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Research Article

Effect of Soil on the Physicochemical Properties and Bacterial Load of Palm Wine in Benue South Senatorial District

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Abstract- Palm wine is a culturally significant traditional beverage in Nigeria, yet its quality varies widely across regions due to environmental and handling factors. This study investigated the influence of soil physicochemical properties on the physicochemical characteristics, microbial load, and sensory quality of palm wine produced in six communities: Otukpa A, Otukpa B, Ugbokolo A, Ugbokolo B, Owukpa A, and Owukpa B, within the Benue South Senatorial District. Composite soil samples and freshly tapped palm wine were collected and analyzed using standardized methods for nutrient composition, microbial enumeration, and sensory evaluation. Soil analysis revealed considerable spatial variation, with loamy sandy soils in Owukpa and Otukpa exhibiting higher organic matter, nitrogen, and potassium levels compared to the nutrient-poor loam soils of Ugbokolo B. These soil differences significantly influenced palm wine quality. Palm wine from Owukpa B, which had the most balanced soil nutrient profile, recorded the highest sweetness, superior aroma, lower viscosity, and the lowest microbial load. Conversely, Ugbokolo B exhibited reduced sweetness, higher off-odor scores, and mildly elevated microbial counts, corresponding to its depleted soil nutrient status. Microbial analysis identified common fermenting organisms, including Lactobacillus, Staphylococcus, Bacillus, and Serratia species, with variations across locations reflecting differences in both soil pH and tapping hygiene. Overall, the findings demonstrate a clear soil–sap–wine continuum, establishing that soil nutrient balance plays a crucial role in palm wine's sensory quality and microbial stability. The study highlights the need for soil fertility management and improved tapping practices to enhance palm wine quality and safety in rural communities.

Article Key Information

Keywords: Palm wine quality; Soil physicochemical properties; Microbial load; Sensory evaluation

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1.0 Introduction

Palm wine is a naturally fermented alcoholic beverage derived from the sap of palm trees such as *Elaeis guineensis* and *Raffia hookeri*, and it remains one of the most culturally significant traditional drinks in West and Central Africa. In Nigeria, its consumption cuts across rural and urban populations, playing central roles in social ceremonies, traditional rites, and daily nutrition. Fresh palm wine is a rich matrix of fermentable sugars, vitamins, organic acids, minerals, phenolic compounds, and diverse microorganisms that drive its rapid and spontaneous fermentation. The unique biochemical composition of palm wine makes it both nutritionally valuable and highly perishable, with quality undergoing dynamic changes within hours of extraction due to microbial metabolism and environmental factors [1]–[3]. These characteristics highlight the need for continuous scientific evaluation of the determinants of palm wine quality, especially in major production regions like the Benue South Senatorial District of Nigeria.

The quality of palm wine is shaped by a complex interplay of biological, environmental, and anthropogenic influences. While microbial ecology and fermentation dynamics have been widely recognized as the primary drivers of palm wine transformation, emerging evidence suggests that the physicochemical properties of the soils where palm trees grow also significantly affect the sap composition prior to tapping [4], [5]. Soil properties, including pH, nutrient profile, organic matter content, cation exchange capacity, and texture, directly influence palm tree physiology, root development, nutrient uptake, and metabolic processes. Healthy soils with balanced nitrogen (N), phosphorus (P), potassium (K), and adequate organic matter promote vigorous growth and enhance carbohydrate formation in the palm tree, which translates into higher sugar concentrations in the sap [6], [7]. Conversely, nutrient-poor or highly acidic soils may limit sap volume, reduce sugar content, and predispose the sap to faster microbial spoilage due to compromised biochemical stability.

Despite these scientific insights, very limited work has been conducted in Nigeria to understand the soil–sap relationship in palm wine production. Studies in Cameroon and Ghana have shown that the mineral composition and acidity of soils correlate with sugar content, alcohol yield, and volatile aroma compounds in palm sap [3], [8]. However, such findings cannot be generalized to Nigeria due to differences in vegetation, geology, soil fertility gradients, and local tapping practices across regions. In Benue South Senatorial District, comprising communities such as Otukpa, Ugbokolo, and Owukpa, palm wine tapping is a major livelihood activity, yet empirical data on how local soil environments influence palm wine quality remain sparse. Local consumers frequently report variations in sweetness, aroma, color, spoilage rate, and perceived "freshness" among palm wine sourced from different villages. Such anecdotal evidence strongly suggests that environmental factors, including soil properties, may be contributing to the observed sensory and microbial differences.

Apart from soil conditions, palm wine quality is also sensitive to the microbiological load introduced during tapping, collection, and storage. Freshly collected palm sap typically contains yeasts such as *Saccharomyces cerevisiae*, *Candida* spp., and *Pichia* spp., in addition to lactic acid bacteria (*Lactobacillus*, *Leuconostoc*) and acetic acid bacteria [2], [9], [10]. These organisms initiate fermentation almost immediately after sap exudation, converting sugars to ethanol, organic acids, and aromatic compounds. While some of these microbes are desirable for enhancing flavor and aroma, contamination by spoilage or pathogenic microorganisms, such as *Staphylococcus* spp., *Serratia* spp., *Bacillus* spp., and *Enterobacter* spp. poses serious public health concerns [11]. The interaction between soil properties and microbial proliferation in palm wine has not been thoroughly explored, although soil-derived microbes and environmental pH may influence initial sap microflora.

Given the socio-economic importance of palm wine in Benue South, a scientific investigation into how soil characteristics influence sap quality is essential. Understanding this relationship can guide farmers, tappers, and local communities in improving production practices. It also offers insights for agricultural extension programs aimed at enhancing palm tree productivity, optimizing soil health, and reducing microbial hazards in palm wine. Additionally, such knowledge is critical for public health authorities seeking to minimize foodborne risks associated with traditionally fermented beverages.

This study, therefore, evaluates the physicochemical properties of soils surrounding palm wine–producing palm trees in Otukpa, Ugbokolo, and Owukpa, and examines how these properties influence the physicochemical profile, microbial load, and sensory attributes of palm wine from these locations. By integrating soil analysis with microbiological and sensory evaluation of sap, the study provides a holistic understanding of environmental determinants of palm wine quality. The research addresses a critical knowledge gap and contributes new evidence that links soil environment to palm wine safety, fermentation quality, and consumer acceptability in a region where palm wine plays significant cultural and nutritional roles.

2.0 Review of Related Literature

Palm wine has attracted extensive scholarly attention due to its cultural relevance, nutritional potential, and complex fermentation dynamics. Numerous studies have characterized the biochemical composition of palm sap, emphasizing its high sugar content, minerals, vitamins, amino acids, and bioactive compounds that support a diverse microbial ecology and rapid fermentation shortly after tapping. Recent investigations report that fresh palm sap typically contains sucrose, glucose, fructose, organic acids, phenolic compounds, and a wide spectrum of volatile constituents that contribute to its aroma and flavor profile [12]. These biochemical features make palm wine highly susceptible to quality changes, thereby necessitating a deeper understanding of the environmental and processing factors that drive its variability.

A central theme in palm wine research concerns the microbiological ecosystem responsible for its spontaneous fermentation. Yeasts such as *Saccharomyces cerevisiae*, *Pichia exigua*, *Candida tropicalis*, and *Hanseniaspora guilliermondii* are reported as primary fermenters that convert sugars into ethanol, carbon dioxide, and an array of aromatic compounds [13]. In addition to yeasts, lactic acid bacteria, including *Lactobacillus plantarum*, *Leuconostoc mesenteroides*, and *Lactococcus lactis*, play important roles in acidification, flavor modification, and inhibition of undesirable microbes through bacteriocin production [14]. Studies have also documented the presence of acetic acid bacteria and several non-beneficial microorganisms such as *Staphylococcus*, *Micrococcus*, and *Bacillus* species, which may enter the sap through contaminated tapping implements or environmental exposure [15]. These microbial fluctuations significantly influence pH reduction, alcohol yield, color changes, clarity, viscosity, and sensory attributes of palm wine throughout fermentation.

Beyond microbiology, growing attention has been directed toward the role of soil characteristics in shaping sap quality before tapping. Soil properties influence palm tree physiology, photosynthesis rates, root absorption efficiency, and metabolic pathways that regulate sap production. Research in West Africa indicates that soil pH, organic matter, nitrogen, phosphorus, and potassium levels correlate strongly with sap sugar content, sap flow rate, and eventual alcohol concentration after fermentation [16]. For instance, nutrient-rich soils with balanced macronutrients enable palm trees to synthesize higher carbohydrate reserves, resulting in sweeter sap with enhanced fermentability. Conversely, acidic or nutrient-depleted soils may lead to lower sap volumes, reduced °Brix values, and diminished organoleptic properties, such as poor sweetness and lower aroma quality.

Environmental studies have further highlighted that soil texture, particularly loamy sand and sandy loam, promotes optimal water drainage, aeration, and root penetration, enabling palm trees to achieve more efficient uptake of essential ions [17]. Such soils often result in higher sap quality compared to clayey or compacted soils, which may retain excessive moisture and restrict root respiration. Additionally, soil microbial communities interact with the rhizosphere of palm trees, influencing nutrient cycling and indirectly affecting sap composition. Although this relationship is less understood in palm wine research, broader agricultural literature suggests that beneficial soil microbes can increase nutrient bioavailability and improve plant metabolic profiles [18].

Several scholars have also noted significant geographical variations in palm wine quality, attributing these differences to environmental gradients, tapping methods, palm species, and soil fertility. Studies from Ghana, Cameroon, and Southern Nigeria report spatial differences in °Brix levels, alcohol yield, acidity, and flavor profiles of palm wine sourced from adjacent communities [19]. These variations underscore the importance of local environmental conditions and suggest that soil–sap relationships may differ even within the same ecological zone. However, despite these insights, limited empirical data exist linking soil physicochemical characteristics directly to palm wine quality in Benue South Senatorial District. Most available studies in Nigeria have explored microbial composition, fermentation kinetics, storage stability, or health risks associated with palm wine, with insufficient focus on the foundational environmental determinants.

Furthermore, sensory quality, which includes color, clarity, aroma, taste, mouthfeel, and overall acceptability, has been recognized as a critical dimension of palm wine research. Sensory attributes are shaped not only by intrinsic sap composition but also by fermentation temperature, microbial metabolic pathways, and environmental conditions surrounding palm trees [20]. Studies indicate that higher sugar content enhances sweetness and aroma, while balanced acidity supports brightness and freshness in taste. Off-flavors, on the other hand, are frequently linked to spoilage organisms and unsanitary tapping conditions. As such, understanding the soil–plant–sap continuum provides a more holistic perspective in evaluating palm wine quality.

Collectively, the literature demonstrates that palm wine quality is influenced by multiple interacting factors across biological, environmental, and anthropogenic dimensions. However, a conspicuous gap persists regarding the specific role of soil properties in determining physicochemical attributes, microbial load, and sensory characteristics of palm wine within Benue South Senatorial District. This study seeks to fill this gap by integrating soil analysis with a comprehensive evaluation of palm wine quality across production locations, thereby supplying new evidence relevant to food quality management, public health, and sustainable palm wine production systems.

3.0 Materials and Methods

This study adopted a comparative analytical design aimed at determining the influence of soil characteristics on the physicochemical properties, microbial load, and sensory quality of palm wine across selected production sites within the Benue South Senatorial District. The methods used were adapted from internationally recognized analytical protocols for soil science, food microbiology, and sensory evaluation, with modifications to suit local conditions and ensure reliability of results [21], [22].

3.1 Study Area and Sampling Locations

Sampling was conducted across six locations representing the major palm wine–producing communities in the district: Otukpa A, Otukpa B, Ugbokolo A, Ugbokolo B, Owukpa A, and Owukpa B. These communities differ in topography, soil fertility gradients, vegetation cover, and palm tree density. Geographic spread and environmental heterogeneity allowed for comparative evaluation of soil–sap interactions. Sampling was carried out during the peak tapping season to ensure consistency in sap flow and minimize seasonal bias.

3.2 Soil Sample Collection and Preparation

Soil samples were collected from the base of palm trees actively used for tapping. From each location, composite soil samples were obtained from a depth of 0–20 cm using a stainless-steel soil auger to prevent contamination. Three subsamples per site were homogenized to produce representative composite samples. Soil samples were stored in sterile polythene bags, labeled, transported to the laboratory, and air-dried at room temperature before sieving through a 2 mm mesh for physicochemical analyses.

3.3 Soil Physicochemical Analysis

The physicochemical parameters determined included pH, organic matter, total nitrogen (N), available phosphorus (P), exchangeable potassium (K), cation exchange capacity (CEC), and textural class. Soil pH was measured in a 1:2.5 soil-to-distilled water suspension using a calibrated pH meter. Organic matter was quantified using the Walkley–Black dichromate oxidation method. Total nitrogen was estimated using the Kjeldahl digestion and distillation technique, while available phosphorus was determined using the Bray-1 extraction method followed by spectrophotometric measurement. Exchangeable potassium was determined using flame photometry. Soil texture was classified using the hydrometer method based on particle size distribution [23], [24].

3.4 Palm Wine Sample Collection

Fresh palm wine samples were obtained directly from tappers in sterile 1 L screw-capped plastic containers. Samples were collected within 2–4 hours of tapping to prevent excessive fermentation and ensure comparability across locations. Containers were pre-sterilized with 70% ethanol and rinsed with sterile distilled water before collection. Samples were immediately transported in insulated coolers to the laboratory and analyzed within 4 hours of arrival to limit biochemical alterations.

3.5 Determination of Physicochemical Properties of Palm Wine

The physicochemical properties evaluated included pH, temperature, total soluble solids (°Brix), specific gravity, and alcohol content.

- pH was measured using a digital pH meter standardized with buffer solutions of pH 4.0 and 7.0.
- Total soluble solids (°Brix) were measured using a handheld refractometer.
- Specific gravity was determined using a 25 °C hydrometer.
- Alcohol content was quantified by distillation followed by specific gravity measurement of the distillate at 20 °C in accordance with AOAC methods.
  All measurements were conducted in triplicate to improve precision and reduce experimental error [25].

3.6 Microbiological Analysis

The microbial load of the palm wine samples was assessed using the standard plate count technique. Serial dilutions (10^{-1} to 10^{-6}) were prepared using sterile physiological saline. Aliquots (0.1 mL) from each dilution were spread on nutrient agar plates and incubated at 37 °C for 24–48 hours. Colony-forming units (CFU/mL) were determined by multiplying average colony counts by dilution factors. Distinct colonies were purified and subjected to Gram staining and biochemical characterization, including catalase, oxidase, citrate utilization, indole production, and sugar fermentation tests for proper identification of bacterial species [26], [27].

3.7 Sensory Evaluation of Palm Wine

A semi-trained sensory panel consisting of 20 assessors evaluated the palm wine samples using a structured 9-point hedonic scale. Attributes assessed included color, clarity, viscosity, sweetness, acidity, bitterness, aroma, mouthfeel, and overall acceptability. Samples were served in transparent disposable cups maintained at 10 °C. Panelists rinsed their mouths with water between evaluations. The test environment was controlled for lighting, noise, and odor to ensure unbiased assessments. Sensory evaluation protocols followed international standards for sensory analysis of fermented beverages [28].

3.8 Statistical Analysis

Data were analyzed using one-way analysis of variance (ANOVA) to determine significant differences among locations at $p < 0.05$. Means were separated using Tukey's HSD post hoc test. Statistical analyses were conducted using SPSS version 26. Results were presented in standardized tables and figures for clarity and ease of interpretation.

4.0 Results and Discussion

This section presents the results of soil physicochemical properties, microbial load, and sensory quality of palm wine samples obtained from six study locations within Benue South Senatorial District. The findings are discussed in a sequential and integrative manner, connecting soil characteristics to palm wine quality. Tables are included within the narrative to ensure clarity and accurate interpretation. Results are critically compared with established scientific literature to strengthen validity and contextual relevance.

4.1 Microbial Load of Palm Wine Across Locations

Table 1 shows that the bacterial load varied significantly across locations, with Otukpa B exhibiting the highest count (2.0×10^4 CFU/mL), while Owukpa B recorded the lowest (1.0×10^4 CFU/mL). The higher microbial load in Otukpa B may be attributed to higher sugar concentrations, warmer microclimate, and possibly less sanitary tapping conditions, all of which promote microbial proliferation. Similar observations were reported by Ogbuagu and colleagues, who linked elevated microbial counts to higher sugar availability and prolonged sap exposure [29].

Table 1: Total Bacterial Count of Palm Wine Samples (CFU/mL $\times10^4$)

Location	Bacterial Load ($\times10^4$ CFU/mL)
Otukpa A	1.3
Otukpa B	2.0
Ugbokolo A	1.1
Ugbokolo B	1.4
Owukpa A	1.3
Owukpa B	1.0

The spatial variation in microbial load across the six sampling locations is illustrated in Figure 1.

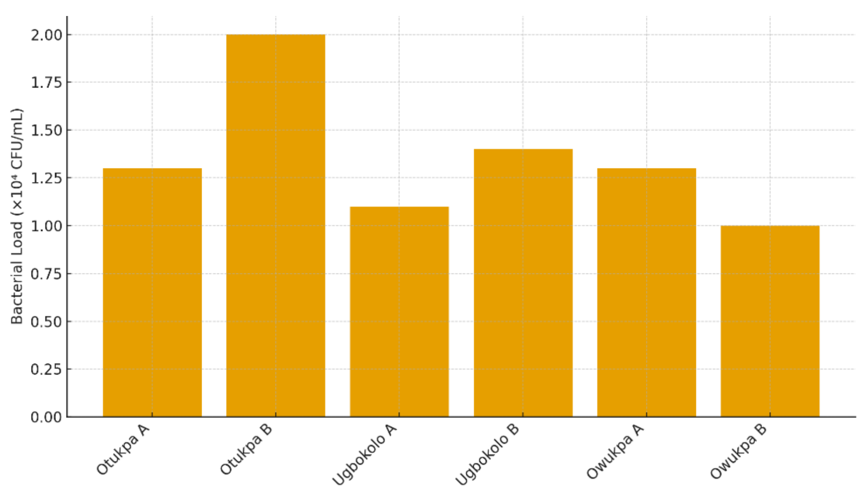

Figure 1. Bacterial load ($\times10^4$ CFU/mL) of palm wine obtained from the six sampling locations in Benue South Senatorial District.

Owukpa B's low bacterial load aligns with the community's relatively lower pH soil profile and balanced nutrient availability, suggesting that sap produced under slightly acidic soil conditions may exhibit slower microbial colonization. This finding corroborates earlier reports that palm wine from trees grown on nutrient-balanced soils tends to show a slower onset of spoilage [30].

4.2 Identification of Microbial Isolates

As presented in Table 2, the isolates obtained are consistent with those commonly found in fermented beverages. *Lactobacillus* spp. and *Staphylococcus* spp. were among the dominant organisms, supporting findings by Jahan et al. [22] and Lugha and Akpata [27], who reported similar microbial species in indigenous palm wine.

Table 2: Bacterial Isolates Identified in Palm Wine Samples

Bacterial Species	Presence
Staphylococcus spp.	+
Lactobacillus spp.	+
Micrococcus spp.	+
Serratia spp.	+
Bacillus spp.	+
Streptococcus spp.	+

The presence of *Serratia* and *Bacillus* is noteworthy; these organisms are often associated with environmental contamination and poor handling practices. Their presence thus reflects the need for enhanced sanitary tapping and storage conditions, as underscored in earlier works on traditional beverages [31].

4.3 Sensory Characteristics of Palm Wine

Significant differences in color and viscosity (Table 3) indicate that the soil environment influences the visual perception of palm wine. Locations with loamy sandy soils (Owukpa and Otukpa) produced palm wine with superior color intensity and lower viscosity, reflecting better sap quality.

Table 3: Appearance Attributes (Color, Clarity, Viscosity) – ANOVA Summary

Attribute	F-statistic	p-value	Interpretation
Color	4.32	0.015	Significant difference
Clarity	2.78	0.062	Not significant
Viscosity	8.45	0.001	Highly significant

The non-significance in clarity suggests uniformity in suspended particles across samples—likely due to similar tapping and collection methods. Literature acknowledges that clarity in palm wine is more affected by handling and storage rather than soil properties [32]. Figure 2 illustrates the differences in sweetness intensity of palm wine samples across the study locations.

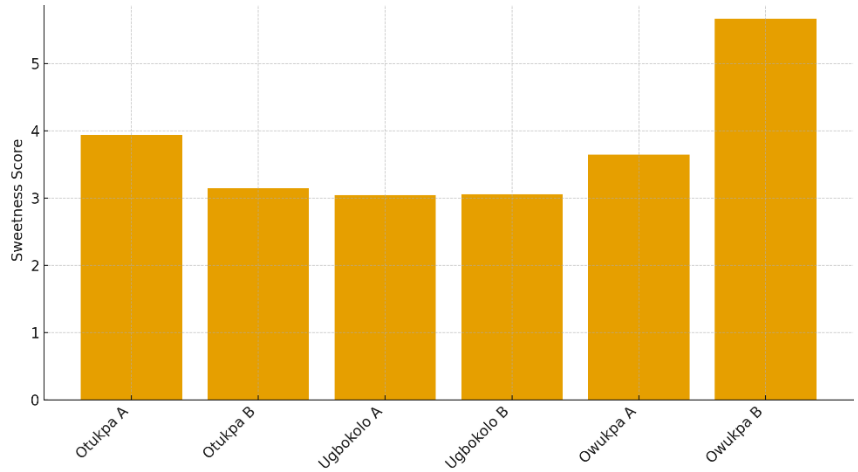

Figure 2. Sensory sweetness scores of palm wine obtained from the six sampling locations.

Owukpa B (Table 4) consistently exhibited superior sensory performance with the highest sweetness (5.67) and lowest off-odor (0.65). This aligns with its balanced soil nutrient profile, which enhances sugar biosynthesis in palm trees. Similar findings were reported by Karamoko et al., who associated higher sugar content with improved aroma profiles in palm sap [14].

Table 4: Mean Aroma Scores for Palm Wine Samples

Location	Sweetness	Fruity Notes	Fermented/Bready	Off-Odor
Otukpa A	3.94	2.75	3.63	0.85
Otukpa B	3.15	2.39	3.49	2.00
Ugbokolo A	3.05	2.01	3.23	2.45
Ugbokolo B	3.06	2.35	3.04	2.05
Owukpa A	3.65	2.44	3.63	2.35
Owukpa B	5.67	2.93	2.64	0.65

In contrast, Ugbokolo samples recorded lower sweetness and higher off-odor scores, likely due to nutrient-poor loam soils (particularly low K levels), limiting carbohydrate synthesis.

Taste attributes (Table 5) further reinforce the dominance of Owukpa B, with the best overall flavor score (4.39). The higher acidity in Otukpa B and Ugbokolo samples suggests more intense fermentation due to higher microbial activity, aligning with observed bacterial loads.

Table 5: Mean Taste Attributes of Palm Wine Samples

Location	Sweetness	Acidity	Bitterness	Overall Flavor
Otukpa A	3.68	2.62	0.30	3.64
Otukpa B	3.02	2.74	0.30	3.58
Ugbokolo A	2.88	2.60	0.30	2.99
Ugbokolo B	2.25	2.48	1.10	3.05
Owukpa A	2.86	2.19	1.00	3.64
Owukpa B	2.96	1.53	1.10	4.39

The generally low bitterness values reflect the natural characteristics of palm sap, as documented by Santiago-Urbina and Ruiz-Teran [1], indicating the absence of spoilage compounds, such as phenolics, associated with oxidation or contamination.

4.4 Soil Physicochemical Properties and Their Influence on Palm Wine Quality

Soil data (Table 6) indicate that loamy sandy soils (Owukpa and Otukpa) generally possessed better nutrient balance and organic matter conducive for palm tree metabolism. Notably, Owukpa A and B exhibited higher organic matter and nitrogen content, which are essential for carbohydrate synthesis in palm trees.

Table 6: Soil Physicochemical Properties of Sampling Sites

Location	pH	Organic Matter (%)	Nitrogen (%)	Available P (mg/L)	K (Cmol/kg)	Texture
Otukpa A	6.58	1.03	0.052	5.33	0.26	Loamy sand
Otukpa B	6.55	0.70	0.041	5.06	0.25	Loamy sand
Ugbokolo A	6.00	1.20	0.063	5.64	0.27	Loam
Ugbokolo B	5.81	0.34	0.034	3.81	0.17	Loam
Owukpa A	5.31	1.38	0.069	5.71	0.27	Loamy sand
Owukpa B	5.88	1.21	0.067	5.68	0.27	Loamy sand

The positive relationship between soil nutrient levels (N, P, K) and palm wine sweetness/aroma is consistent with earlier reports showing that nutrient-rich soils promote higher sap °Brix and improved sensory attributes [33].

Conversely, nutrient-deficient loam soils in **Ugbokolo B** (low OM = 0.34% and low K = 0.17 Cmol/kg) were associated with the poorest sensory scores and slightly elevated microbial loads, indicating weaker biochemical stability of sap.

The soil pH range (5.31–6.58) falls within the favorable range for oil palm physiology, but the lower pH observed in Owukpa A may have contributed to moderate microbial loads due to increased acidity tolerance of lactic acid bacteria [14], [27].

Overall, the results underscore that soil quality directly influences palm wine characteristics, validating the soil–plant–sap continuum highlighted in recent agronomic literature [34]. Figure 3 provides a graphical comparison of soil organic matter levels across the six sampling locations.

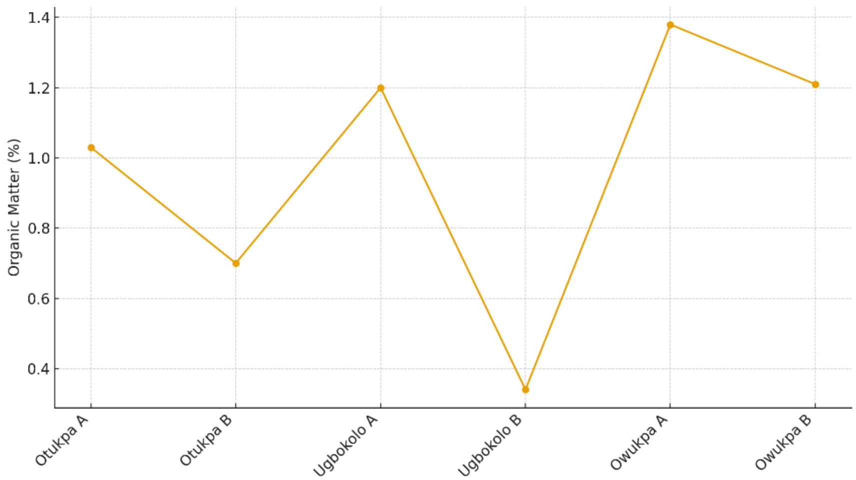

Figure 3. Organic matter (%) content of soils surrounding palm wine–producing palm trees in the six study locations.

Critical Interpretation

1. Soil nutrient balance is the strongest determinant of palm wine sensory quality. Owukpa B, with optimal OM, N, and K levels, consistently outperformed other locations.
2. Microbial quality correlates with both soil pH and tapping hygiene. Higher bacterial loads in Otukpa B reflect both high sugar availability and probable lapses in handling.
3. Physicochemical and sensory parameters are interconnected. Lower viscosity and superior aroma profiles correspond to nutrient-rich loamy sand soils.
4. The study provides evidence that soil–based interventions can enhance palm wine quality, which aligns with broader agroecological findings linking soil fertility to fruit sap quality.

5.0 Conclusion and Recommendations

5.1 Conclusion

This study demonstrated that soil physicochemical properties significantly influence the quality of palm wine produced across Benue South Senatorial District. Palm wine from locations with nutrient-rich loamy sand soils, particularly Owukpa B, showed superior sweetness, aroma, appearance, and lower microbial load. In contrast, nutrient-poor loam soils, such as Ugbokolo B, produced palm wine with lower sensory scores and slightly higher contamination. The presence of common fermentative and contaminant bacteria highlights the combined effects of soil conditions and tapping hygiene on palm wine quality. Overall, the findings confirm that soil fertility, sap biochemical composition, and sanitary handling practices jointly determine the sensory, physicochemical, and microbiological characteristics of palm wine.

5.2 Recommendations

i Improve Soil Fertility: Producers should enhance soil organic matter and N–P–K levels through organic amendments, especially in nutrient-deficient areas.

ii Prefer Optimal Sites: Palm wine tapping should be prioritized in locations with loamy sand soils that consistently yield higher-quality sap.

iii Strengthen Hygiene Practices: Tappers must sterilize tools, use clean containers, and limit sap exposure to reduce contamination by spoilage organisms.

iv Early Handling and Storage: Palm wine should be collected, transported, and consumed or processed promptly to minimize microbial growth.

v Capacity Building: Local training programs should promote good soil management, hygienic tapping, and safe handling techniques.

vi Further Research: Additional studies should explore soil microbial interactions, seasonal soil effects on sap quality, and controlled fermentation using beneficial native microbes.

Declarations

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the conduct or publication of this study.

Ethical Approval

No human or animal subjects were involved in this study. All procedures for sample collection and laboratory analysis complied with institutional and national research guidelines.

Consent to Participate and Consent for Publication

Not applicable.

Data Availability

All data generated or analyzed during this study are included in this manuscript and are available from the corresponding author upon reasonable request.

Authors' Contributions

All authors contributed to the study conception, design, data collection, analysis, interpretation, and manuscript preparation. All authors reviewed and approved the final manuscript.

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