Investigational
Medicinal Chemistry & Pharmacology

Research Article **Open Access**

Investigation of heavy and trace metals contamination in palm wine and locally brewed alcohol from the Ashanti Region of Ghana

Moses Atosiko Agbala*, Joseph Kwasi Adu, John Nii Adotey Addotey

Abstract

Background: Palm wine and locally produced alcoholic beverages are widely consumed in rural communities in Africa, due to their perceived health benefits. However, their safety regarding heavy and trace metal contamination is lacking, particularly in Ghana. This study quantitatively assessed heavy-metal contamination in fresh palm wine (FPW), fermented palm wine (FEPW), freshly brewed alcohol (FAL), and stored alcohol (SAL) from 5 brewing sites in the Ashanti region of Ghana.

Methods: Palm wine and locally brewed alcohols were collected and wet digested with nitric acid. Digested samples were analyzed for heavy and trace metals using an atomic absorption spectrophotometer (AAS).

Results: The mean concentration (mg/L) of five selected metals, namely zinc (Zn), copper (Cu), iron (Fe), aluminum (Al), Lead (Pb), and silver (Ag), were investigated. Pb and Ag were below detectable limits across all investigated sites. Cu and Fe had the highest mean concentrations, with Cu at 25.200 mg/L in SAL and Fe at 21.060 mg/L in FEPW. Al and Zn remained consistently low across all samples, generally maintaining levels below 1.200 mg/L and 0.700 mg/L, respectively.

Conclusion: The concentrations of metals in the raw palm sap and brewed alcohol (*akpeteshie*) generally exceeded recommended levels, rendering them unsafe for consumption. However, Cu levels in all fresh palm wine and all analyzed metals in fresh palm wine from Juaben 2 and Effiduasi Asokore were within moderately safe limits.

Keywords: Akpeteshie production; Atomic absorption spectrophotometer; Local distillation; Sample digestion.

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Citation on this article: Agbala MA, Adu JK, Adotey Addotey JN. Investigation of heavy and trace metals contamination in palm wine and locally brewed alcohol from the Ashanti Region of Ghana. Investigational Medicinal Chemistry and Pharmacology (2026) 9(1):127; Doi: https://dx.doi.org/10.31183/imcp.2026.00127

Invest. Med. Chem. Pharmacol. (IMCP) ISSN: 2617-0019 (Print)/ 2617-0027 (Online);

Background

The production and consumption of palm wine and locally brewed alcoholic beverages are common practices among various tribes in Ghana. However, some local brewers add metallic substances, such as iron nails, based on the belief that metal additives enhance alcohol yield. This has raised concerns and increased research interest in the potential contamination of these indigenous beverages with toxic metals [1-2].

Different types of palm species exist across the world from which palm wine can be obtained. However, the most common ones from Africa, especially in Ghana and Nigeria, are oil palm (*Elaeis guineensis*) and *Raphia* specie. The former is preferred for the production of palm wine and, subsequently, for producing local alcohol (*akpeteshie*) in Ghana [3].

Palm wine is a sweet, milky, and effervescent sap obtained from palm trees. It is composed of several essential nutrients, including vitamins, sugars, proteins, and amino acids, which contribute to human growth and development [4-5]. Fresh palm sap contains several compounds, with sucrose accounting for about 12-15% w/v of the total [6]. Aside from sucrose, small amounts of reducing sugars such as glucose, fructose, maltose, and raffinose are present [4]. Apart from sugars, the sap comprises 0.23 % w/v protein, 0.02 % w/v fat, mineral matter, and vitamin C 5.7×10^{-3} g/100 mL [7]. This makes palm wine useful to the human body or system. Making it widely consumed across many African countries, including Ghana, Nigeria, and Cameroon, as well as in some non-African countries such as India and Brazil [8]. Due to its widespread consumption, palm wine is known by different names across different regions and countries. For example, it is referred to as "*nsafufuo*" in southern Ghana, and "*Emu*" in Nigeria [9].

Palm wine is found inside the stem of a palm tree. A tapper extracts the sap through tapping. Generally, there are two methods of tapping palm sap from palm trees [8]. Firstly, it involves tapping a live palm tree by cutting its blossom, then fixing a container or gourd to the blossom stump to collect the palm sap [8]. The white, clear sap collected at first is sweet and non-alcoholic, but over a long storage period, unconstrained fermentation occurs due to the innate yeast present in the sap. Secondly, is tapping from a felled palm tree. This type of palm wine tapping requires that the tapper fells the palm tree for certain days (5 to 7 days) before the tapping process [10]. An opening of about 15 cm is cut on the stem of the palm tree, and fire is sometimes lit at the sliced end to quicken the fast flow of the palm sap [11]. A container or gourd is then positioned under the opening to collect the palm sap. The latter is generally practiced in Ghana, while both tapping methods are practiced in Nigeria and other countries.

The consumption rate of palm wine and akpeteshie is high because they are inexpensive, sweet when fresh, and thirst-quenching. Palm wine consumption is commonly believed to enhance vision and promote the rapid flow of breast milk in nursing mothers [5]. In addition, palm wine plays an important sociocultural role in Ghana and across Africa. Again, it is sometimes combined with medicinal herbs by local herbalists for the treatment of various ailments [9].

Fresh palm sap, naturally sweet, provides a favorable environment for microbial growth and multiplication. The sap undergoes natural fermentation due to the presence of inherent yeast and other microorganisms. These aid in the conversion of sugars into products such as ethyl alcohol and ethanoic acid [11]. Moderately fermented palm wine has been recognized by national authorities and primary care providers for its potential benefits in disease therapy and in the management of malnutrition, including vitamin A and C deficiencies [12].

Metals are an essential component of the human diet and play vital roles in physiological processes. However, excessive intake can result in severe human health challenges. Some metals can bioaccumulate, making them increasingly toxic after ingestion through food or beverages. Earlier research revealed that the rate at which metallic ions or their compounds are eliminated or metabolized is much lower than the rate at which they accumulate in the living system [13]. Metal contamination of food or drinking substances continues to increase. This contamination is often due to industrial waste, the food chain, geographic location, type of storage material, and anthropogenic activities around food or drinking substances [14].

Heavy metals, which occur naturally, are usually non-toxic to the environment because they occur only at trace levels or in insoluble form. Notwithstanding, when these metals exceed their health-recommended levels of consumption, their desired roles in the human body shift to harmful effects. Food and water are the main direct routes of heavy metal uptake into the human system, while industrial and agricultural activities are the indirect routes of exposure to heavy metals [15]. Heavy metals such as mercury (Hg), lead (Pb), arsenic (As), and cadmium (Cd) are toxic with no known biological benefits. On the contrary, trace elements such as copper (Cu), iron (Fe), and manganese (Mn) are essential for human survival at recommended amounts [16].

Palm wine and locally brewed alcohol (*akpeteshie*) play important roles in ceremonies, human nutrition, and local medicine. Concerns remain about contamination with toxic elements arising from local collection methods, the fermentation process, and distillation. The conversion of fermented palm wine into alcohol through heating is a method for producing *akpeteshie* in Ghana and other African countries. The production process is of concern because, at some brewing sites, metals such as iron nails are deliberately added to enhance fermentation. This increases the risk of introducing toxic metals into the final product, potentially posing serious health risks to consumers.

The consumption of palm wine and *akpeteshie* in Ghana is widespread, with both beverages sold in bulk or in smaller volumes in boutiques, restaurants, and bars. Despite the lack of formal advertising, *akpeteshie* remains highly popular, largely due to its affordability compared to bottled and imported alcoholic beverages. Due to high consumption rates and potential contamination, it is imperative to assess the safety of these beverages, particularly with respect to heavy and trace metal content. Therefore, this study aimed to quantitatively determine the concentrations of heavy and trace metals in palm wine and locally brewed alcohol collected from five different sites within the Ashanti Region of Ghana. For precise, reliable, and accurate analysis of heavy and trace metal ions in liquid samples, inductively coupled plasma-mass spectrometry (ICP-MS) and atomic absorption spectrophotometry (AAS) are good choices. However, AAS was preferred to ICP-MS because it is cheaper and readily available.

Methods

Reagents, chemicals, and equipment

All the reagents used in this study were of analytical grade and were obtained commercially from Fisher Scientific ™ (United Kingdom) and BDH chemicals (United Kingdom). Nitric acids (68%, Merck, Germany) and standard stock solutions (1000 mg/L) of Ag, Pb, Fe, Zn, Cu, and Al (Merck, Darmstadt, Germany) were also used for sample digestion and calibration, respectively.

Sample containers and glassware were washed and cleaned with washing powder-detergent grade, soaked in 20% (v/v) nitric acid for a day, and finally rinsed several times with double-distilled water. All metal standards, diluted, and analytical solutions were prepared with deionized water (Siemens Water Technologies – Ultra Clear RO EDI 10) before AAS analysis. The equipment and instruments used in this study were a VELP Scientifica Hot plate (Usmate Velate, Italy), a Binatone refrigerator (model FR-2300), and an Atomic Absorption Spectrophotometer (Analytik Jena novAA 400P, Germany).

Sampling strategy

The study was conducted in the Ashanti Region of Ghana, specifically targeting three major palm wine and local Alcohol (*Akpeteshie*) production hubs: Juaben, Apincra, and Effiduase Asokore (EA). These locations were selected via purposive sampling to ensure a representative cross-section of local artisanal distillation practices within the region. To account for localized environmental and equipment-related variance, two distinct sampling points were established in Juaben (J1, J2) and Apincra (A1, A2), along with a single point in Effiduase Asokore (EA). A longitudinal batch-tracking approach was employed to monitor the evolution of heavy metal concentrations, specifically Zn, Fe, Cu, Pb, Ag, and Al, through the entire value chain. Samples were collected from the same production batch at four main processing stages: Fresh Palm Wine (FPW), Fermented Palm Wine (FEPW), Fresh Alcohol (FAL), and Stored Alcohol (SAL). FPW represents raw sap collected immediately after tapping. FEPW was the palm sap after a standard fermentation period. FAL was the immediate distillate collected from the local distillation apparatus. SAL was the final product after a period of storage in local containers.

Sample collection and storage

Palm wine and locally brewed alcohol (*akpeteshie*) were obtained from brewing sites in the Ashanti Region of Ghana. Palm wine samples consisted of fresh palm wine and fermented palm wine, which were 5-9 days old. The locally brewed alcohol samples comprised freshly brewed alcohol (zero-day-old) and stored alcohol aged 1-3 days after brewing. The samples were collected from five sites across three communities in the Ashanti Region of Ghana. The sampling locations included Juaben (two different sites: Juaben 1 and Juaben 2), Effiduase Asokore (one site), and Apincra (two sites: Apincra 1 and Apincra 2). These locations were chosen because they are among the most palm-dense areas where major palm wine and locally brewed alcohols are produced in the Ashanti region of Ghana. About 500 mL of each sample was collected into a clean and airtight plastic container. All the samples were immediately transported to the laboratory in an ice container containing an ice block to inhibit enzymatic and microbial activity. To minimize analyte loss or contamination, samples were collected carefully to ensure they were representative of their respective batches. This was done by taking samples from different depths, particularly the top, middle, and bottom of each sample. The proportions were mixed to representation. To ensure statistical rigor and minimize experimental error, all samples were collected and analyzed in triplicate (n=3). This provided a robust assessment of how local distillation equipment, such as copper cooling coils and aluminum vessels, contributes to metallic contaminations. All the samples were stored in a Binatone refrigerator (model FR-2300) until sample preparation for analysis was completed. Figure 1 shows the locations where samples were collected in the Ashanti Region of Ghana.

Sample preparation and analysis

An aliquot of 50 mL from each sample was digested with 68% nitric acid before AAS analysis.

Digestion procedure

Nitric acid wet digestion of the samples was carried out as follows:

1. Each sample was measured (50 mL) and transferred into a Pyrex glass beaker, after which 10 mL of nitric acid (HNO_3) was added.
2. The mixture was gently swirled to ensure proper mixing, then placed on a hot plate at 60 to 105˚C ± 5˚C for 30 minutes.
3. Exactly 10 mL of HNO_3 was added to each sample just when the solution began to boil.
4. A yellowish color formed during the process disappeared, leaving a clear solution.
5. The solution was cooled to room temperature for 30 minutes after removal from the hot plate.
6. The resultant solution was filtered (using Whatman no. 42 filter paper) into a Teflon airtight container, correctly labeled, and stored in a refrigerator pending AAS analysis.

The digestion was carried out alongside a reagent blank without the sample while keeping the digestion procedure and conditions constant, following standard methods [17-18] with modifications. Flame Atomic Absorption Spectrometry (FAAS) was used to analyze the metal standards and the absorbance of the selected metals. Analysis was carried out in triplicate on each sample for each metal determination. The concentrations of selected metals were calculated from calibration curves of the metal standards.

Calibration standards preparation and analysis

Working standards (5) at 1000 mg/L for each metal (Cu, Zn, Pb, Al, Ag, and Fe) were prepared for calibration using a diluent (1% HNO_3). For accurate and reliable analysis of the analyte of interest, all solutions were prepared in accordance with quality control measures. The instrument was calibrated with a blank (1% HNO_3). The concentration range from which calibration curves for each metal standard were obtained were: 1, 2, 3, 4, and 5 mg/L for Ag, 2, 4, 6, 8, and 10 mg/L for Al, Cu, and Pb. 0.2, 0.4, 0.6, 0.8, and 1.0 mg/L for Fe and Zn. The different concentrations are due to differences in the detection limits of the individual metals. Metal concentrations in the samples were quantified by FAAS using an internal calibration curve, after optimization of instrument conditions to achieve the highest signal strength. For each standard, sample, and blank, 3 replicate analyses were carried out. The working parameters for AAS analysis of the samples are presented in Table 1.

Statistical analysis

Heavy and trace metals were analyzed in triplicate, and the results were averaged. These replicates were used for a one-way analysis of variance at the 95% confidence level ($P < 0.05$) using GraphPad Prism version 8 and Microsoft Excel (2016). All data were reported as mean ± standard deviation (Mean ± SD). The data were statistically analyzed to assess whether there were significant differences in the levels of each heavy or trace metal across processing stages and between sample sites.

Results

Heavy and Trace Metals Determination

The levels of Zn, Cu, Al, Fe and Ag were quantified in triplicate using AAS. The results are presented in Figures 2 to 5 in the form of mean and standard deviation. The concentrations and trends of each metal across the different processing stages are separately outlined.

Zinc

In the initial Fresh Palm Wine (FPW) stage, concentrations were relatively low, ranging from approximately 0.090 to 0.250 mg/L (Figure 2). However, a significant divergence occurs during fermentation (FEPW), most notably at the Juaben 1 (J1) site, where Zn levels peak sharply at a mean of 0.620 mg/L. This spike, characterized by a high standard deviation, suggests localized environmental factors or container leaching during fermentation. Conversely, the distillation to Fresh Alcohol (FAL) marked a universal decline in Zn content across all batches, likely due to the metal's low volatility during distillation. At the final Stored Alcohol (SAL) stage, Zn levels were stabilized between 0.040 and 0.150 mg/L, indicating that subsequent storage does not introduce further metallic contamination. This data confirmed that while fermentation can temporarily increase Zn solubility, the distillation process effectively purifies the final alcohol.

Iron

In the Fresh Palm Wine (FPW) stage, Fe levels ranged from baseline levels, with Juaben sites (J1, J2) showing near-zero concentrations, while Effiduase Asokore (EA) and Apincra 2 (A2) started at approximately 12.500 mg/L (Figure 3). A dramatic increase occurs during the fermentation (FEPW) stage, with EA peaking at 51.000 mg/L and A2 reaching 42.000 mg/L. This pronounced surge, characterized by notable standard deviations, suggested that the fermentation environment or vessel types may facilitate Fe leaching or solubility. Conversely, the transition to Fresh Alcohol (FAL) initiated a sharp decline across the high-concentration sites, with EA and A2 dropping to approximately 11.000 to 12.000 mg/L. This reduction confirmed the efficacy of distillation in sequestering heavy metals, as Fe remains largely non-volatile. At the final Stored Alcohol (SAL) stage, concentrations remained stable, clustering between 7.000 mg/L and 13.000 mg/L. This plateau indicated that the storage phase does not introduce further metallic contamination, resulting in a final product with significantly lower Fe content than the intermediate fermented wine.

Copper

At Fresh Palm Wine (FPW) and Fermented Palm Wine (FEPW) stages, Cu levels remained remarkably low across all sites, hovering near 0.000 mg/L (Figure 4). A notable shift occurred during the distillation to Fresh Alcohol (FAL), where concentrations began to rise, particularly at the Apincra sites (A1 and A2), which reached approximately 7.000 mg/L. This emergence of Cu post-distillation likely indicated the leaching of Cu from components within the local distillation apparatus. The most significant increase was observed in the Stored Alcohol (SAL) stage, where concentrations for A1 and A2 skyrocketed to approximately 25.000 mg/L and 24.000 mg/L, respectively. In contrast, the Juaben (J1, J2) and Effiduase Asokore (EA) sites maintained much lower and more stable levels, clustering between 3.000 mg/L and 5.000 mg/L during storage. The substantial increase and high variability observed at the Apincra sites suggested that specific storage vessels or prolonged contact with reactive containers were major sources of secondary Cu contamination. This trend highlights a critical accumulation of Cu, which distinguishes it from the reduction patterns observed in Zn and Fe processing.

Aluminum

Aluminum was already present, with concentrations ranging from 0.320 mg/L at Effiduase Asokore (EA) to 0.800 mg/L at Apincra 1 (A1) in Fresh Palm Wine (FPW) (Figure 5). A general increase was observed during the fermentation (FEPW) stage, where A1 and A2 reached approximately 1.050 mg/L. This suggested that the fermentation environment facilitates the leaching of the metal into the wine. The distillation (FAL) stage revealed divergent site behaviors: while most locations showed a reduction, site A2 continues to rise, peaking at 1.200 mg/L. This anomaly suggests the potential use of Al materials in the distillation apparatus at that site. At the final Stored Alcohol (SAL) stage, concentrations for A1 and A2 remained high, hovering around 1.000 mg/L, while Juaben 1 (J1) maintains the lowest final level at approximately 0.200 mg/L. These results indicated that, unlike Fe and Zn, Al levels do not consistently decrease after distillation. The final metallic load is heavily dependent on site-specific equipment and storage conditions.

Discussion

This study tracked heavy and trace metals concentrations across three distinct stages: Fresh Palm Wine, Fermented Palm Wine, and distilled alcohol (*Akpeteshie*). Comparing these findings to related literature was a little difficult because most studies do not record the specific duration of the collection process for fresh palm wine. Furthermore, related studies do not mention the exact duration of the fermentation period before distillation into *akpeteshie*. These temporal factors are crucial, as the duration directly affects metal leaching and concentration.

The Zn concentrations across all stages, as seen in Figure 2, remained consistently below the World Health Organization (WHO) permissible limit of 3 mg/L [19]. This suggests that consumption of these beverages from all the studied sites poses a minimal risk of Zn-induced toxicity, such as kidney damage or muscle cramps, which is often associated with higher ingestion [20].

While the levels were safe, the statistical analysis revealed significant variation in Zn concentrations across the sampling sites ($p < 0.004$). This study suggests that these differences were not random but were likely attributable to distinct environmental factors and geographical locations [21]. The specific application of Zn-containing fertilizers or pesticides during palm cultivation was a primary driver of the higher baseline levels observed in Effiduase Asokore compared to Juaben [22].

A major observation of this study was the behavior of Zn levels during processing. Although ANOVA indicated no significant difference across processing stages ($p \leq 0.44$), analysis of the fermentation stage revealed a localized, statistically significant increase. Notably, Zn levels increased from fresh to fermented palm wine across all sites, with Juaben 1 (J1FEPW) exhibiting a concentration 3 times higher than its fresh counterpart. Since Zn is neither a reducing nor an oxidizing agent and does not naturally change state to increase quantity [23]. However, the increase may be exogenous. We posit that this elevation resulted from leaching. The use of metallic storage containers, roofing sheets used as lids, and "tin-tomato" cups for the transfer of palm wine likely introduced Zn into the acidic fermenting medium [24]. Furthermore, the spikes in Juaben 1 samples relied on the assumption that the specific storage container used at this site was zinc-based or galvanized, rendering it highly prone to leaching when in contact with the wine.

The distillation process (brewing into Fresh Alcohol) significantly reduced Zn concentrations. This reduction aligned with the mechanism where metal ions complex with precipitated trub during boiling, effectively removing them from the liquid phase [25].

However, the final stage storage reintroduced variability. Fermented palm wine showed a relative increase in Zn compared to the other stages of samples. The increase was likely due to leaching from storage vessels over the 2–4 day storage period [24]. Conversely, the decrease observed at site A2 (A2SAL) was a novel finding, suggesting that the specific storage material used at this site may possess zinc-absorbent properties, distinct from the standard containers used at other sites. Despite Zn's essential role in human development, excess intake can lead to toxicity [20].

Iron is essential for physiological function, yet excessive accumulation can lead to organ dysfunction [26]. Unlike Pb and Pb, Fe concentrations consistently exceeded the World Health Organization (WHO) permissible limit of 0.3000 mg/L [19] across most sampling sites and processing stages. This raises a potential public health concern about Fe overload among regular consumers of these beverages.

Statistical analysis showed no significant difference in mean Fe concentrations across sites generally ($p \leq 0.77$). However, specific locations displayed distinct anomalies. Apincra (A1 and A2) samples exhibited the highest initial concentrations (4.934 mg/L and 6.714 mg/L, respectively) in terms of fresh palm wine (FPW). Effiduase Asokore (EA) and Juaben 2 (J2) samples were the only ones within safe limits (< 0.300 mg/L). These high baseline levels could be attributed to geographical mineral abundance [27] and agricultural practices. It is suggested that the high Fe levels in the fresh sap result from either the absorption of iron-rich fertilizers/soil through the palm roots or direct contamination from the metallic tools (cutlasses, knives) used during tapping [22]. A significant variation was observed between processing stages ($p \leq 0.01$). Lactic acid bacteria activity during fermentation enhances Fe bioavailability [28]. The substantial increase in Fe concentration might have come from metallic fermentation vessels, which are susceptible to acid corrosion, leading to metal leaching. The fermentation process may have led to a significant increase in Fe levels, particularly in A1FEPW (19.220 mg/L) and A2FEPW (21.060 mg/L).

Distillation generally reduced Fe concentrations, likely due to thermal loss or complexation during heating, though levels remained above WHO limits [19]. The slight increase in J2FAL suggests localized contamination during the brewing process [16]. Storage (SAL) typically resulted in renewed increases in Fe levels. This is likely due to dilution with groundwater containing Fe salts [29] or leaching from storage containers. Conversely, site A1 showed a decrease during storage. This implied that the specific storage vessel used there was non-reactive, or the dilution water was treated with a metal adsorbent, effectively reducing the Fe levels. The Fe levels (1.980 mg/L) reported in locally brewed alcohol (*akpeteshie*) from Ho Municipality [30] were lower than those in the current study (Figure 3).

All Fresh Palm Wine (FPW) samples, across all sites (J1, J2, A1, A2, and EA), contained Cu levels well below the WHO and GSA permissible limit of 2.000 mg/L [19]. This indicated that the raw sap was safe for consumption with respect to Cu toxicity. Despite the overall safety of the fresh sap, there was a statistically significant variation ($p \leq 0.005$) in Cu concentrations. It is suggested that the soil at site J1 was either naturally richer in Cu or subject to higher applications of Cu-containing fertilizers and pesticides compared to the EA site [22].

During the fermentation stage (FEPW), Cu levels increased across all sites, remaining within safe limits. This increase was likely twofold. Firstly, minor contamination from storage vessels occurred. Secondly, biochemical oxidation may play a role. Cu exists as Cu^{+}, Cu^{2+}, and Cu^{3+}, though Cu^{3+} is biologically irrelevant [31]. We posit that the oxidizing environment of fermentation facilitated the conversion of Cu^{+} to the more stable Cu^{2+}, effectively increasing the detectable free Cu in the solution.

The distillation stage (Fresh Alcohol - FAL) marked a drastic shift in safety. Unlike fresh sap (Fresh palm wine – FPW), the distilled alcohol samples largely exceeded the permissible limit of 2.000 mg/L. While J2FAL was only slightly elevated (2.183 mg/L), sites A1 and A2 exhibited markedly higher concentrations reaching 6.742 mg/L and 6.676 mg/L, respectively. This suggests that the distillation process itself was the primary source of heavy metal contamination. Based on reports of trace metal contamination in Nigerian alcoholic beverages, some brewers use Cu equipment, leading to substantial leaching during heating [16]. Distillers at sites A1 and A2 may have used equipment predominantly made of Cu, leading to substantial leaching during heating.

The major concerns in this study were Stored Alcohol (SAL). Instead of stabilizing, Cu levels increased further, approximately quadrupling in A1SAL and A2SAL compared to their fresh alcohol counterparts. These levels are far beyond any safety standard [19]. This massive increase points to post-distillation handling. These secondary spikes may have resulted from two factors: storage containers, which were likely copper-based or reactive alloys, or the water used to dilute the alcohol for sale, which may have contained dissolved Cu salts [32], further compounding the contamination.

In contrast, Cu levels in *akpeteshie* (locally brewed alcohol) from the Ho Municipality (Volta Region, Ghana) ranged from 1.39 to 4.12 mg/L [30]. Levels lower than both fresh and stored akpeteshie. Although both regions exceed safety standards, the peak concentration in the Ashanti hubs is nearly 64% higher than the maximum recorded in Ho.

It is worth noting that while the specific spikes in alcohol were massive, the overall ANOVA for processing stages ($p \leq 0.09$) and within sites ($p \leq 0.21$) did not show broad statistical significance across the *entire* dataset. This indicates that Cu contamination was not a uniform, systemic issue but rather a localized hazard specific to the equipment choices (distillation and storage) at sites like A1 and A2.

The biological importance of Al remains largely undefined, yet its abundance in the earth's crust is well established [27]. Aluminum concentrations in Fresh Palm Wine (FPW) across all sampling sites exceeded the World Health Organization's permissible limit of 0.2000 mg/L [19] (Figure 5). This was significant, given that high levels of Al are detrimental to human health, particularly by interfering with organelles and disrupting cell detoxification processes [33].

Although statistical analysis indicated no significant difference in the mean Al concentration across the different fresh palm wine sites ($p \leq 0.05$), the absolute levels varied substantially (Figure 5). The presence of Al above permissible limits in the raw sap suggests external contamination sources beyond natural elemental abundance [27]. It is suggested that this elevation is attributable to environmental pollution and the application of farming chemicals containing Al compounds in the plantation areas [22]. Furthermore, cross-contamination from containers used during the tapping process may be a contributing factor.

Analyzing the processing stages reveals distinct trends in metal accumulation and reduction. While there was no statistically significant variation in mean Al concentration across processing stages overall ($F(4, 16) = 0.7682$, $p \leq 0.56$), site-specific differences were significant ($F(1.583, 6.333) = 5.343$, $p \leq 0.05$). Notably, Al levels increased during fermentation (FEPW) compared to the fresh sap. This suggested that the fermentation stage introduced new contamination, possibly through leaching from fermentation vessels or the deliberate introduction of chemical additives by brewers to accelerate the process. As brewers typically dilute fresh alcohol to lower concentrations, the dilution water may contain Al salts, thereby recontaminating the product. The stability of Al levels in the J1SAL sample supports this hypothesis, indicating that the dilution using water or the storage container was free of Al contamination.

Given the severe health risks associated with Pb toxicity, strict monitoring of drinking water to ensure compliance with the WHO permissible limit of 0.010 mg/L is critical [12]. Notably, Pb was not detected or quantified in any sample batch across all processing stages and sites. As in the current study, [30] explicitly reported Pb as undetected. This suggests that lead was not a significant contaminant in these specific artisanal value chains. This further suggested that palm wine products from these regions do not pose a risk of Pb poisoning to consumers. Based on this, the farms where the palm trees were cultivated were likely free from soil-based Pb contamination. Furthermore, the data suggested that the processing equipment did not introduce Pb contaminants during brewing or storage.

The complete absence of detectable Ag in all samples (fresh palm wine, fermented wine, fresh alcohol, and stored alcohol) was a positive indicator in terms of the safety of the production process. Though WHO (2003) notes that average Ag concentrations in natural waters are typically 0.0002 mg/L [19]. No specific permissible limit for the metal in drinking water has been explicitly stated. The fact that Ag was below detection limits at all sites suggests that the materials used throughout the processing chain, from tapping containers to storage vessels, did not introduce Ag contaminants.

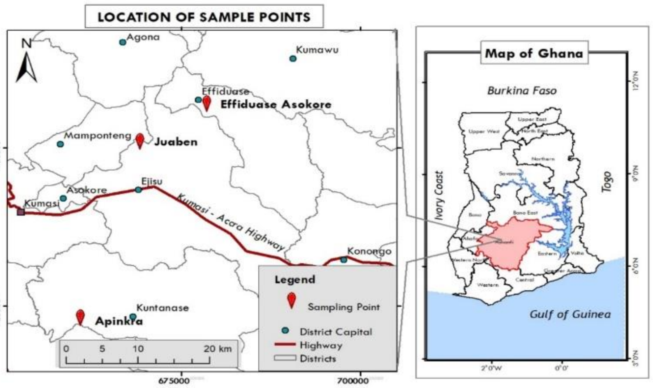

Figure 1. Study area map indicating the sampling points (generated using ARCGIS software and Ghana shapefiles) in the Ashanti Region of Ghana.

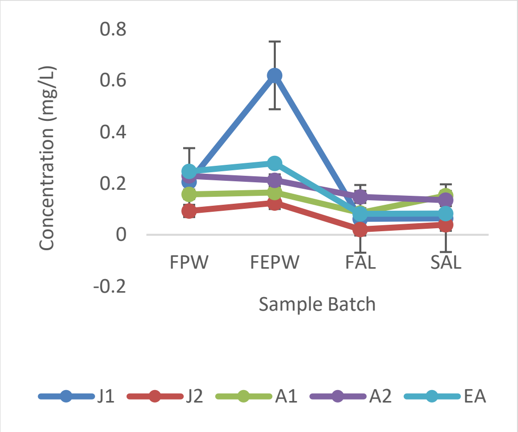

Figure 2. Variations in Zinc (Zn) content (mg/L) across different batch processing stages.

Results were presented as mean concentration and standard deviation (mean ± SD, n= 3) of Zinc content in four different batches (FPW, FEPW, FAL and SAL). Sample sites include: Juaben 1 (J1), Juaben 2 (J2), Apincra 1 (A1), Apincra 2 (A2) and Effiduase Asokore (EA) in the Ashanti region. FPW; Fresh Palm Wine, FEPW; Fermented Palm Wine, FAL; Fresh Alcohol, SAL; Stored Alcohol.

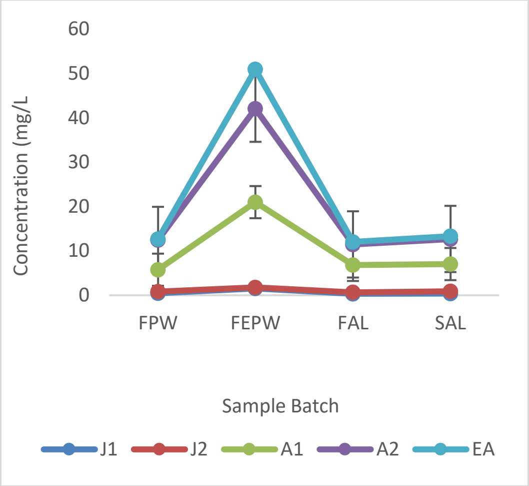

Figure 3. Variations in Iron (Fe) content (mg/L) across different batch processing stages.

Results were presented as mean concentration and standard deviation (mean ± SD, n= 3) of iron content in four different batches (FPW, FEPW, FAL and SAL). Sample sites include: Juaben 1 (J1), Juaben 2 (J2), Apincra 1 (A1), Apincra 2 (A2) and Effiduase Asokore (EA) in the Ashanti region. FPW; Fresh Palm Wine, FEPW; Fermented Palm Wine, FAL; Fresh Alcohol, SAL; Stored Alcohol.

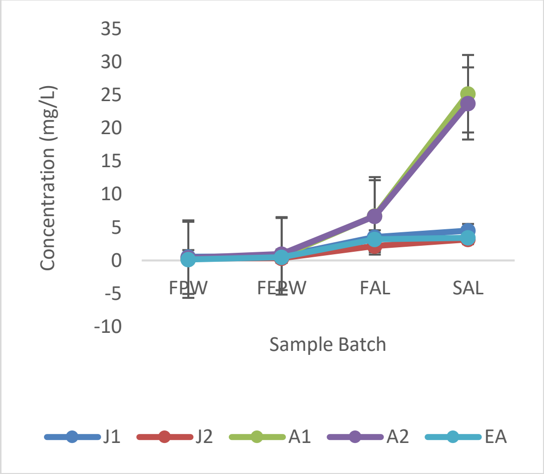

Figure 4. Variations in Copper (Cu) content (mg/L) across different batch processing stages.

Results were presented as mean concentration and standard deviation (mean ± SD, n= 3) of copper content in four different batches (FPW, FEPW, FAL and SAL). Sample sites include: Juaben 1 (J1), Juaben 2 (J2), Apincra 1 (A1), Apincra 2 (A2) and Effiduase Asokore (EA) in the Ashanti region. FPW; Fresh Palm Wine, FEPW; Fermented Palm Wine, FAL; Fresh Alcohol, SAL; Stored Alcohol.

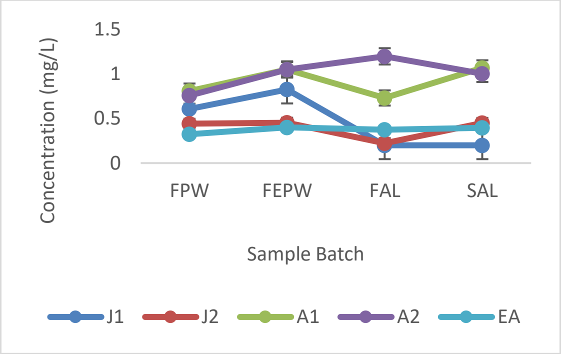

Figure 5. Variations in Aluminium (Al) content (mg/L) across different batch processing stages.

Results were presented as mean concentration and standard deviation (mean ± SD, n= 3) of aluminium content in four different batches (FPW, FEPW, FAL and SAL). Sample sites include: Juaben 1 (J1), Juaben 2 (J2), Apincra 1 (A1), Apincra 2 (A2) and Effiduase Asokore (EA) in the Ashanti region. FPW; Fresh Palm Wine, FEPW; Fermented Palm Wine, FAL; Fresh Alcohol, SAL; Stored Alcohol.

Table 1. Working parameters for the AAS analysis

Analyte	Burner height (nm)	Wavelength (nm)	Gas flow rate (L/h)	Lamp current (mA)	Slit width (nm)
Pb	7	283.3	65	2	1.2
Fe	6	248.3	65	4	0.2
Zn	7	213.9	45	2	0.5
Ag	8	328	50	3	1.2
Cu	6	324.8	50	2	1.2
Al	8	309.9	220	5	1.2

Conclusion

The study showed that palm wine and locally brewed alcohol from the Juaben, Apincra, and Effiduase Asokore regions were safe with respect to Pb, Ag, and Zn concentrations. However, significant public health risks arise from contamination with Al, Fe, and Cu. Al and Fe in fresh palm wine consistently exceeded WHO safety thresholds (>0.200 mg/L and >0.300 mg/L, respectively). This baseline contamination indicated the impact of natural soil composition or of unregulated agrochemicals.

The distillation phase was a point where the highest concentrations of Cu were introduced. Cu levels were safe in the raw palm wine. In contrast, concentrations in the distilled alcohol rose sharply to 6.740 mg/L. This was more than triple the 2.000 mg/L limit. Additionally, changes in Fe and Zn levels during fermentation and storage suggested the use of corrodible metal containers and contaminated water. To avoid widespread heavy-metal poisoning, these findings underscore the urgent need for stricter material standards. Local distillers should adopt stainless-steel equipment and improve regulatory oversight to reduce long-term exposure to heavy metals in artisanal production.

This study provided a foundation for future research on metal contaminants in palm wine and locally brewed alcohol from palm trees in the Ashanti region of Ghana. Further investigation should assess other hazardous heavy metals, including mercury, arsenic, and nickel, to generate comprehensive data for monitoring the safety of these beverages. Health risk assessment is recommended to evaluate the safety of long-term consumption. Furthermore, to mitigate metal contamination, metallic storage containers at brewing sites should be replaced with non-reactive alternatives, such as plastic or clay containers. Also, processing materials, including steel drums and copper tubing, should be inspected and replaced with safe, suitable alternatives as necessary. Again, dilution of freshly brewed alcohols with potentially contaminated water should be avoided to minimize potential metal contamination. Local distillers should be educated on maintaining good hygienic practices and a clean environment throughout the collection, storage and processing of palm wine into *akpeteshie.*

Abbreviations

A1: Apincra 1; A1FAL: Apincra 1 Fresh Alcohol; A1FEPW: Apincra 1 Fermented Palm Wine; A1FPW: Apincra 1 Fresh Palm Wine; A1SAL: Apincra 1 Stored Alcohol; A2: Apincra 2; A2FAL: Apincra 2 Fresh Alcohol; A2FPW: Apincra 2 Fermented Palm Wine; A2FPW: Apincra 2 Fresh Palm Wine; A2SAL: Apincra 2 Stored Alcohol; AAS: Atomic Absorption Spectrophotometer; BM: Below Measurement; EA: Effiduase Asokore; EAFAL:Effiduase Asokore Fresh Alcohol; EAFPW: Effiduase Asokore Fermented Palm Wine; EAFPW: Effiduase Asokore Fresh Palm Wine; EASAL: Effiduase Asokore Stored Alcohol; FAL: Fresh Alcohol; FEPW: Fermented Palm Wine; FPW: Fresh Palm Wine; GSA: Ghana Standard Authority; J1: Juaben 1; J1FAL: Juaben 1 Fresh Alcohol; J1FEPW: Juaben 1 Fermented Palm Wine; J1FPW: Juaben 1 Fresh Palm Wine; J1SAL: Juaben 1 Stored Alcohol; J2: Juaben 2; J2FAL: Juaben 2 Fresh Alcohol; J2FPW: Juaben 2 Fermented Palm Wine; J2FPW: Juaben 2 Fresh Palm Wine; J2SAL: Juaben 2 Stored Alcohol; SAL: Stored Alcohol.

Authors' Contribution

All authors conceived the current research, participated in the research process, interpreted the results, and discussed the experimental data. AMA sourced the materials, carried out the laboratory work, and wrote the first draft of the manuscript. JKA and AJNA supervised every step of the research work, reviewed and edited the manuscript.

Acknowledgments

We want to express our profound gratitude to the Department of Pharmaceutical Chemistry and Chemistry at KNUST for providing us with research and library resources. We also wish to thank the technicians and staff of the Departments for their immense support.

Conflict of interest

The authors declare no conflict of interest

Article history:

Received: 18 February 2026
Received in revised form: 7 April 2026
Accepted: 9 April 2026
Available online: 9 April 2026

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