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Impact of Hot Smoke Curing on the Quality and Safety of Freshwater Fish: A Comparative Study of *Gymnarchus niloticus* and *Clarias lazera* Using Different Hardwood Types

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A B S T R A C T

This study investigated the effect of hot smoke curing using two types of hardwood (*Acacia seyal* and *Citrus lemon*) on the total viable counts (TVC), physico-chemical composition, and sensory evaluation of two species of freshwater fish (*Gymnarchus niloticus* and *Clarias lazera*). Ten kilograms of each species were purchased from the Khartoum Center Market and processed with 5% brining. The total viable counts of bacteria in fresh *G. niloticus* and *C. lazera* were 2.8×10^5 CFU/g and 2.4×10^5 CFU/g, respectively. *Staphylococcus aureus* was isolated both before and after smoking. While no significant difference ($P<0.05$) was found between the color of smoked *G. niloticus* and *C. lazera* using either wood type, significant differences were observed between fresh and smoked samples. Highly significant differences ($P<0.05$) were noted in the proximate composition, with total protein, lipid, and ash contents increasing as moisture decreased. Specifically, moisture content ranged from 64.3±0.183% to 62.4±1.105% for *G. niloticus* and 64.15±0.130% to 54.42±0.173% for *C. lazera* when smoked by *Acacia seyal* and *Citrus lemon*, respectively. Sensory evaluation showed significant differences ($P<0.05$) in color, taste, texture, and flavor, with *C. lazera* treated with *Citrus lemon* being the most acceptable product.

Introduction

Fish represents a critical component of global food security, providing high-quality protein, essential fatty acids, and micronutrients to millions of people, particularly in developing nations (Akinjogunla and Shehu, 2024). In regions like Sudan, freshwater fish species such as *Gymnarchus niloticus* (Aba knife fish) and *Clarias lazera* (African catfish) are not only dietary staples but also vital sources of income for local fishing communities. However, the high moisture content and nutrient-rich composition of fish make them highly perishable, leading to rapid spoilage post-harvest due to microbial activity and biochemical changes (Tenyang, 2022). Effective preservation techniques are therefore essential to extend shelf life, reduce post-harvest losses, and ensure food safety. Among various preservation methods, smoking remains one of the oldest and most widely practiced techniques in Africa. Smoking involves the application of heat and chemical components derived from the incomplete combustion of wood to the fish (Arvanitoyannis and Kotsanopoulos, 2012). This process serves multiple functions: it reduces moisture content through evaporation (drying), provides a barrier against microbial growth through the deposition of phenolic and carbonyl compounds, and imparts desirable sensory characteristics such as a distinct smoky flavor and golden-brown color (Ayeloja, 2019; Obugara *et al.,* 2026).

Hot smoking, in particular, combines the effects of cooking and drying, which can significantly reduce the initial microbial load and inactivate enzymes responsible for spoilage.

The choice of wood used for smoking is a decisive factor in determining the quality and safety of the final product. Different wood species contain varying amounts of cellulose, hemicellulose, and lignin, which break down during combustion to produce a complex mixture of smoke components (Barros *et al.,* 2023).

In Sudan, *Acacia seyal* (Talh) and *Citrus lemon* (Lemon wood) are commonly used hardwoods for fish smoking. While *Acacia seyal* is prized for its availability and high heat output, *Citrus lemon* is often favored for the unique aromatic profile it imparts to the fish. Understanding how these specific hardwoods influence the nutritional profile and microbial stability of different fish species is crucial for optimizing traditional processing methods.

Recent research has emphasized the need for standardized smoking protocols to minimize the formation of harmful compounds like polycyclic aromatic hydrocarbons (PAHs) while maximizing nutritional retention (Mondo *et al.,* 2022). Furthermore, the prevalence of foodborne pathogens such as *Staphylococcus aureus* in smoked fish markets remains a significant public health concern, highlighting the importance of evaluating the efficacy of smoking in reducing microbial risks (Boyo-Agbonile *et al.,* 2026). This study aims to fill the knowledge gap by comparing the effects of *Acacia seyal* and *Citrus lemon* smoke on the proximate composition, microbial load, and sensory attributes of *G. niloticus* and *C. lazera*, providing a scientific basis for improving fish processing practices in the region.

Materials and Methods

Sample Collection and Preparation

Fresh samples of *Gymnarchus niloticus* and *Clarias lazera* were purchased from the Khartoum Center Market, Sudan. A total of 10 kg of each species was collected and transported in insulated ice boxes to the laboratory of the Department of Food Science and Technology, College of Agriculture, University of Alzaim Alazhari. Upon arrival, the fish were thoroughly washed with clean water to remove slime and debris. The fish were then gutted, gilled, and re-washed.

Brining and Smoking Process

The prepared fish were subjected to a brining process using a 5% salt (NaCl) solution for 30 minutes. Brining serves to enhance flavor, improve texture, and provide initial antimicrobial action. After brining, the fish were drained and divided into two groups for each species. One group was smoked using *Acacia seyal* hardwood, while the other group was smoked using *Citrus lemon* hardwood. The smoking was conducted in a traditional hot smoking kiln where the temperature was maintained between 70°C and 85°C. The process continued until the fish reached a desired level of dryness and color, typically taking 4 to 6 hours depending on the size and species of the fish.

Microbial Analysis

Microbiological analysis was performed on both fresh and smoked fish samples to determine the Total Viable Count (TVC) and to identify specific pathogens. Ten grams of each sample were homogenized in 90 ml of sterile peptone water. Serial dilutions were prepared, and the TVC was determined using the pour plate method on Plate Count Agar (PCA), with incubation at 37°C for 48 hours. The isolation and identification of *Staphylococcus aureus* were carried out using Mannitol Salt Agar (MSA). Suspect colonies were confirmed through Gram staining and biochemical tests, including catalase and coagulase tests, following standard procedures (Boyo-Agbonile *et al.,* 2026).

Proximate Composition Analysis

The proximate composition of the fish samples, including moisture, total protein, lipid, and ash contents, was determined according to the methods of the Association of Official Analytical Chemists (AOAC).

- Moisture Content: Determined by drying the samples in an oven at 105°C until a constant weight was achieved.
- Total Protein: Analyzed using the Kjeldahl method, where the nitrogen content was multiplied by a factor of 6.25.
- Lipid Content: Extracted using the Soxhlet method with petroleum ether as the solvent.
- Ash Content: Determined by incinerating the samples in a muffle furnace at 550°C for 6 hours.

Sensory Evaluation

The sensory quality of the smoked fish products was assessed by a semi-trained panel of 10 members from the Department of Food Science and Technology. The parameters evaluated included color, taste, texture, and flavor. A 9-point hedonic scale was used, ranging from 1 (dislike extremely) to 9 (like extremely). Additionally, the color of the smoked fish was quantitatively measured using a Hunter lab colorimeter to determine the L* (lightness), a* (redness/greenness), and b* (yellowness/blueness) values.

Statistical Analysis

All experiments were performed in triplicate. The data obtained were subjected to Analysis of Variance (ANOVA) using SPSS software. Significant differences between means were determined using Duncan's Multiple Range Test at a significance level of $P < 0.05$.

Results and Discussion

Microbial Load Analysis

The total viable counts (TVC) of bacteria in fresh fish used as raw material (*Gymnarchus niloticus* and *Clarias lazera*) were 2.8×10^5 CFU/g and 2.4×10^5 CFU/g, respectively. These values reflect the initial microbial load typical for freshwater fish in tropical environments (Tenyang *et al.,* 2022). After hot smoking, a significant reduction in the TVC was observed for both species. The TVC of smoked *G. niloticus* was reduced to 2.0×10^3 CFU/g, while for *C. lazera*, it decreased to 6.0×10^3 CFU/g. This reduction indicates the effectiveness of hot smoking in inactivating bacteria through heat and the antimicrobial components of the smoke (Obugara *et al.,* 2026). However, the bacteria isolated both before and after smoking was *Staphylococcus aureus*, which suggests potential contamination during processing or the survival of some strains through the smoking process (Boyo-Agbonile *et al.,* 2026).

Proximate Composition

Highly significant differences ($P<0.05$) were observed in the proximate composition between fresh and smoked fish for both species. The smoking process led to a substantial increase in the percentage of total protein, lipid, and ash contents, which was primarily due to the decrease in moisture content. The changes in moisture content for *G. niloticus* and *C. lazera* when smoked by *Acacia seyal* and *Citrus lemon* are summarized in Table 1.

The moisture content of *C. lazera* smoked with *Citrus lemon* was the lowest (54.42 ± 0.173%), which corresponded to the highest protein and lipid contents. This indicates that *Citrus lemon* wood might provide more efficient drying or a higher temperature during the smoking process compared to *Acacia seyal*.

Sensory Evaluation

The results of the sensory evaluation showed significant differences ($P<0.05$) in the parameters of color, taste, texture, and flavor between the different treatments.

The color test using a Hunter lab colorimeter revealed no significant difference ($P<0.05$) between the color of smoked *G. niloticus* and *C. lazera* when the same wood type was used. However, there was a significant difference between fresh and smoked samples, as smoking imparted a darker, more golden-brown hue.

As shown in Figure 2. *Clarias lazera* treated with *Citrus lemon* appeared to be the most acceptable of all the products, receiving the highest scores in all sensory categories.

From figure 3. A significant reduction in lightness (L^*) was observed for both fish species across their external and internal surfaces after smoking treatments. This uniform darkening across both species and surfaces suggests a high degree of heat-induced browning and smoke component deposition.

Yellowness (b^*) values increased significantly post-smoking for both species.

Redness (a^*) values showed contrasting trends between species; while external redness in *G. niloticus* decreased, internal redness slightly increased, For *C. lazera*, external redness increased whereas internal redness decreased.

The data indicates that the type of wood used (*Acacia seyal* vs. *Citrus lemon*) had a negligible impact on the final external color parameters of either species. However, minor variations were detected in the internal color of *G. niloticus*.

Impact of Smoking on Microbial Stability

The reduction of total viable counts (TVC) from approximately 10^5 CFU/g in fresh fish to 10^3 CFU/g in smoked fish underscores the efficacy of hot smoking as a preservation method. The combination of heat (70-85°C) and the deposition of antimicrobial compounds from the wood smoke, such as phenols and organic acids, works synergistically to inhibit bacterial growth (Obugara *et al.,* 2026). Phenolic compounds, in particular, are known to disrupt bacterial cell membranes and interfere with enzyme systems. The lower TVC observed in *G. niloticus* ($2.0x10^3$ CFU/g) compared to *C. lazera* ($6.0x10^3$ CFU/g) may be related to differences in the muscle structure and moisture retention of the two species. The persistent presence of *Staphylococcus aureus* post-smoking is a concern. *S. aureus* is a common inhabitant of the skin and mucous membranes of humans and animals, and its presence in smoked fish often indicates poor hygienic practices during handling, processing, or storage (Boyo-Agbonile *et al.,* 2026).

While hot smoking reduces the overall microbial load, *S. aureus* can produce heat-stable enterotoxins that are not inactivated by subsequent cooking. Recent studies have shown that traditional smoking kilns may not always achieve uniform temperatures, allowing for the survival of some pathogens in "cold spots" within the smoking chamber (Likongwe *et al.,* 2018). This highlights the need for improved kiln designs and stricter adherence to Good Manufacturing Practices (GMP).

Nutritional Quality and Proximate Changes

The significant increase in protein, lipid, and ash contents in smoked fish is a direct consequence of moisture loss. As water is removed during the smoking process, the nutrients become more concentrated. This concentration effect is beneficial from a nutritional standpoint, as it increases the nutrient density of the final product. For instance, the protein content of *C. lazera* increased from 15.8% in the fresh state to 28.6% when smoked with *Citrus lemon*. This finding is consistent with recent studies by Tenyang *et al.,* (2022) and Paul *et al.,* (2022), who reported similar increases in the nutritional value of smoked freshwater fish.

The choice of wood played a significant role in the degree of moisture loss. *Citrus lemon* wood appeared to be more effective in reducing moisture content, particularly in *C. lazera*. This could be attributed to the combustion characteristics of lemon wood, which may produce a more intense or sustained heat compared to *Acacia seyal*. The lower moisture content in *Citrus lemon*-smoked fish (54.42%) not only enhances nutrient concentration but also contributes to a longer shelf life by reducing the water activity (aw) available for microbial growth (Akinjogunla and Shehu, 2024).

Sensory Attributes and Consumer Preference

Sensory quality is the primary driver of consumer acceptance for smoked fish. The results indicate that both *Acacia seyal* and *Citrus lemon* produce acceptable products, but *Citrus lemon* imparts superior sensory characteristics.

The high scores for flavor and taste in *C. lazera* smoked with *Citrus lemon* suggest that the volatile compounds released during the combustion of lemon wood such as certain aldehydes and esters complement the natural flavor of the catfish more effectively than the compounds from *Acacia seyal*.

The quantitative color measurement showed that while wood type did not significantly alter the color between the two fish species, the smoking process itself created a significant change from the fresh state. The development of the characteristic golden-brown color in smoked fish is the result of Maillard reactions between amino acids and reducing sugars, as well as the deposition of colored smoke components like phenols and carbonyls (Arvanitoyannis and Kotsanopoulos, 2012). The higher acceptability of *C. lazera* treated with *Citrus lemon* (8.30 overall score) highlights the potential for using specific hardwoods to create premium smoked fish products with enhanced market value.

Table.1 Proximate composition of fresh and smoked fish samples (Mean ± SD)

Fish Species	Treatment	Moisture (%)	Protein (%)	Lipid (%)	Ash (%)
G. niloticus	Fresh	78.4 ± 0.52	16.2 ± 0.31	3.1 ± 0.12	1.2 ± 0.05
G. niloticus	*Acacia seyal*	64.3 ± 0.183	24.5 ± 0.45	5.8 ± 0.21	2.4 ± 0.11
G. niloticus	*Citrus lemon*	62.4 ± 1.105	25.8 ± 0.56	6.2 ± 0.28	2.6 ± 0.15
C. lazera	Fresh	79.1 ± 0.48	15.8 ± 0.25	2.9 ± 0.10	1.1 ± 0.04
C. lazera	*Acacia seyal*	64.15 ±0.130	23.9 ± 0.42	6.1 ± 0.18	2.3 ± 0.09
C. lazera	*Citrus lemon*	54.42 ±0.173	28.6 ± 0.68	8.4 ± 0.35	3.2 ± 0.18

Table.2 Sensory evaluation scores (9-point hedonic scale).

Parameter	*G. niloticus (A. seyal)*	*G. niloticus (C. lemon)*	*C. lazera (A. seyal)*	*C. lazera (C. Lemon)*
Color	7.2 ± 0.45	7.5 ± 0.38	7.3 ± 0.42	8.2 ± 0.35
Taste	7.0 ± 0.52	7.4 ± 0.41	7.1 ± 0.48	8.5 ± 0.32
Texture	7.1 ± 0.39	7.3 ± 0.45	7.2 ± 0.37	8.1 ± 0.40
Flavor	7.3 ± 0.48	7.6 ± 0.35	7.4 ± 0.44	8.4 ± 0.29
Overall Acceptability	7.15	7.45	7.25	8.30

Figure.1 The proximate composition of fresh and smoked fish samples.

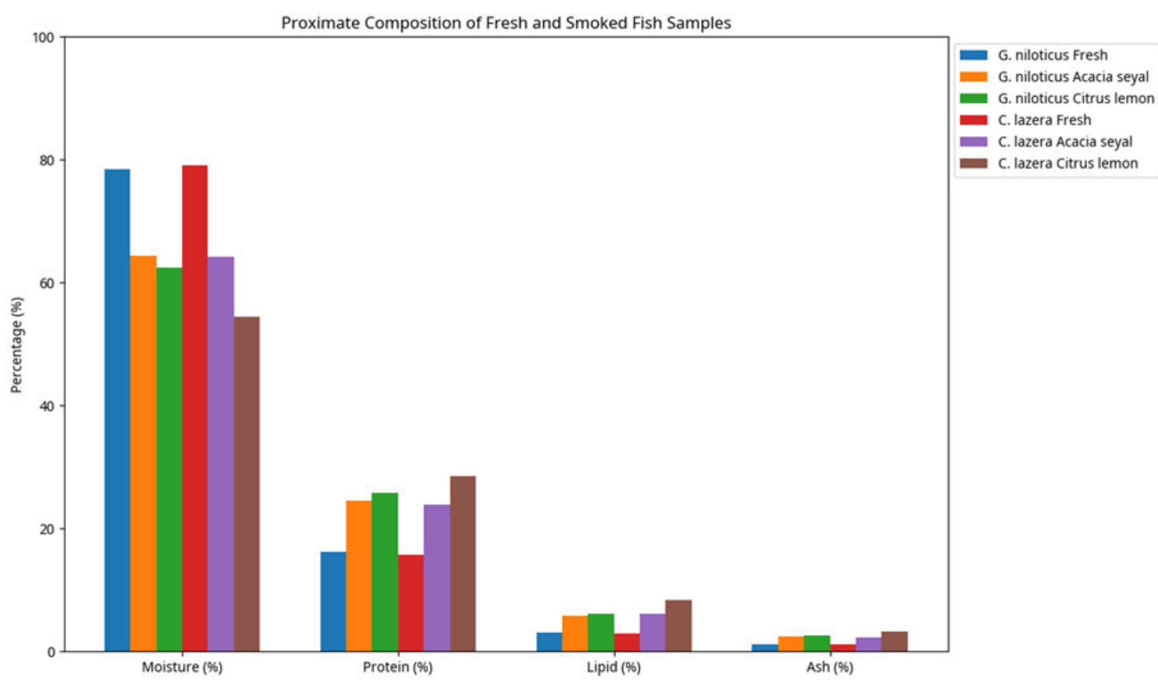


Figure.2 The sensory evaluation scores of smoked fish samples.

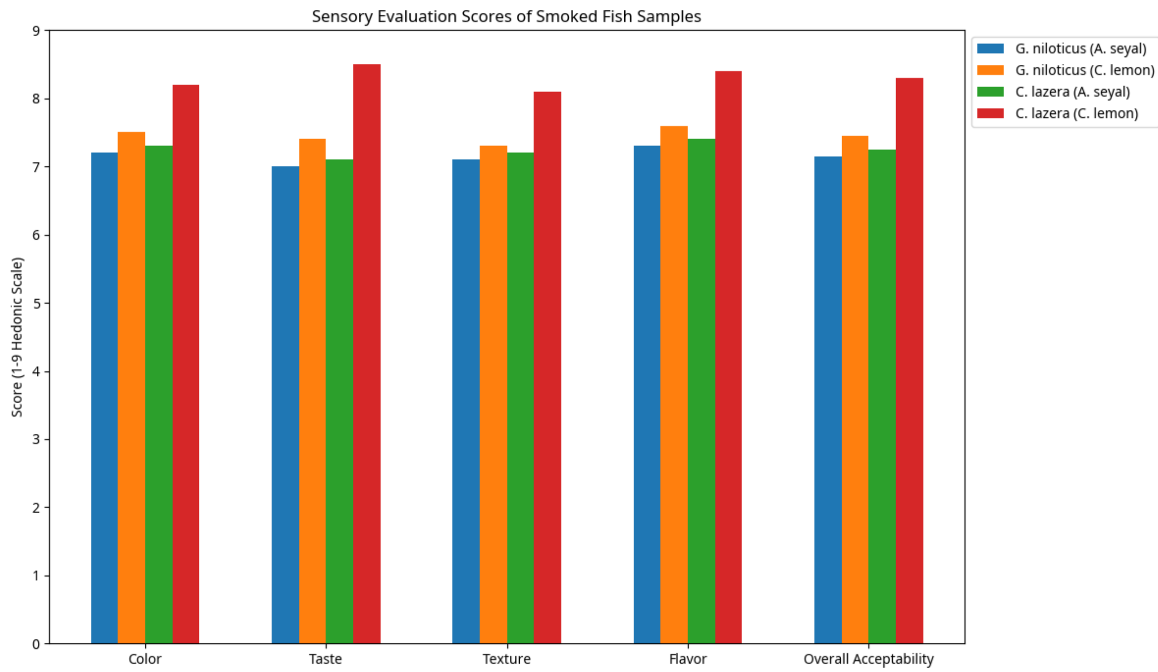
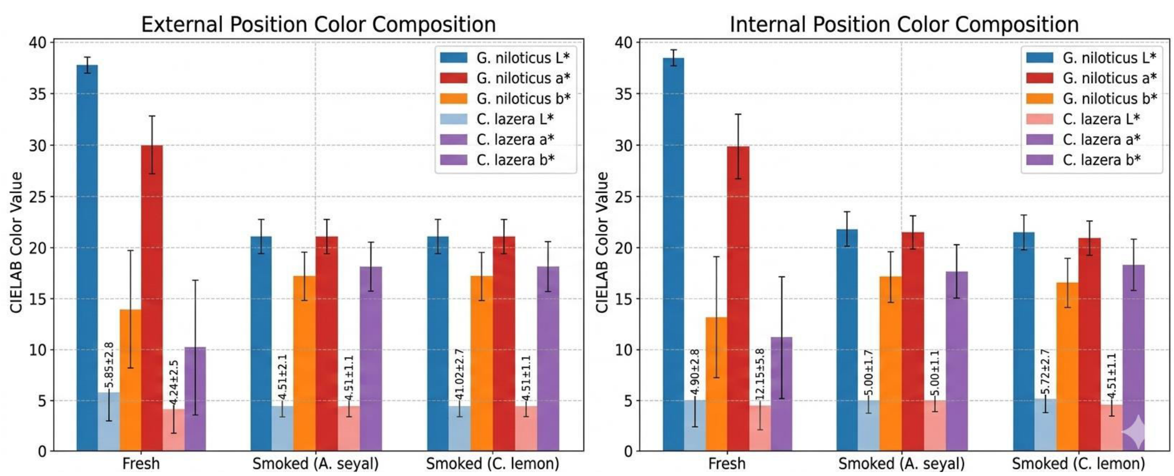


Figure.3 Comparison of external and internal color profile changes in processed



Comparative Analysis with Recent Literature

The findings of this study align with recent research trends in fish processing. For example, the use of natural plant extracts and specific wood types to enhance the stability and sensory profile of smoked fish is a growing area of interest (Akinjogunla and Shehu, 2024; Barros *et al.,* 2023). The significant reduction in TVC observed here is consistent with the results of Ayeloja (2020), who emphasized the role of smoking in extending the shelf life of *Oreochromis niloticus*. Furthermore, the nutritional enhancement through moisture reduction is a well-documented phenomenon in recent studies of various African freshwater species (Paul *et al.,* 2022; Tenyang *et al.,* 2022)

However, the presence of *S. aureus* remains a recurring theme in smoked fish research. Boyo-Agbonile *et al.,* (2026) recently reported high levels of staphylococcal contamination in informal fish markets, which mirrors the isolation of *S. aureus* in this study. This suggests that while smoking is an effective preservation tool, it must be part of a broader food safety management system that includes proper sanitation and temperature control throughout the value chain.

In conclusion, this study demonstrates that hot smoke curing using *Acacia seyal* and *Citrus lemon* hardwoods is an effective method for reducing the initial microbial load of *Gymnarchus niloticus* and *Clarias lazera*. The smoking process significantly reduced the total viable counts (TVC) from 10^5 CFU/g to 10^3 CFU/g, thereby extending the shelf life of the fish. Furthermore, hot smoking led to a substantial increase in the percentage of total protein, lipid, and ash contents as a result of moisture reduction, effectively enhancing the nutrient density of the final products. Among the treatments, *Clarias lazera* smoked with *Citrus lemon* wood was found to be the most acceptable in terms of color, taste, texture, and flavor. However, the isolation of *Staphylococcus aureus* both before and after smoking indicates a need for improved hygiene during the processing stages.

Recommendations

Based on the findings of this study, the following recommendations are proposed:

1 **Selection of Smoking Materials:** Small-scale fish processors should consider using *Citrus lemon* hardwood for smoking, particularly for *Clarias lazera*, to achieve superior sensory characteristics and higher consumer acceptability.

2 **Improved Hygiene and Handling:** To mitigate the risk of *Staphylococcus aureus* contamination, strict adherence to hygienic practices is essential during the collection, brining, and smoking of fish. This includes regular handwashing, cleaning of equipment, and the use of potable water.

3 **Optimizing Smoking Parameters:** Further research is needed to determine the optimal temperature and duration for hot smoking to ensure the complete inactivation of pathogens while minimizing the formation of harmful compounds like polycyclic aromatic hydrocarbons (PAHs).

4 **Standardization of Traditional Methods:** Government and non-governmental organizations should work with local fishing communities to standardize traditional smoking techniques, providing training and improved kiln designs to enhance food safety and nutritional quality.

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Author Contributions

Adel S. Alhedi: Investigation, conducting the experiments. Samia H. Ahmed: formal analysis, writing original draft. Ramzy A. Yousif: Formal analysis, Writing review and editing.Fouzi A. Mohamed Validation, methodology, Writing reviewing.

Data Availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethical Approval Not applicable.

Consent to Participate Not applicable.

Consent to Publish Not applicable.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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