deterioration of bananas sold at Rumuokoro Market in Port Harcourt, Rivers State. By identifying the major bacterial and fungal species present, the study aims to contribute to improved postharvest management, inform food safety interventions, and enhance consumer protection in local produce markets.

2. MATERIALS AND METHODS

2.1: Study Area

This study was conducted at Rumuokoro Market, a principal agricultural produce marketplace located in Port Harcourt, Rivers State, Nigeria (Latitude: 4.8390°N, Longitude: 7.0097°E), between April and August 2024. Rumuokoro Market is a critical distribution center within the Niger Delta region, characterized by tropical rainforest climatic conditions with high humidity and temperatures conducive to microbial proliferation (Oguoma, 2017; Eze & Okafor, 2019). The selected period coincides with the peak wet season, during which environmental factors such as elevated moisture and temperature amplify postharvest spoilage risks (Adeleke & Babalola, 2021). The location and timing provide an appropriate framework for examining the microbial dynamics associated with banana deterioration under typical tropical market conditions.

2.2: Collection of Samples

A total of twenty (20) banana fruit samples were systematically procured from multiple vendors across various retail points within the mini-market section of Rumuokoro Market, Port Harcourt, Rivers State. Sampling was conducted using sterile polythene bags to minimize external contamination during collection (ISO, 2017). The samples were promptly transported under ambient conditions to the Microbiology Laboratory for subsequent microbial isolation and analysis. This approach ensured representative sampling reflective of typical market handling and conditions (Ibe & Ogbulie, 2005; Nwachukwu et al., 2008).

2.3: Sterilization of Materials

All glassware, including test tubes, pipettes, conical flasks, beakers, and microscope slides, were initially cleaned thoroughly with a laboratory-grade detergent to remove residues and contaminants. Subsequently, the glassware openings were sealed with aluminum foil and sterilized in a hot air oven at 160°C for 3 hours, following standard dry heat sterilization protocols to ensure the complete elimination of microbial contaminants (Block, 2001; APHA, 2015). This sterilization procedure is critical for maintaining aseptic conditions during microbiological analyses.

2.4: Media Preparation

The culture media employed for microbial isolation in this study included Sabouraud Dextrose Agar (SDA), MacConkey Agar, and Nutrient Agar. Each medium was prepared in accordance with the manufacturer's specifications and subsequently sterilized by autoclaving at 121°C and 15 psi for 15 minutes to ensure sterility (Cheesbrough, 2006). Upon cooling to 45–50°C, the molten media were aseptically poured into sterile Petri dishes and allowed to solidify under aseptic conditions prior to inoculation.

2.5: Microbiological Investigation

2.5.1: Isolation of Microorganisms from Banana Fruit Samples

Ten grams each of deteriorated and undeteriorated banana fruit tissues were aseptically excised, weighed, and homogenized in 90 mL of sterile distilled water using an electric blender (Michael et al., 2022). Serial ten-fold dilutions were prepared using sterilized peptone water, and 1 mL aliquots of the 10^{-4} dilution were inoculated into appropriately labeled Petri dishes containing selective media via the pour plate method, followed by solidification (Michael et al., 2022).

Plates for bacterial isolation were incubated at 37°C for 24 hours, while fungal cultures were incubated at room temperature (25 ± 2°C) for 3–5 days. Post-incubation, colony-forming units were enumerated, and pure isolates were obtained through repeated streaking. Isolates were subsequently maintained on agar slants and refrigerated at 4°C pending further analysis.

2.5.2: Identification of Bacterial Isolates

Bacterial identification was based on colonial, cultural, morphological, and biochemical characteristics. Gram staining was performed by preparing a bacterial smear on a clean glass slide, heat-fixing it, and sequentially applying crystal violet, iodine mordant, acetone/ethanol decolorizer, and safranin counterstain, with appropriate rinsing steps between each reagent (Cheesbrough, 2006). The stained slides were air-dried and examined under a microscope using an oil immersion objective (100×) to differentiate Gram-positive from Gram-negative bacteria. This staining technique provides critical information on the bacterial cell wall structure, which is fundamental to subsequent identification and classification. The methodology followed established protocols to ensure reproducibility and accuracy in bacterial characterization.

2.5.3: Biochemical Tests

A battery of biochemical assays, including catalase, indole production, motility, citrate utilization, urease, methyl red, oxidase, and sugar fermentation tests, were employed to characterize bacterial isolates following standardized protocols (Cheesbrough, 2003, 2006; Harley & Prescott, 2002). These tests assess enzymatic activities, metabolic capabilities, and physiological traits critical for bacterial identification, such as oxygen bubble formation in catalase testing, colorimetric changes in citrate and urease tests, and gas production in sugar fermentation. Each assay was conducted under controlled incubation conditions, with specific indicators applied to interpret positive or negative results, thereby facilitating accurate differentiation of isolates. Collectively, these methods provide a comprehensive framework for the phenotypic characterization of bacterial isolates from banana fruit samples.

2.5.4: Fungal Isolation and Identification

The isolation of fungal species associated with the spoilage of banana fruits was conducted using internationally standardized mycological protocols (Pitt & Hocking, 2009). Samples exhibiting visible signs of fungal decay were aseptically excised and homogenized under sterile conditions. Approximately 1 g of each homogenized sample was suspended in 9 mL of sterile distilled water and serially diluted to 10^{-4}. From each dilution, 0.1 mL aliquots were plated in triplicate onto Potato Dextrose Agar (PDA; Oxoid, UK) supplemented with 100 mg/L chloramphenicol to inhibit bacterial interference (Samson et al., 2010).

Plates were incubated aerobically at 28 ± 2°C for 5–7 days. Emerging fungal colonies were sub-cultured onto fresh PDA to obtain pure cultures. Morphological identification was initially based on colony characteristics texture, pigmentation, and growth rate followed by microscopic examination using lactophenol cotton blue staining for spore and hyphal structure visualization (Watanabe, 2010).

3. RESULTS

3.1: Microbial count on Deteriorated Banana sold at Rumuokoro Market, RiversState, Nigeria.

The microbial analysis of deteriorated banana samples collected from four points at Rumuokoro Market, Rivers State, Nigeria, indicates substantial microbial contamination. The Total Heterotrophic Bacterial Counts (THBC) ranged from 3.5×10^6 to 9.8×10^6 CFU/g, while the Total Fungal Counts (TFC) ranged between 2.5×10^4 and 4.2×10^4 CFU/g. Point B exhibited the highest levels of both bacterial (9.8×10^6 CFU/g) and fungal contamination (4.2×10^4 CFU/g), indicating greater microbial proliferation likely due to poor handling or storage conditions.

Table 1: Microbial count on Deteriorated Banana sold at Rumuokoro Market, Rivers State, Nigeria

Samples	THBC(CFU/g)	TFC(CFU/g)
Point A Sample	3.5×10^6	2.5×10^4
Point B Sample	9.8×10^6	4.2×10^4
Point C Sample	5.2×10^6	2.9×10^4
Point D Sample	6.7×10^6	3.4×10^4

Keys: THBC (Total Heterotrophic Bacteria Count), TFC (Total Fungi Count), CFU/g (Colony Forming Unit/ Gram).

3.2: Frequency of Occurrence of Bacteria Isolates Obtained from Banana Purchased from Rumuokoro Market, Rivers State, Nigeria.

Table 2 shows the frequency of occurrence of bacterial, out of 15 bacterial isolates obtained from deteriorated bananas at Rumuokoro market, *Staphylococcus* was the most frequent, accounting for 8 isolates (53.3%). *Streptococcus* followed with 4 isolates (26.7%), while *Escherichia coli* had 3 isolates (20.0%). Location D recorded the highest number of isolates (5), followed by Locations A and C with 4 each, and Location B with 2. This indicates varying levels of bacterial contamination across the sampled locations.

Table 2: Frequency of occurrence of Bacteria isolates obtained from Banana purchased from Rumuokoro market, Rivers State, Nigeria.

Bacteria	Locations				Total Isolates (n=15)	Percentage (%)
	A	B	C	D		
Staphylococcus	2	1	3	2	8	53.3
Streptococcus	1	1	0	2	4	26.7
Escherichia coli	1	0	1	1	3	20.0
Total per location	**4**	**2**	**4**	**5**	**15**	**100%**

3.3: Frequency of Occurrence of Fungal Isolates Obtained from Banana Purchased from Rumuokoro Market, Rivers State, Nigeria.

A total of 13 fungal isolates from six genera were identified from deteriorated bananas across four locations in Rumuokoro Market. *Fusarium spp.* was the most prevalent, representing 38.4% of isolates and occurring in all locations, with Sample D having the highest count (2). *Aspergillus fumigatus*, *Mucor*, and *Candida spp.* each accounted for 15.4%, while *A. flavus* and *Rhizopus* were least frequent at 7.7% each, found only in Sample A. Sample A showed the highest fungal load (38.4%), followed by Sample D (30.8%), B (23.1%), and C (7.7%). The distribution reflects varying contamination levels likely influenced by handling and environmental conditions.

Table 3: Frequency of occurrence of fungal isolates obtained from Banana purchased from Rumuokoro market, Rivers State, Nigeria.

Fungal Isolates	Frequency (%)	Samples Locations			
		A	B	C	D
Fasarium	5(38.4)	1	1	1	2
Aspergillus fumigatus	2(15.4)	1	0	0	1
Aspergillus flavus	1(7.7)	1	0	0	0
Mucor	2(15.4)	1	1	0	0
Candida	2(15.4)	0	1	0	1
Rhizopus	1(7.7)	1	0	0	0
Total	**13(100%)**	**5(38.4)**	**3(23.1)**	**1(7.7)**	**4(30.8)**

4. DISCUSSION

Microbial count on Deteriorated Banana sold at Rumuokoro Market, RiversState, Nigeria.

The microbiological evaluation of deteriorated banana samples from Rumuokoro Market reveals a significant burden of both bacterial and fungal contaminants, with Total Heterotrophic Bacterial Counts (THBC) ranging from 3.5×10^6 to 9.8×10^6 CFU/g, and Total Fungal Counts (TFC) spanning 2.5×10^4 to 4.2×10^4 CFU/g. These findings surpass the internationally recommended microbial safety limits for fresh produce, as set by the International Commission on Microbiological Specifications for Foods (ICMSF), which suggest a maximum threshold of 10^5 CFU/g for aerobic mesophilic bacteria and 10^4 CFU/g for yeasts and molds in ready-to-eat fruits (ICMSF, 2005; FAO/WHO, 2019).

The highest microbial burden was observed in the Point B sample, where THBC reached 9.8×10^6 CFU/g, and TFC peaked at 4.2×10^4 CFU/g. Such elevated counts are indicative of advanced microbial colonization, likely facilitated by prolonged exposure to ambient conditions, improper handling, and inadequate sanitation practices during post-harvest processing and market display. This observation is consistent with findings by Okorondu et al. (2020), who reported that open-market fruits in southern Nigeria frequently exhibit microbial counts exceeding acceptable food safety limits due to unhygienic display conditions and cross-contamination from handlers and the environment.

Bacteria at such high concentrations are not only spoilage agents but may also serve as indicators of fecal contamination or pathogenic presence, such as *Salmonella spp.*, *Escherichia coli*, or *Listeria monocytogenes* (Oliveira et al., 2011). In parallel, the elevated fungal counts, particularly *Aspergillus*, *Penicillium*, and *Fusarium* spp., raise concerns over the potential production of mycotoxins, such as ochratoxin A or aflatoxins, which pose serious health risks when consumed even at trace levels (Pitt & Hocking, 2009).

Comparative studies in similar tropical marketplaces underscore the role of environmental humidity and temperature in promoting microbial proliferation. For example, Eni et al. (2010) observed that deteriorated plantain and banana samples from Nigerian markets harbored bacterial loads between 10^5 and 10^7 CFU/g, often correlating with physical damage and storage conditions. The consistency between those findings and the present study confirms a recurring microbial hazard in open-market fruit sales.

Furthermore, international best practices, such as those outlined in the European Commission Regulation (EC) No. 2073/2005, emphasize the need for strict microbiological criteria for ready-to-eat foods. The banana samples analyzed in this study fall well outside the regulatory thresholds, reinforcing the urgency of implementing Good Agricultural Practices (GAP), Good Hygiene Practices (GHP), and Hazard Analysis and Critical Control Points (HACCP) protocols across the fruit supply chain (EFSA, 2020).

Frequency of occurrence of Bacteria isolates obtained from Banana purchased from Rumuokoro market, Rivers State, Nigeria.

The present investigation of 15 bacterial isolates from deteriorated bananas at Rumuokoro Market, Rivers State, Nigeria, reveals a microbial consortium dominated by *Staphylococcus* spp. (53.3%), followed by *Streptococcus* spp. (26.7%) and *Escherichia coli* (20.0%). Such predominance of *Staphylococcus* aligns with analogous findings in Port Harcourt markets, where *Staphylococcus aureus* comprised approximately 27% of isolates in ready-to-eat fruits, underscoring its ubiquity and potential for foodborne illness via handling contamination (Sornka et al., 2024).

The isolation of *E. coli* from 20% of samples signifies a non-negligible risk of fecal contamination. In Port Harcourt, coliform counts in Rumuokoro Market fruits were reported at 5.16×10^3 CFU/ml, substantiating environmental and hygienic deficits (Omorodion & Nwiyege, 2023; Sornka et al., 2024). Isolation of *Streptococcus* spp. further suggests cross-contamination via handlers or shared utensils, corroborating reported risks in similar street-vended produce (Omorodion & Nwiyege, 2023).

Spatial analysis unveiled significant heterogeneity: Location D exhibited the highest bacterial burden (33.3%), followed by Locations A and C (each 26.7%), and Location B (13.3%). This uneven distribution echoes contamination gradients observed across markets in Port Harcourt and Zaria, where vendor practices and sanitation varied markedly among sampling sites (Sornka et al., 2024; Omorodion& Nwiyege, 2023).

Collectively, the prevalence of *Staphylococcus* a human skin commensal and *E. coli* a fecal indicator suggests dual contamination pathways: direct human handling and exposure to unsanitary environmental sources. This duality is emblematic of systemic gaps in post-harvest hygiene, consistent with broader Nigerian studies on market-sold fruits (Abdulrahaman et al., 2024).

Frequency of occurrence of fungal isolates obtained from Banana purchased from Rumuokoro market, Rivers State, Nigeria.

The analysis of fungal isolates from deteriorated bananas sold at Rumuokoro Market, Port Harcourt, Nigeria, revealed a diverse assemblage of spoilage-associated fungi, comprising six genera with a total of 13 isolates**.** These results underscore the microbiological vulnerability of post-harvest bananas under informal market conditions, reflecting both the perishability of the fruit and suboptimal handling and storage practices. The genus *Fusarium* was the most frequently occurring fungal isolates, accounting for 38.4% (5 out of 13) of the total isolates and being present at all sample locations (A–D).

The widespread presence of *Fusarium* is consistent with its known role as a major post-harvest pathogen in tropical fruits, including bananas, where it contributes to soft rot, tissue maceration, and off-odors due to enzymatic degradation of fruit pectins and starches (Ploetz, 2006; Sharma et al., 2020). Moreover, *Fusarium* species are notorious for their ability to produce mycotoxins such as fumonisins and trichothecenes, which pose significant food safety risks to consumers (Bennett & Klich, 2003). Two *Aspergillus* species were detected: *A. fumigatus* **(**15.4%**)** and *A. flavus* (7.7%**).** *A. fumigatus* was isolated from samples at Points A and D, while *A. flavus* was confined to Point A. These species are not only associated with post-harvest decay but are also important mycotoxigenic fungi**,** particularly *A. flavus*, which is a known producer of aflatoxin**s,** one of the most potent naturally occurring carcinogens (Wild & Gong, 2010; Pitt & Hocking, 2009). Their presence suggests environmental contamination during display or handling, possibly via dust, insects, or poor vendor hygiene, particularly in open-air market settings (Enyiukwu et al., 2014). *Candida* spp. and *Mucor* spp. each accounted for 15.4% of the total isolates. *Candida* was detected at Points B and D, which could indicate prolonged contact with human hands or surfaces, as it is often associated with human microbiota and poorly cleaned storage equipment (Fleet, 2003). *Mucor*, typically involved in soft rot of high-sugar-content fruits, was found at Points A and B, likely a result of moisture buildup and lack of airflow—conditions favorable to *zygomycete* proliferation (Nguyen et al., 2010). *Rhizopus* spp., although detected only once (7.7%) in sample A, is a well-documented spoilage fungus in bananas, where it can cause rapid softening and liquefaction of tissues due to its production of extracellular pectinases and cellulases (Lima et al., 2013).

Sample locations showed variable fungal diversity and load. Point A exhibited the highest diversity and abundance, harboring five fungal types, including *Fusarium*, *A. fumigatus*, *A. flavus*, *Mucor*, and *Rhizopus*. This suggests significant spoilage pressure, possibly due to longer market exposure, higher temperatures, or greater vendor-customer contact. Conversely, Point C yielded only one isolate, implying either a shorter exposure time or better preservation conditions.

This spatial heterogeneity supports previous findings that microbial load in retail markets is influenced by microclimatic conditions, fruit turnover rate, and handling practices (Oliveira et al., 2011; Eni et al., 2010). The observed pattern also indicates that fungal contamination in fruit markets is **non-uniform**, reinforcing the need for point-specific interventions.

The presence of toxigenic and opportunistic fungi, especially *Fusarium* and *Aspergillus*, in bananas intended for human consumption raises critical public health concerns. These fungi, under favorable conditions, can contaminate fruits with toxins that are thermally stable and not eliminated by conventional washing or cooking (FAO/WHO, 2019). Without proper monitoring, consumers risk exposure to chronic mycotoxin ingestion, which has been linked to liver cancer, immunosuppression, and stunted growth in children (Wild & Gong, 2010).

5. CONCLUSION

This study provides compelling evidence of significant microbial contamination both bacterial and fungal associated with deteriorated bananas sold at Rumuokoro Market, Port Harcourt, highlighting critical food safety breaches characterized by excessive microbial loads far exceeding international standards. The predominance of *Staphylococcus spp.*, *Escherichia coli*, and toxigenic fungi such as *Fusarium* and *Aspergillus* underscores a dual-pathway contamination model involving human handling and environmental exposure, exacerbated by inadequate post-harvest hygiene and substandard market practices. The spatial heterogeneity in microbial profiles further reveals the influence of localized factors such as temperature, humidity, and vendor behavior, demanding urgent adoption of Good Agricultural Practices (GAP), Good Hygiene Practices (GHP), and Hazard Analysis and Critical Control Point (HACCP) systems. These findings serve as a clarion call for policymakers, public health officials, and market stakeholders to establish a structured surveillance and regulatory framework that safeguards consumers against microbial hazards and chronic mycotoxin exposure linked to informal fresh produce markets in low- and middle-income settings.

6. RECOMMENDATIONS

It is imperative that there should be:

i) Implementation of comprehensive post-harvest hygiene protocols by enforcing Good Agricultural Practices (GAP) and Good Hygiene Practices (GHP) throughout the banana supply chain, coupled with vendor training and regular sanitation audits to reduce microbial contamination.

ii) Establish rapid microbiological surveillance systems at points of sale using advanced molecular and biosensor technologies to promptly detect and quantify bacterial and fungal pathogens, facilitating timely public health interventions.

iii) Develop targeted mycotoxin risk management strategies that integrate pre- and post-harvest controls, including improved storage conditions, environmental regulation, and consumer education on the dangers of chronic mycotoxin exposure from contaminated bananas.

7. CONTRIBUTIONS TO KNOWLEDGE

This study offers the first comprehensive

microbiological profiling of deteriorated bananas in Rumuokoro Market, Port Harcourt, revealing alarmingly high bacterial and fungal loads that far exceed global food safety thresholds. The identification of dominant pathogens such as *Staphylococcus spp.*, *E. coli*, *Fusarium spp.*, and *Aspergillus spp.* underscores critical gaps in hygiene and postharvest handling within informal market systems. Notably, the dual-pathway contamination model via human handling and environmental exposure presents a novel perspective on spoilage dynamics in tropical fruit markets. Furthermore, the spatial analysis of microbial distribution introduces a localized framework for targeted interventions. This research thus provides a vital empirical foundation for policy-driven food safety reforms in low- and middle-income settings.

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