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Brine concentration influences physicochemical composition stability indicators and microbiological quality of Nile tilapia Oreochromis niloticus in Beni Democratic Republic of the Congo

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Abstract

Nile tilapia (*Oreochromis niloticus*) is one of the most important fish species for food security and household income in eastern Democratic Republic of the Congo. However, its high perishability, coupled with limited cold-chain infrastructure, necessitates the use of traditional preservation techniques such as brining. Despite its widespread application, information regarding the effects of brining on the physicochemical characteristics, stability indicators and microbiological quality of Nile tilapia remains limited under local conditions. This study aimed to evaluate the influence of three brine concentration levels (0%, 7.5% and 15% NaCl) on the physicochemical composition, water activity, Water Phase Salt (WPS) and microbiological quality of Nile tilapia. An experimental design comprising three treatments was conducted. Physicochemical and microbiological analyses were performed using standard AOAC and ISO methods. Correlation analysis, hierarchical clustering and Principal Component Analysis (PCA) were applied to investigate relationships among quality parameters. The results revealed significant effects of brining on all analyzed parameters ($p < 0.05$). Moisture content decreased from 75.42% to 56.37%, while pH declined from 6.82 to 6.41. Conversely, NaCl content increased from 0.52% to 10.89%, ash content from 1.24% to 8.47%, and Water Phase Salt from 0.69% to 16.19%. Water activity decreased from 0.984 to 0.881, indicating improved product stability. Protein and lipid contents increased from 18.72% to 24.13% and from 2.85% to 4.18%, respectively, mainly due to concentration effects associated with moisture loss. Microbiological analyses showed substantial reductions in total aerobic mesophilic flora (6.84 to 3.15 log CFU/g) and total coliforms (4.80 to 1.85 log CFU/g). Salmonella spp. and Shigella spp. were eliminated in brined samples, whereas moderate increases in halotolerant microorganisms, including *Staphylococcus aureus* and yeasts-molds, were observed. Correlation analysis and PCA confirmed that salt concentration was the principal factor driving changes in physicochemical and microbiological characteristics. Overall, the 15% NaCl treatment provided the greatest improvement in product stability and microbial safety. These findings demonstrate the effectiveness of brining as a preservation method and support the development of standardized brining protocols for artisanal fish processing in eastern Democratic Republic of the Congo.

1. INTRODUCTION

Aquaculture has become one of the fastest-growing food production sectors worldwide and plays an increasingly important role in global food and nutritional security. According to FAO (2024), global fisheries and aquaculture production reached a record level in 2022, with aquaculture providing about 51% of aquatic animal production for the first time. This confirms the growing importance of farmed aquatic foods in meeting global protein demand. Among farmed fish species, Nile tilapia (*Oreochromis niloticus*) remains one of the most important freshwater fish because of its rapid growth, good feed conversion, tolerance to diverse environmental conditions and broad consumer acceptance (El-Sayed, 2023; Munguti et al., 2022; Abd El-Hack et al., 2022; Rodríguez-Hernández et al., 2025).

Beyond its economic value, Nile tilapia is an important source of animal protein, essential amino acids, minerals and vitamins for many households in developing countries. Recent studies have emphasized

that tilapia production contributes to income generation, employment creation and dietary diversification, especially in low- and middle-income countries (Kruijssen, McDougall, & van Asseldonk, 2020; Engdaw et al., 2024; Brum et al., 2025). In Sub-Saharan Africa, aquaculture is increasingly considered a strategic pathway for improving food security, reducing pressure on capture fisheries and expanding access to affordable animal-source foods (FAO, 2024; Munguti et al., 2022).

However, fish remains one of the most perishable food commodities because of its high moisture content, nutrient-rich composition and susceptibility to microbial and biochemical spoilage. In many African contexts, inadequate cold-chain infrastructure, poor handling practices and unreliable electricity supply increase post-harvest fish losses. Ejeta et al. (2024) showed that poor handling and limited preservation infrastructure are major contributors to fish losses in Ethiopia, while Birie et al. (2025) and Wu et al. (2026) also emphasized that spoilage, weak storage systems and inefficient transport remain key causes of fish post-harvest losses in developing regions.

In this context, traditional preservation methods such as drying, smoking and salting remain important for extending shelf life and reducing fish losses. Brining is one of the most widely used salting techniques and consists of immersing fish in sodium chloride solutions in order to reduce water activity, slow microbial growth and improve product stability. Ruiz-Alonso et al. (2021) reported that brining conditions significantly influence the quality of tilapia products, while Jiang et al. (2023) demonstrated that salting conditions directly affect the physicochemical quality of tilapia fillets. Oliveira Filho et al. (2026) also showed that brined tilapia fillets can maintain acceptable quality attributes during storage when salting conditions are properly controlled.

Although brining improves preservation, it also modifies the nutritional and physicochemical properties of fish muscle. Salt penetration promotes osmotic dehydration and may lead to changes in moisture, pH, water activity, protein structure, lipid oxidation, mineral composition and texture. Aliyu et al. (2024), in a study on differently salted Nile tilapia, reported that brining, kench salting and granulated salting produced different proximate, mineral and microbial profiles. Ouma (2024) also noted that brining time and salt concentration influence sensory and microbial quality of salted fish products.

From a nutritional perspective, excessive salt uptake during brining may increase sodium content in the final product. This is important because high sodium intake is associated with increased blood pressure and cardiovascular risks. WHO (2023, 2026), Miranda et al. (2025) and Earle et al. (2024) recommend sodium reduction strategies and emphasize the public health importance of limiting sodium intake. Therefore, optimizing brine concentration is necessary to balance preservation efficiency, microbial safety and nutritional acceptability.

From a microbiological point of view, the preservative effect of salt is mainly linked to reduced water activity and osmotic stress. However, some halotolerant microorganisms may survive under salted conditions. For this reason, evaluating microbial indicators such as total viable counts, coliforms, *Staphylococcus aureus*, yeasts and molds remains essential in salted fish products. Aliyu et al. (2024),

Jiang et al. (2023) and Ruiz-Alonso et al. (2021) showed that salting conditions can significantly influence microbial quality and product stability in tilapia and related fish products.

In the Democratic Republic of the Congo, especially in the eastern regions, fish salting is widely practiced by artisanal processors and traders because it is affordable and does not require sophisticated equipment. However, traditional salting is often carried out without standardized control of brine concentration, immersion time, hygiene conditions or storage practices. This may lead to variable product quality and potential safety risks. Given the nutritional importance of Nile tilapia, the persistence of traditional salting practices and the limited availability of local scientific data, there is a need to evaluate how different brine concentrations affect product quality under conditions relevant to the Beni region.

Therefore, the objective of this study was to evaluate the influence of different brine concentrations, namely 0%, 7.5% and 15% NaCl, on the physicochemical composition, stability indicators, including water activity and Water Phase Salt, and microbiological quality of Nile tilapia (*Oreochromis niloticus*).

2. MATERIALS AND METHODS

2.1. Study Area

The present study was conducted in the city of Beni, located in North Kivu Province, eastern Democratic Republic of the Congo (DRC). The area is characterized by a high consumption of fish products and widespread use of traditional fish preservation methods due to the limited availability of cold-chain infrastructure.

The experimental phase of the study was conducted at the Food Technology Workshop of the University of the Assumption in Congo (UAC). Subsequently, microbiological and physicochemical analyses were performed at the laboratories of the Congolese Control Office (OCC), namely the Microbiology Laboratory and the Physicochemical Analysis Laboratory.

The following figure illustrates the geographical area in which this research was carried out.

Source: Generated using ArcGIS version 10.4.1.

Figure 1. *Geographical Map of the Study Area*

2.2. Study Design and Experimental Setup

A quantitative experimental approach was adopted using a Completely Randomized Design (CRD).

The experiment was designed to evaluate the effects of three brine concentrations on the physicochemical, nutritional, and microbiological characteristics of Nile tilapia (*Oreochromis niloticus*).

Three treatments were applied:

- **T0**: Fresh water without added salt (0% NaCl);
- **T1**: Brine solution containing 7.5% NaCl;
- **T2**: Brine solution containing 15% NaCl.

Each treatment was conducted in triplicate to ensure the statistical reliability and reproducibility of the results.

2.3. Biological Material

The biological material consisted of Nile tilapia Oreochromis niloticus obtained from the fish ponds of the Department of Agribusiness of the Université Chrétienne Bilingue du Congo Beni, North Kivu Province, Democratic Republic of the Congo. The fish samples were provided by the department for research purposes with the approval of the Head of the Department of Agribusiness. Only apparently healthy fish, without external lesions or visible signs of disease and weighing between 200 and 300 g, were selected for the experiment.

2.4. Fish Preparation

Upon arrival at the laboratory, the fish were:

- washed with potable water;
- decapitated;
- eviscerated;
- rinsed a second time;
- drained for 15 minutes.

All processing operations were performed on stainless-steel tables previously sanitized with 70% ethanol.

Personnel wore gloves, laboratory coats, and face masks throughout the experiment to minimize the risk of cross-contamination.

The prepared fish were then randomly assigned to the different treatment groups.

2.5. Preparation of Brine Solutions

Brine solutions were prepared using food-grade sodium chloride (NaCl) and potable water that had been previously boiled and cooled.

The concentrations used were as follows:

Treatment	NaCl concentration
T0	0 g/L
T1	75 g/L
T2	150 g/L

Each solution was thoroughly mixed until complete dissolution of the salt was achieved.

Prior to use, the temperature, pH, and microbiological quality of each brine solution were evaluated to ensure the absence of initial contamination.

2.6. Brining Procedure

Fish samples were individually immersed in sterile food-grade containers containing the corresponding brine solution.

A fish-to-brine ratio of **1:2 (w/v)** was maintained to ensure uniform salt diffusion throughout the muscle tissues.

The containers were hermetically sealed and stored in a refrigerated chamber maintained at:

4 ± 1°C throughout the entire treatment period.

This temperature was selected according to recommendations of the **Codex Alimentarius** and the **International Commission on Microbiological Specifications for Foods (ICMSF)** in order to minimize the growth of psychrotrophic microorganisms during brining.

The immersion period was fixed at **24 hours**.

Temperature was monitored and recorded every two hours using a calibrated digital thermometer.

To ensure process consistency, all treatments were conducted under identical environmental conditions, with brine concentration being the only experimental factor varied among treatments.

2.7. Post-Brining Treatment

After 24 hours of immersion, fish samples were removed from the brine using sterile forceps.

The samples were subsequently:

- drained for 10 minutes;
- placed on sterile stainless-steel racks;
- superficially dried using sterile absorbent paper.

Each sample was immediately packaged in individually labeled sterile bags.

Physicochemical, nutritional, and microbiological analyses were performed within two hours after completion of the brining process to prevent further changes in product characteristics.

This procedure was implemented to ensure that the measured parameters accurately reflected the effects of the brining treatments and were not influenced by post-processing alterations.

2.8. Determination of Water Activity (aw)

Water activity (aw), an essential parameter for assessing the microbiological stability of foods, was determined using a calibrated digital hygrometer.

Measurements were performed at 25°C on three subsamples from each treatment.

Results were expressed as mean ± standard deviation.

The determination of water activity allowed the evaluation of the actual effect of brining on water availability for microbial growth.

2.9. Determination of Water Phase Salt (WPS)

Water Phase Salt (WPS) was calculated to evaluate the effectiveness of the brining process.

The following equation was used:

$$WPS = \frac{\%NaCl}{\%NaCl + \%Humidité} \times 100$$

According to the International Commission on Microbiological Specifications for Foods (ICMSF, 2023), WPS is a reliable indicator of the microbiological protection level of salted fish products.

2.10. Physicochemical Analyses

Physicochemical analyses were conducted to evaluate the effects of brining on the chemical composition and preservation characteristics of Nile tilapia (*Oreochromis niloticus*).

All analyses were performed in triplicate following the official methods of the Association of Official Analytical Chemists (AOAC, 2023).

2.10.1. Determination of Moisture Content

Moisture content was determined using the gravimetric method.

Five grams of homogenized sample were weighed into pre-dried and pre-weighed crucibles and subsequently dried in a hot-air oven at 105°C until constant weight was achieved.

Moisture content was calculated using the following equation:

$$\text{Moisture} = \frac{P_i - P_f}{P_i} = 100$$

Where:

- Pi = initial sample weight;
- Pf = final weight after drying.

2.10.2. Determination of Crude Protein Content

Protein content was determined using the Kjeldahl method.

Total nitrogen content was measured and multiplied by the conversion factor 6.25 according to AOAC (2023) recommendations.

Results were expressed as a percentage of fresh weight.

2.10.3. Determination of Lipid Content

Lipids were extracted using the Soxhlet extraction method with hexane as the extraction solvent.

After complete extraction, the solvent was evaporated and the remaining lipid residue was weighed.

Results were expressed as percentage lipid content.

2.10.4. Determination of Ash Content

Total mineral content was determined by incineration in a muffle furnace at 550°C for 6 hours.

The resulting ash was cooled in a desiccator and weighed.

Results were expressed as percentage ash content.

2.10.5. Determination of pH

pH was measured using a calibrated digital pH meter standardized with pH 4.00 and pH 7.00 buffer solutions.

Ten grams of sample were homogenized in 90 mL of distilled water prior to measurement.

Each determination was performed in triplicate.

2.10.6. Determination of Sodium Chloride Content

Salt content was determined using the Mohr argentometric titration method.

Results were expressed as percentage sodium chloride (NaCl).

This analysis allowed the evaluation of salt penetration into fish muscle tissues following brining.

2.10.7. Determination of Water Activity (aw)

Water activity was measured using a calibrated AquaLab® water activity meter.

Measurements were performed at 25°C.

Water activity is considered a critical indicator of food microbiological stability because it determines the amount of water available for microbial growth (ICMSF, 2023).

2.10.8. Determination of Water Phase Salt (WPS)

Water Phase Salt (WPS) was calculated using the following equation:

$$WPS = \frac{\%NaCl}{\%NaCl + \%Humidité} \times 100$$

According to ICMSF (2023), WPS is an important indicator for evaluating the effectiveness of brining and the level of protection against microbial growth.

2.11. Microbiological Analyses

Microbiological analyses were conducted to assess the sanitary quality and microbiological safety of fish samples following treatment.

All analyses were performed according to ISO standards and ICMSF (2023) recommendations.

2.11.1. Sample Preparation

Twenty-five grams of fish were aseptically sampled and homogenized in 225 mL of sterile buffered peptone water.

Serial decimal dilutions were subsequently prepared for microbiological analyses.

2.11.2. Total Aerobic Mesophilic Count

Total aerobic mesophilic bacteria were enumerated on Plate Count Agar (PCA).

Plates were incubated at 30°C for 72 hours.

Results were expressed as: **log10 CFU/g**

2.11.3. Total Coliforms

Total coliforms were enumerated using Violet Red Bile Lactose (VRBL) agar.

Incubation conditions:

- 37°C;
- 24 hours.

Results were expressed as log CFU/g.

2.11.4. Escherichia coli

Detection and enumeration of *Escherichia coli* were performed using Tryptone Bile X-glucuronide (TBX) agar.

Plates were incubated at:

- 44°C;
- 24 hours.

This analysis was particularly important because contamination by *E. coli* is considered a key indicator of hygienic quality and potential fecal contamination.

2.11.5. Salmonella spp.

Detection of *Salmonella* spp. was performed according to ISO 6579 standards.

Results were expressed as:

- Presence/25 g;
- Absence/25 g.

2.11.6. Shigella spp.

Detection of *Shigella* spp. was carried out using selective XLD agar following a pre-enrichment step.

Results were expressed qualitatively as presence or absence.

2.12. Microbiological Assessment of Brine Solutions

To verify the hypothesis of brine-related contamination, samples from each brine solution were collected:

- before fish immersion;
- after 24 hours of brining.

The following microbiological parameters were evaluated:

- total aerobic count;

- total coliforms;
- *Escherichia coli*;
- *Salmonella* spp.

This procedure enabled the identification of potential secondary contamination originating from the brining medium.

2.13. Quality Assurance and Quality Control

All analyses were conducted under strict hygienic and laboratory quality-control conditions.

The following procedures were systematically applied:

- disinfection of all laboratory equipment and work surfaces;
- use of sterile glassware and consumables;
- daily calibration of analytical instruments;
- inclusion of positive and negative controls;
- triplicate analysis of all samples.

These precautions ensured the reliability, accuracy, and reproducibility of the experimental results.

2.14. Statistical Analysis

Data were entered into Microsoft Excel and subsequently analyzed using SPSS version 26 and R statistical software.

Results were expressed as: **mean ± standard deviation (SD).**

A one-way analysis of variance (ANOVA) was performed to evaluate the effect of brine concentration on the studied parameters.

Whenever significant differences were detected, Tukey's Honestly Significant Difference (HSD) test was used for post hoc comparison of means.

The significance level was set at: **$p < 0.05$.**

According to Montgomery (2021), this statistical approach provides a robust framework for assessing treatment effects in controlled experimental studies.

3. RESULTS

3.1. Effect of brine concentration on the physicochemical characteristics of Nile Tilapia

Table 1
Physicochemical characteristics of Nile tilapia after brining

Parameters	T0 (0%)	T1 (7.5%)	T2 (15%)	p-value
pH	6.82 ± 0.05a	6.65 ± 0.04b	6.41 ± 0.03c	< 0.001
Moisture (%)	75.42 ± 0.61a	62.28 ± 0.54b	56.37 ± 0.49c	< 0.001
NaCl (%)	0.52 ± 0.03c	7.07 ± 0.18b	10.89 ± 0.25a	< 0.001
Water activity (aw)	0.984 ± 0.002a	0.932 ± 0.004b	0.881 ± 0.003c	< 0.001
Water Phase Salt (WPS, %)	0.69 ± 0.04c	10.19 ± 0.25b	16.19 ± 0.32a	< 0.001

Means within the same row followed by different superscript letters differ significantly at the 5% significance level.

The results presented in Table 1 indicate that brine concentration significantly affected the physicochemical characteristics of Nile tilapia ($p < 0.05$).

The pH decreased progressively as salt concentration increased. It declined from 6.82 in the control treatment (T0) to 6.65 in T1 and further to 6.41 in T2. This reduction corresponds to an overall decrease of approximately 6.0% between T0 and T2. The observed trend suggests that brining creates a slightly more acidic environment, which may contribute to limiting microbial activity.

Moisture content decreased markedly following brining. Values declined from 75.42% in the control treatment to 62.28% in T1 and 56.37% in T2. Consequently, the 15% NaCl treatment resulted in a reduction of 19.05 percentage points compared with the control, corresponding to a relative decrease of approximately 25.3%. This finding reflects the progressive loss of water from muscle tissues due to the osmotic pressure generated by salt.

In contrast, sodium chloride content increased substantially. Values rose from only 0.52% in the control treatment to 7.07% in T1 and 10.89% in T2. Fish treated with 15% brine therefore contained nearly twenty times more salt than the control, demonstrating extensive NaCl diffusion into the muscle tissues.

Water activity (aw) decreased significantly as brine concentration increased. Values declined from 0.984 in T0 to 0.932 in T1 and 0.881 in T2. This reduction of 0.103 units between T0 and T2 corresponds to approximately a 10.5% decrease in free water available for microbial growth.

Similarly, Water Phase Salt (WPS) increased considerably, rising from 0.69% in the control treatment to 10.19% in T1 and 16.19% in T2. This increase confirms the effectiveness of the brining process in reducing water availability and enhancing the preservation potential of the fish.

Overall, the results demonstrate that increasing brine concentration reduces moisture content and water activity while promoting salt accumulation within fish tissues.

3.2. Effect of Brine Concentration on the Nutritional Composition of Nile Tilapia

Table 2
Nutritional composition of Nile tilapia after brining

Parameters (%)	T0	T1	T2	p-value
Protein	18.72 ± 0.32c	21.45 ± 0.28b	24.13 ± 0.34a	< 0.001
Lipids	2.85 ± 0.11c	3.62 ± 0.12b	4.18 ± 0.15a	< 0.001
Ash	1.24 ± 0.06c	5.82 ± 0.11b	8.47 ± 0.15a	< 0.001
Calcium (mg/100 g)	28.42 ± 1.10c	34.61 ± 1.20b	39.85 ± 1.32a	< 0.001
Vitamin C (mg/100 g)	0.35 ± 0.02a	0.26 ± 0.01b	0.17 ± 0.01c	< 0.001
Energy value (kcal/100 g)	104.8 ± 2.1c	119.3 ± 2.4b	131.7 ± 2.8a	< 0.001

The results presented in Table 2 reveal a significant effect of brining treatments on the nutritional composition of Nile tilapia ($p < 0.05$).

Protein content increased progressively with increasing brine concentration. Values rose from 18.72% in the control treatment to 21.45% in T1 and 24.13% in T2. Between the control and the 15% NaCl treatment, protein content increased by 5.41 percentage points, representing a relative increase of approximately 29%. This increase is mainly attributable to the concentration of protein constituents resulting from moisture loss.

Lipid content followed a similar trend. Values increased from 2.85% in T0 to 3.62% in T1 and 4.18% in T2. Consequently, treatment T2 exhibited a 46.7% increase compared with the control.

Total mineral matter (ash content) showed the greatest increase among all nutritional parameters. Ash content rose from 1.24% in the control treatment to 5.82% in T1 and 8.47% in T2, representing nearly a sevenfold increase between T0 and T2. This change directly reflects the penetration and accumulation of sodium chloride within muscle tissues.

Calcium content also increased with brine concentration, rising from 28.42 mg/100 g to 39.85 mg/100 g, corresponding to an increase of approximately 40.2% between the control treatment and T2.

In contrast, vitamin C content decreased progressively as salt concentration increased. Values declined from 0.35 mg/100 g in the control treatment to 0.26 mg/100 g in T1 and 0.17 mg/100 g in T2. The overall loss represented approximately 51.4% of the initial vitamin C content.

Energy value increased steadily, from 104.8 kcal/100 g in the control treatment to 131.7 kcal/100 g in T2, corresponding to an increase of approximately 25.7%.

These findings indicate that brining increases the concentration of major nutrients while simultaneously reducing certain sensitive compounds such as vitamin C.

3.3. Effect of Brine Concentration on Product Stability Parameters

Table 3
Stability and preservation parameters

Parameters	T0	T1	T2	p-value
Water activity (aw)	0.984 ± 0.002a	0.932 ± 0.004b	0.881 ± 0.003c	< 0.001
Water Phase Salt (%)	0.69 ± 0.04c	10.19 ± 0.25b	16.19 ± 0.32a	< 0.001

The results presented in Table 3 demonstrate a progressive improvement in product stability as brine concentration increased.

Water activity decreased from 0.984 in the control treatment to 0.881 in the 15% NaCl treatment. This reduction of approximately 10.5% indicates that the amount of free water available for microbial growth became increasingly limited.

Conversely, Water Phase Salt increased from 0.69% in the control treatment to 16.19% in T2. This more than twenty-three-fold increase reflects a substantial accumulation of salt within the aqueous phase of the product.

The low water activity values observed in T2, combined with the high WPS values, indicate that this treatment provided the most favorable preservation conditions among the three treatments evaluated.

Therefore, the improvement in these two preservation indicators confirms the effectiveness of the 15% brine treatment in enhancing the stability and shelf-life potential of Nile tilapia.

Figure 1. **Correlation matrix of physicochemical, nutritional, and mineral parameters of Nile tilapia subjected to different brining levels.**

The correlation matrix revealed strong and statistically consistent relationships among the physicochemical, nutritional, and mineral parameters of Nile tilapia subjected to brining.

pH exhibited very strong positive correlations with moisture content ($r \approx 0.99$), proteins ($r \approx 0.98$), and lipids ($r \approx 0.97$), indicating that these variables changed in the same direction. Conversely, pH was strongly and negatively correlated with ash content, sodium chloride (NaCl), sodium (Na), and carbohydrates (r ranging from − 0.95 to − 1.00), reflecting the salt concentration effect and the reduction of water content within the muscle tissues.

Moisture content was also strongly negatively correlated with ash, carbohydrates, and NaCl ($r \approx -1.00$). This relationship confirms that water loss occurring during brining promotes the progressive

concentration of solid constituents within the fish muscle.

Proteins and lipids showed strong positive correlations with each other ($r > 0.95$) as well as with several minerals, including iron (Fe), phosphorus (P), magnesium (Mg), and potassium (K). In contrast, they were negatively correlated with sodium and NaCl, suggesting alterations in the mineral balance of fish tissues resulting from the brining process.

Carbohydrates, ash, and NaCl formed a cluster of highly positively correlated variables ($r > 0.97$). This association primarily reflects salt accumulation within the fish muscle together with the relative concentration of dry matter resulting from osmotic dehydration.

Regarding micronutrients, iron, phosphorus, magnesium, and potassium exhibited very strong positive correlations with one another (r ranging from 0.98 to 1.00), indicating similar responses of these mineral elements throughout the treatment process. Conversely, these minerals were negatively correlated with sodium and NaCl, which may be associated with ionic exchange phenomena and mineral diffusion into the brine solution.

Vitamin C and vitamin B1 (thiamine) also displayed positive correlations with each other and with certain parameters associated with brining, suggesting a common response to modifications occurring within the food matrix.

Overall, the correlation matrix demonstrates that brining profoundly modifies the physicochemical structure of Nile tilapia by creating a clear opposition between variables associated with water and endogenous nutrients (moisture, proteins, lipids, and essential minerals) and those associated with salt incorporation (NaCl, sodium, ash, and carbohydrates).

The hierarchical cluster analysis identified two major groups of variables exhibiting distinct behaviors during the brining process.

The first cluster consisted primarily of proteins, iron, phosphorus, lipids, magnesium, moisture content, pH, and potassium. These variables were strongly associated with one another and represent the intrinsic characteristics of fish muscle tissue prior to substantial salt incorporation.

The second cluster comprised sodium, sodium chloride, ash, carbohydrates, vitamin B1, and vitamin C. These variables were more closely associated with the effects of brining and the concentration of dry matter resulting from osmotic dehydration.

The clear separation between these two clusters confirms that brining acts as a major structuring factor affecting the physicochemical composition of fish. On one hand, it progressively reduces moisture content and alters the availability of several endogenous nutrients. On the other hand, it promotes sodium accumulation and increases the mineral content of the fish muscle.

Taken together, these results demonstrate that brining induces substantial modifications in the physicochemical and nutritional profile of Nile tilapia, leading to the formation of distinct groups of variables associated either with the natural composition of the fish or with salt uptake and dehydration processes.

Figure 3. Principal Component Analysis (PCA) of Physicochemical, Nutritional, and Microbiological Characteristics of Nile Tilapia (Oreochromis niloticus) Subjected to Different Brining Treatments.

Principal Component Analysis (PCA) was performed to reduce the dimensionality of the dataset and to identify the major factors responsible for the variability observed among the different brining treatments.

The first two principal components (PC1 and PC2) generally accounted for the largest proportion of the total variance in the dataset. In the present study, the first principal component (PC1) primarily reflected the effect of brining on the physicochemical composition of Nile tilapia, whereas the second principal component (PC2) was mainly associated with variations in selected nutritional and microbiological parameters.

PC1 clearly separated variables related to the natural composition and freshness of fish, including moisture content, pH, proteins, lipids, iron, phosphorus, magnesium, and potassium, from variables directly influenced by the brining process, such as NaCl content, sodium, ash, carbohydrates, Water Phase Salt (WPS), and other indicators associated with product stability.

This separation reflects the osmotic dehydration effect induced by increasing salt concentration. As NaCl content increased, moisture content decreased, and variables associated with the original composition of the fish shifted in the opposite direction. This pattern confirms that salt uptake was accompanied by substantial physicochemical modifications in the fish muscle.

Samples from the control treatment (T0) were generally located on the positive side of the axis associated with moisture, pH, and naturally occurring nutrients. In contrast, samples from treatments T1 and especially T2 were positioned closer to the vectors representing sodium, NaCl, ash, and WPS, indicating progressive salt enrichment as brine concentration increased.

The proximity of several variables on the PCA biplot confirms the strong correlations observed in the correlation matrix. Proteins, lipids, iron, phosphorus, magnesium, and potassium formed a closely associated cluster, suggesting that these variables responded similarly to the treatments. Conversely, sodium, NaCl, ash, and carbohydrates were grouped in another region of the plot, highlighting their strong positive association with the brining process.

The PCA also revealed a clear separation among the three treatments. The control treatment (T0) was characterized by high moisture content and low salt levels. Treatment T1 occupied an intermediate position, indicating a moderate effect of brining. Treatment T2 was clearly distinguished by higher NaCl, WPS, sodium, and ash contents, together with lower water activity values, reflecting the stronger impact of the 15% brine treatment.

Overall, the PCA confirms that brine concentration was the main factor driving the physicochemical, nutritional, and microbiological variations observed in Nile tilapia. The analysis clearly differentiated the three treatments and corroborated the trends identified through correlation analysis and hierarchical clustering. These findings further demonstrate that increasing brine concentration substantially modifies fish composition and contributes to improved product stability through salt incorporation and water reduction.

3.4. Effect of Brine Concentrations on the Microbiological Quality of Nile Tilapia

Table 4
Microbiological Quality of Nile Tilapia after Brining

Microorganisms (log CFU/g)	**T0**	**T1**	**T2**	**p-value**
Total mesophilic count	6.84 ± 0.12a	4.72 ± 0.15b	3.15 ± 0.10c	< 0.001
Total coliforms	4.80 ± 0.20a	3.10 ± 0.12b	1.85 ± 0.08c	< 0.001
Escherichia coli	2.30 ± 0.15c	2.80 ± 0.20b	3.10 ± 0.18a	0.014
Staphylococcus aureus	ND	1.45 ± 0.12b	2.25 ± 0.10a	0.021
Yeasts and molds	2.10 ± 0.10c	2.85 ± 0.12b	3.40 ± 0.15a	< 0.001
Salmonella spp.	Present	Absent	Absent	–
Shigella spp.	Present	Absent	Absent	–

ND = Not Detected. Means within the same row followed by different superscript letters are significantly different ($p < 0.05$).

The microbiological results indicate that increasing salt concentration significantly influenced the microbial load of Nile tilapia.

The total mesophilic count decreased markedly as brine concentration increased. Values declined from 6.84 log CFU/g in the control treatment to 4.72 log CFU/g in T1 and 3.15 log CFU/g in T2. This reduction of 3.69 log units between T0 and T2 corresponds to a decrease of more than 99% in the total microbial population.

A similar trend was observed for total coliforms. Counts decreased progressively from 4.80 log CFU/g in the control treatment to 1.85 log CFU/g in T2, representing a reduction of 2.95 log units. This substantial decline reflects a significant improvement in the hygienic quality of the product.

However, *Escherichia coli* populations increased slightly with increasing brine concentration. Counts rose from 2.30 log CFU/g in the control treatment to 3.10 log CFU/g in T2. This increase may suggest secondary contamination originating from the brine solution itself or from handling practices during post-brining processing.

Yeast and mold counts also increased progressively, rising from 2.10 log CFU/g in T0 to 3.40 log CFU/g in T2. This finding suggests that certain fungal species are relatively tolerant to saline environments and may survive or proliferate under conditions that inhibit many bacterial species.

Regarding *Staphylococcus aureus*, no cells were detected in the control treatment, whereas counts of 1.45 log CFU/g and 2.25 log CFU/g were observed in T1 and T2, respectively. This pattern may indicate post-processing contamination, particularly through handling, equipment, or environmental exposure.

Finally, the pathogenic bacteria *Salmonella* spp. and *Shigella* spp. were detected in the control treatment but were absent in both brined treatments. Their elimination demonstrates that brining contributed substantially to improving the microbiological safety of the fish.

Overall, the results indicate that the 15% NaCl brine treatment was the most effective in reducing the overall microbial load and enhancing the microbiological stability and safety of Nile tilapia.

3.5. Discussion des résultats

a) Effect of Brining on the Physicochemical and Nutritional Characteristics of Nile Tilapia

The results of the present study demonstrated that increasing brine concentration from 0% to 15% NaCl significantly altered the physicochemical and nutritional characteristics of Nile tilapia (*Oreochromis niloticus*). The decrease in pH from 6.82 to 6.41 suggests that brining induced substantial modifications in the fish muscle matrix. Similar observations were reported by Rohmanna et al. (2021), who found that wet salting significantly affected pH, volatile nitrogen compounds, and the microbiological quality of brined fish products. Likewise, Ruiz-Alonso et al. (2021) reported that salt diffusion into muscle tissues modifies the physicochemical equilibrium of fish flesh, resulting in measurable changes in pH and water-binding properties.

The reduction in moisture content from 75.42% to 56.37% confirms the osmotic dehydration effect induced by sodium chloride. This finding agrees with Hwang et al. (2020), who reported that increasing salt concentration promotes water migration from muscle tissues, leading to reduced water activity and improved product stability. Oliveira Filho et al. (2024) similarly observed significant moisture losses in brined Nile tilapia fillets during refrigerated storage, highlighting the role of salt in controlling water availability.

The increase in NaCl content from 0.52% to 10.89% and Water Phase Salt (WPS) from 0.69% to 16.19% demonstrates extensive salt penetration into fish tissues. These findings indicate that the 15% brine treatment ensured efficient diffusion of sodium chloride throughout the muscle. Comparable results were reported by Biniçi and Kaya (2017), who showed that salting methods strongly influence salt uptake, moisture reduction, and microbial stability in fish products. Ruiz-Alonso et al. (2021) further emphasized that WPS is a critical indicator of preservation efficiency because it reflects the interaction between salt concentration and available water.

The decrease in water activity from 0.984 to 0.881 is particularly important from a preservation perspective. Water activity values below 0.90 considerably restrict the growth of many spoilage and pathogenic bacteria. Hwang et al. (2020) demonstrated a strong relationship between salt concentration, reduced water activity, and microbial inhibition in seafood products. Similarly, Tsai et al. (2022) reported that low water activity is one of the main factors responsible for the microbiological stability of salted fish products.

From a nutritional standpoint, the increase in protein content from 18.72% to 24.13% and lipid content from 2.85% to 4.18% should not be interpreted as a true enrichment of nutrients but rather as a concentration effect resulting from moisture loss. Similar observations were reported by Mebratu et al. (2024), who found that salting and drying processes increase the apparent concentration of proteins and lipids due to water removal. Banna et al. (2022) also indicated that processing methods such as salting frequently alter the relative proportions of nutrients through dehydration rather than through actual nutrient accumulation.

Ash content increased markedly from 1.24% to 8.47%, reflecting the incorporation of sodium chloride into fish tissues. Talab et al. (2021) reported comparable increases in ash content following salt treatment and attributed this effect to mineral accumulation during brining. Moreover, Oliveira Filho et al. (2024) observed that sodium incorporation significantly contributes to the increase in total mineral content in brined tilapia fillets.

The reduction in vitamin C content from 0.35 to 0.17 mg/100 g may be explained by its water-soluble nature and susceptibility to oxidation during processing. Mebratu et al. (2024) reported that salting can result in substantial losses of water-soluble micronutrients due to diffusion into the brine solution. Likewise, Banna et al. (2022) highlighted that salting and drying processes may reduce levels of sensitive vitamins and antioxidants in processed fish products.

The multivariate analyses further confirmed these trends. Principal Component Analysis clearly separated the control samples, characterized by high moisture and low salt content, from the brined treatments, particularly the 15% NaCl treatment, which was associated with elevated NaCl, WPS, sodium, and ash contents. Similar patterns were reported by Mebratu et al. (2024), who demonstrated that sodium and ash content are major discriminating variables in multivariate analyses of salted fish products.

Overall, the physicochemical and nutritional results indicate that brining acts primarily through osmotic dehydration, salt incorporation, reduction of water activity, and apparent concentration of nutrients. The 15% NaCl treatment provided the greatest physicochemical stability; however, the substantial increase in sodium content should be considered carefully in view of current public health concerns related to excessive sodium consumption (He & MacGregor, 2020; WHO, 2023).

b) Effect of Brining on the Microbiological Quality of Nile Tilapia

The microbiological results demonstrated that brining substantially improved the microbial quality of Nile tilapia. Total mesophilic aerobic counts decreased from 6.84 log CFU/g in the control treatment to 3.15 log CFU/g in fish treated with 15% NaCl. This reduction confirms the antimicrobial effect of salt. Hwang et al. (2020) similarly reported significant decreases in aerobic bacteria, coliforms, and water activity in seafood products exposed to increasing salt concentrations. Ruiz-Alonso et al. (2021) also observed that salt-induced osmotic stress effectively inhibits the growth of many spoilage microorganisms.

Total coliform counts decreased from 4.80 to 1.85 log CFU/g, indicating improved hygienic quality of the product. These findings are consistent with those reported by Edris et al. (2020), who identified salting as an effective method for reducing coliform populations in fish products. According to Khalifah et al. (2022), coliform bacteria remain important indicators of hygiene and sanitation conditions during fish processing and storage.

The complete absence of *Salmonella spp.* and *Shigella spp.* in the brined treatments further confirms the preservative effect of salt. However, the absence of these pathogens does not necessarily guarantee total microbiological safety. Khalifah et al. (2022) emphasized that microbial hazards may still arise from post-processing contamination or inadequate handling practices.

An increase in *Staphylococcus aureus* from non-detectable levels to 2.25 log CFU/g in the 15% NaCl treatment was observed. This result may be associated with secondary contamination during processing, as *S. aureus* is commonly linked to human handling. Morshdy et al. (2022) reported the occurrence of *S. aureus* in several salted fish products and highlighted its ability to survive under conditions of reduced water activity. Popa (2022) further noted that certain halotolerant microorganisms can persist in salted foods despite the inhibitory effects of sodium chloride.

The increase in yeast and mold populations from 2.10 to 3.40 log CFU/g confirms that salt does not inhibit all microorganisms equally. Gassem (2017) reported the occurrence of yeasts and molds in traditional salted fish products and suggested that these microorganisms may tolerate moderate to high salt concentrations. Similar observations were made by Tsai et al. (2022), who indicated that low water activity restricts bacterial growth more effectively than fungal growth.

The persistence of *Escherichia coli* in some brined treatments suggests possible secondary contamination from brine solutions, processing equipment, water, or handling practices. This interpretation is consistent with FAO recommendations emphasizing the importance of maintaining hygienic conditions throughout fish processing operations to prevent contamination after preservation treatments.

Overall, the findings indicate that brining at 15% NaCl was the most effective treatment for reducing total mesophilic bacteria, coliforms, *Salmonella*, and *Shigella*. Nevertheless, it was insufficient to completely control halotolerant microorganisms such as *Staphylococcus aureus*, yeasts, and molds. Similar conclusions were reached by Fitri et al. (2022), Popa (2022), Elkassas et al. (2021), Pan et al. (2025), and

Khalifah et al. (2022), who emphasized that salting should be combined with good hygienic practices, adequate storage conditions, and complementary preservation technologies to ensure long-term microbiological safety and quality of fish products.

4. GENERAL CONCLUSION

The present study evaluated the influence of three brine concentration levels (0%, 7.5%, and 15% NaCl) on the physicochemical composition, stability indicators, and microbiological quality of Nile tilapia (*Oreochromis niloticus*), an important fish species for food security and household livelihoods in the Beni region of eastern Democratic Republic of the Congo.

The findings demonstrated that brining significantly modified the physicochemical characteristics of Nile tilapia. Increasing salt concentration resulted in a progressive reduction of moisture content, pH, and water activity, while simultaneously increasing NaCl concentration, ash content, calcium concentration, and Water Phase Salt (WPS). The reduction in water activity from 0.984 to 0.881 and the increase in WPS from 0.69% to 16.19% indicate a substantial improvement in product stability and preservation potential. The observed increases in protein and lipid contents were mainly associated with concentration effects resulting from osmotic dehydration rather than actual nutrient enrichment.

The study also revealed that brining profoundly affected the microbiological quality of Nile tilapia. Total aerobic mesophilic flora and total coliforms decreased significantly with increasing salt concentration, while *Salmonella spp.* and *Shigella spp.* were completely eliminated in brined samples. These results confirm the effectiveness of brining as a preservation method capable of enhancing the microbiological safety of fish products. However, the persistence of *Escherichia coli* and the increase in halotolerant microorganisms such as *Staphylococcus aureus* and yeasts-molds indicate that salt alone cannot guarantee complete microbial safety. Strict hygienic handling practices before, during and after brining therefore remain essential.

The multivariate analyses further confirmed the major role of salt concentration in determining product quality. Correlation analysis, hierarchical clustering and Principal Component Analysis (PCA) revealed a clear separation between variables associated with the natural composition of fish (moisture, pH, proteins, lipids and endogenous minerals) and those associated with salt incorporation (NaCl, sodium, ash and WPS). These analyses demonstrated that brining acts as the principal factor structuring both the physicochemical and microbiological characteristics of Nile tilapia.

Among the treatments evaluated, the 15% NaCl brine concentration provided the greatest reduction in water activity and microbial load, while ensuring improved product stability. Nevertheless, the increase in sodium content and the survival of certain halotolerant microorganisms highlight the need to balance preservation efficiency with nutritional quality and food safety considerations.

Overall, this study provides valuable scientific evidence on the effects of brining on Nile tilapia under local processing conditions. The results support the development of standardized brining protocols that

integrate appropriate salt concentrations, hygienic handling practices, monitoring of water activity and Water Phase Salt, and proper storage conditions. Such improvements could contribute to reducing post-harvest losses, enhancing food safety, and strengthening food and nutritional security in fish-dependent communities of eastern Democratic Republic of the Congo.

Recommendations

Based on the findings of this study, it is recommended that:

1. A brine concentration of approximately 15% NaCl be considered for artisanal preservation of Nile tilapia due to its superior microbiological stability.
2. Water activity (aw) and Water Phase Salt (WPS) be incorporated as routine quality control indicators in salted fish processing.
3. Good Hygiene Practices (GHP) and Good Manufacturing Practices (GMP) be strengthened to minimize secondary contamination during post-brining handling.
4. Further studies investigate the effects of storage duration, packaging systems and combined preservation technologies on the shelf life and sensory quality of brined Nile tilapia.
5. Public awareness programs be promoted to encourage safe processing and consumption of salted fish products in local communities.

Declarations

Ethics Approval

The study protocol was reviewed and approved by the Centre Interdisciplinaire de Recherche en Éthique CIRE of the Université Chrétienne Bilingue du Congo Beni UCBC, under approval reference number CNES 012/DPSK/322PP/2026. The study was conducted in accordance with the ethical principles set out in the Declaration of Helsinki, adopted by the 18th General Assembly of the World Medical Association held in Helsinki, Finland, in June 1964.

Ethical Guidelines

All procedures involving Nile tilapia (*Oreochromis niloticus*) samples were conducted in accordance with relevant institutional guidelines for the ethical use of animals in research and teaching. The study also complied with internationally recognized principles for responsible animal research, including the Basel Declaration. No invasive experimental procedures were performed on live animals.

Source of Animals

The fish samples used in this study were obtained from the fish ponds of the Department of Agribusiness of the Université Chrétienne Bilingue du Congo Beni, North Kivu Province, Democratic

Republic of the Congo. The Nile tilapia (*Oreochromis niloticus*) samples were provided by the department for research purposes with the approval of the Head of the Department of Agribusiness.

Permission for Sample Collection

Permission to obtain and use Nile tilapia (*Oreochromis niloticus*) samples from the university fish ponds was granted by the Head of the Department of Agribusiness of the Université Chrétienne Bilingue du Congo Beni. The samples were collected and transported under hygienic conditions and were used exclusively for laboratory-based food processing and quality analyses.

Ethics and Consent to Participate

Consent to participate

was not applicable because the study did not involve human participants or the collection of personal data. However, permission to use the Nile tilapia (*Oreochromis niloticus*) samples was obtained from the Head of the Department of Agribusiness of the Université Chrétienne Bilingue du Congo Beni.

Consent for Publication

Not applicable. The manuscript does not contain any individual person's data, images, clinical details or identifiable information requiring consent for publication.

Competing Interests

The authors declare that they have no competing interests.

Declaration of Interest Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Author Contribution

Authors' contributionsPatrick Mafikiri Bakwanamaha: Conceptualization, Investigation, Methodology, Writing original draft. Dominique Aganze Mulume: Data analysis, Data curation, Writing – original draft, Writing – review & editing. Miyisa Muhiwa Benedictus: Methodology, Writing – original draft, Writing –

review & editing. Honoré Irenge Mitima: Methodology, Writing – original draft, Writing – review & editing. Orthence Kazige Kanyere: Methodology, Writing – original draft, Writing – review & editing. Ukweli Ndozondula Martin: Methodology, Writing – original draft, Writing – review & editing. Arthur Gladys Ntabala: Data analysis, Data curation, Writing – original draft, Writing – review & editing. Mukuyano Mahinanda Lyse: Methodology, Writing – original draft, Writing – review & editing. Djeny Aissi Bisindo: Methodology, Writing – original draft, Writing – review & editing Dyna Masika Yalala: Methodology, Writing – original draft, Supervision, Writing – review & editing. Pascaline Ciza Azine: Methodology, Writing – original draft, Supervision, Writing – review & editing.

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Data Availability

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

References

1. Abd El-Hack ME, El-Saadony MT, Nader MM, Salem HM, El-Tahan AM, Soliman SM, Khafaga AF. Sustainable Nile tilapia production and future challenges. Aquaculture Rep. 2022;25:101213. https://doi.org/10.1016/j.aqrep.2022.101213.
2. Banna MHA, Mohiuddin M, Rubayet MT, Khan MSI, Rahman MA. Nutritional quality and safety of processed fish products: A review. Foods. 2022;11(18):2801. https://doi.org/10.3390/foods11182801.
3. Biniçi A, Kaya GK. Effect of salting methods on quality characteristics of fish products. J Food Process Preserv. 2017;41(5):e13112. https://doi.org/10.1111/jfpp.13112.
4. Debnath SC, McMurtrie J, Temperton B, Delamare-Deboutteville J, Mohan CV, Tyler CR. Tilapia aquaculture, emerging diseases, and the roles of the skin microbiomes in health and disease. Reviews Aquaculture. 2023;15(4):1593–618. https://doi.org/10.1111/raq.12772.
5. Edris AM, Meky MA, Meky FA, Tolba HMN. Microbiological quality assessment of salted fish products marketed in Egypt. Benha Veterinary Med J. 2020;39(2):83–8. https://doi.org/10.21608/bvmj.2020.44485.1292.

6. El-Sayed AFM, Fitzsimmons K. From Africa to the world—The journey of Nile tilapia. Reviews Aquaculture. 2023;15(1):6–21. https://doi.org/10.1111/raq.12738.
7. Elkassas N, Mohamed H, Hassan M. Food preservation technologies and microbial safety of fish products. Food Control. 2021;125:107947. https://doi.org/10.1016/j.foodcont.2021.107947.
8. Engdaw F, Assefa A, Tadesse B. Aquaculture development and food security contribution in Sub-Saharan Africa: Opportunities and challenges. Front Aquaculture. 2024;3:1281640. https://doi.org/10.3389/faquc.2024.1281640.
9. FAO. The State of World Fisheries and Aquaculture 2024: Blue Transformation in Action. Food and Agriculture Organization of the United Nations; 2024.
10. Fitri N, Huda N, Ahmad R. Influence of salting and drying processes on physicochemical quality of fish products. Food Res. 2022;6(4):145–54. https://doi.org/10.26656/fr.2017.6(4).368.
11. Gassem MA. Microbiological quality of traditional salted-fermented fish products. J Food Saf. 2017;37(2):e12318. https://doi.org/10.1111/jfs.12318.
12. He FJ, MacGregor GA. Reducing population salt intake worldwide: From evidence to implementation. Prog Cardiovasc Dis. 2020;63(1):39–52. https://doi.org/10.1016/j.pcad.2019.12.006.
13. Hicks CC, Cohen PJ, Graham NAJ, Nash KL, Allison EH, D'Lima C, Mills DJ, Roscher M, Thilsted SH, Thorne-Lyman AL, MacNeil MA. Harnessing global fisheries to tackle micronutrient deficiencies. Nature. 2019;574(7776):95–8. https://doi.org/10.1038/s41586-019-1592-6.
14. Hwang CA, Porto-Fett ACS, Juneja VK. Effects of salt concentration on microbial growth and water activity in fish products. Foods. 2020;9(11):1597. https://doi.org/10.3390/foods9111597.
15. Jiang Y, Zhang X, Liu W, Wang H, Chen J. Effects of brining conditions on physicochemical and microbial characteristics of Nile tilapia fillets during storage. Food Control. 2023;149:109689. https://doi.org/10.1016/j.foodcont.2023.109689.
16. Khalifah AM, Elhady M, Abdelrahman H. Microbial hazards associated with processed fish products and control measures. Fishes. 2022;7(4):175. https://doi.org/10.3390/fishes7040175.
17. Kruijssen F, McDougall CL, van Asseldonk IJM. Gender and aquaculture value chains: A review of key issues and implications for research. Aquaculture. 2018;493:328–37. https://doi.org/10.1016/j.aquaculture.2017.12.038.
18. Mebratu Y, Assefa A, Tadesse B. Effects of traditional fish processing methods on nutritional composition and mineral profile of fish products. PLoS ONE. 2024;19(3):e0299926. https://doi.org/10.1371/journal.pone.0299926.
19. Morshdy AEMA, Hussein MA, Elbayomi RM. Occurrence of *Staphylococcus aureus* in salted fish products. Veterinary World. 2022;15(5):1175–82. https://doi.org/10.14202/vetworld.2022.1175-1182.
20. Munguti JM, Obiero KO, Orina PS, Charo-Karisa H. Status and prospects of tilapia aquaculture in Africa. Aquacult Int. 2022;30(3):1121–40. https://doi.org/10.1007/s10499-022-00858-2.

21. Oliveira Filho PRC, Santos AB, Silva FM, Costa RP. Quality characteristics of brined Nile tilapia fillets during refrigerated storage. LWT – Food Sci Technol. 2024;196:115689. https://doi.org/10.1016/j.lwt.2024.115689.
22. Pan J, Wang Y, Li X. Combined preservation technologies for improving fish product safety and shelf life. Food Bioscience. 2025;63:105210. https://doi.org/10.1016/j.fbio.2024.105210.
23. Popa ME. Modern approaches for microbial control in salted fish products. Foods. 2022;11(9):1284. https://doi.org/10.3390/foods11091284.
24. Rohmanna K, Schottroff F, Hildebrandt G. Physicochemical and microbiological changes during brining of fish products. LWT – Food Sci Technol. 2021;148:111741. https://doi.org/10.1016/j.lwt.2021.111741.
25. Ruiz-Alonso R, Fuentes A, Fernández-Segovia I, Barat JM, Escriche I. Influence of brining conditions on physicochemical properties and quality of fish products. Foods. 2021;10(11):2685. https://doi.org/10.3390/foods10112685.
26. Talab AS, Mohamed GF, Ibrahim HM. Effect of salting concentration on proximate composition and quality attributes of fish. Egypt J Aquat Biology Fisheries. 2021;25(3):385–99. https://doi.org/10.21608/ejabf.2021.176245.
27. Tsai YH, Lin CS, Lee CC. Water activity and microbial stability in salted seafood products. J Food Prot. 2022;85(4):620–8. https://doi.org/10.4315/JFP-21-356.
28. World Health Organization (WHO). WHO global report on sodium intake reduction. World Health Organization; 2023.

Figures

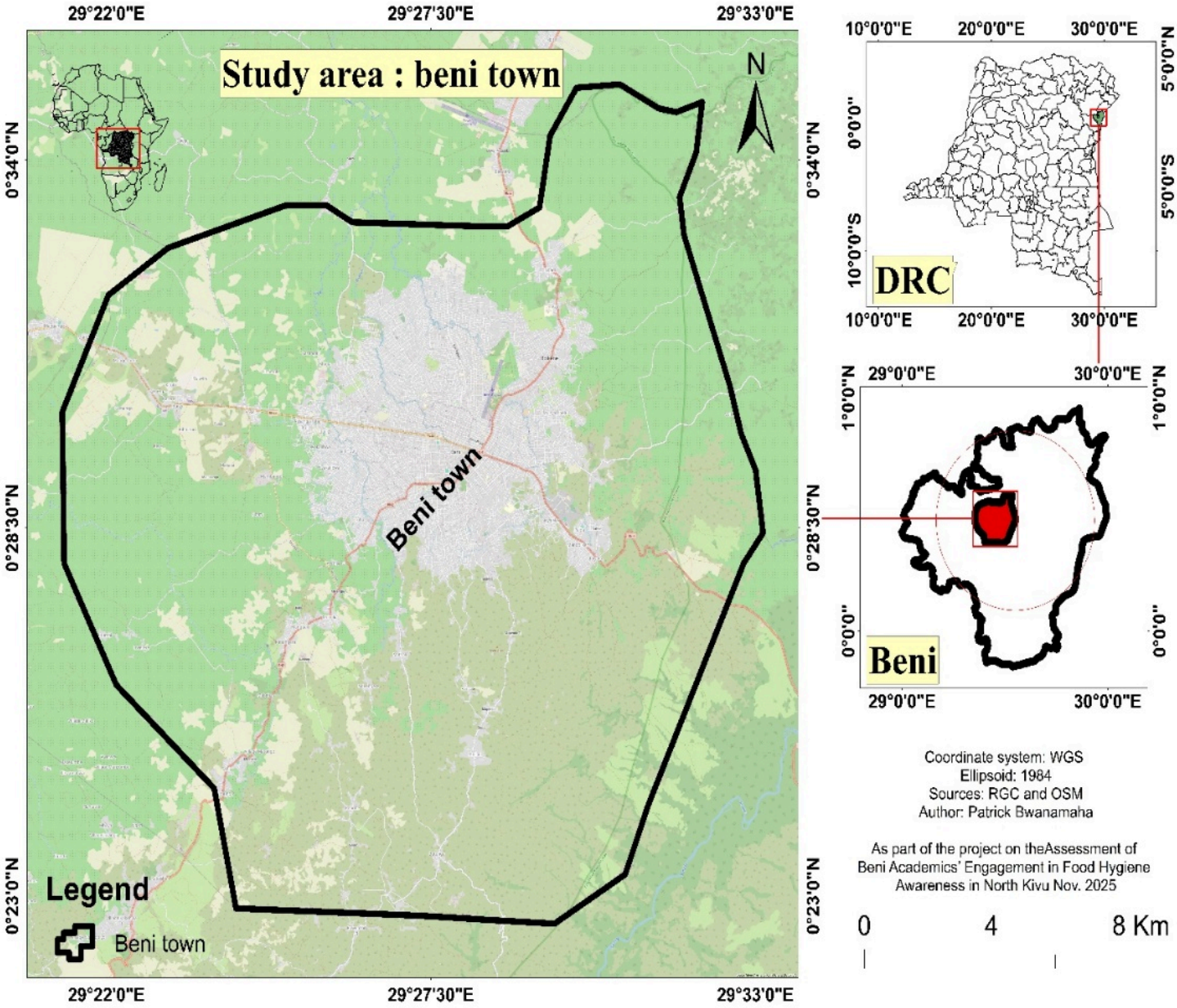
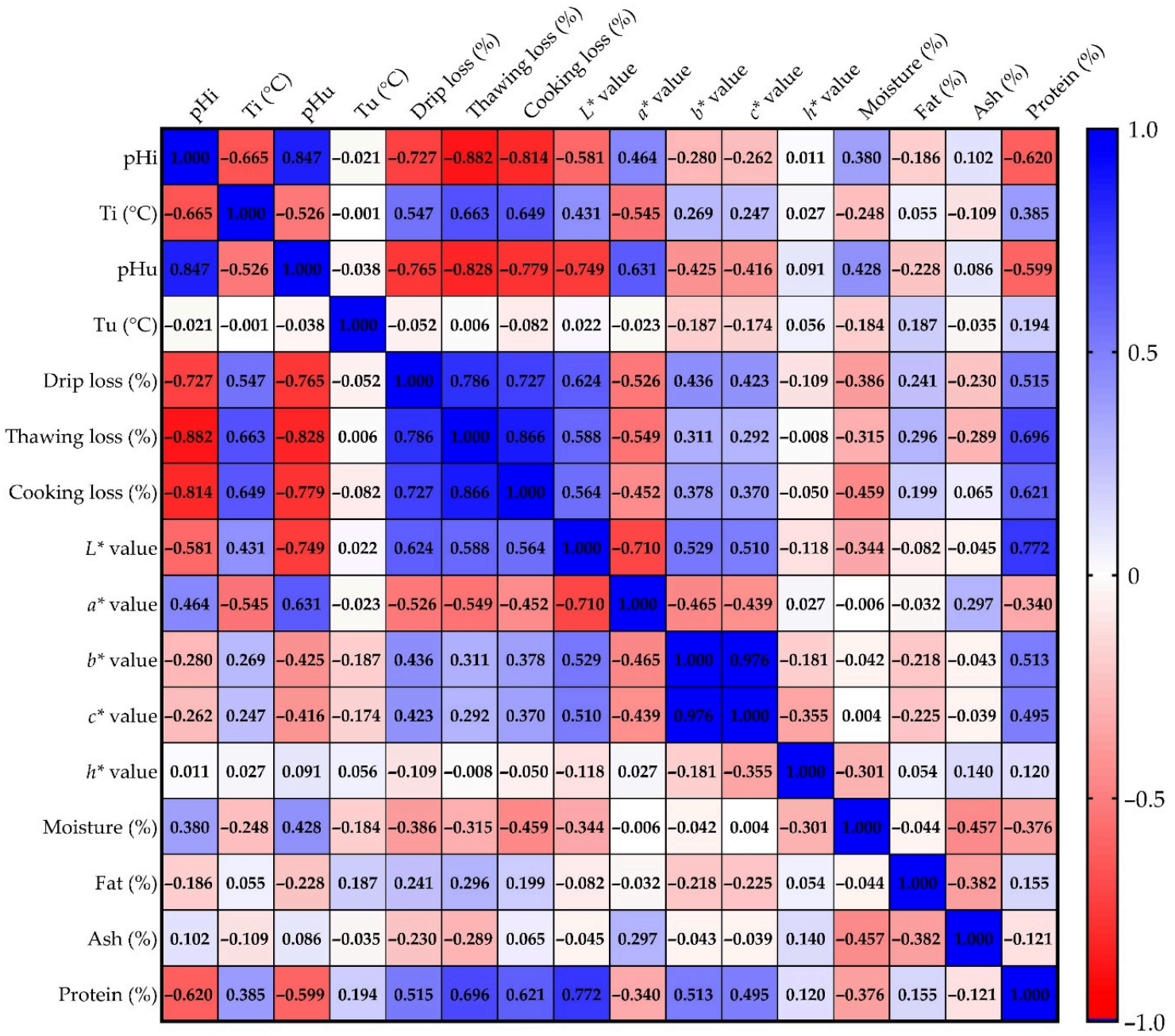


Figure 1

Correlation matrix of physicochemical, nutritional, and mineral parameters of Nile tilapia subjected to different brining levels.



	pHi	Ti (°C)	pHu	Tu (°C)	Drip loss (%)	Thawing loss (%)	Cooking loss (%)	L* value	a* value	b* value	c* value	h* value	Moisture (%)	Fat (%)	Ash (%)	Protein (%)
pHi	1.000	−0.665	0.847	−0.021	−0.727	−0.882	−0.814	−0.581	0.464	−0.280	−0.262	0.011	0.380	−0.186	0.102	−0.620
Ti (°C)	−0.665	1.000	−0.526	−0.001	0.547	0.663	0.649	0.431	−0.545	0.269	0.247	0.027	−0.248	0.055	−0.109	0.385
pHu	0.847	−0.526	1.000	−0.038	−0.765	−0.828	−0.779	−0.749	0.631	−0.425	−0.416	0.091	0.428	−0.228	0.086	−0.599
Tu (°C)	−0.021	−0.001	−0.038	1.000	−0.052	0.006	−0.082	0.022	−0.023	−0.187	−0.174	0.056	−0.184	0.187	−0.035	0.194
Drip loss (%)	−0.727	0.547	−0.765	−0.052	1.000	0.786	0.727	0.624	−0.526	0.436	0.423	−0.109	−0.386	0.241	−0.230	0.515
Thawing loss (%)	−0.882	0.663	−0.828	0.006	0.786	1.000	0.866	0.588	−0.549	0.311	0.292	−0.008	−0.315	0.296	−0.289	0.696
Cooking loss (%)	−0.814	0.649	−0.779	−0.082	0.727	0.866	1.000	0.564	−0.452	0.378	0.370	−0.050	−0.459	0.199	0.065	0.621
L* value	−0.581	0.431	−0.749	0.022	0.624	0.588	0.564	1.000	−0.710	0.529	0.510	−0.118	−0.344	−0.082	−0.045	0.772
a* value	0.464	−0.545	0.631	−0.023	−0.526	−0.549	−0.452	−0.710	1.000	−0.465	−0.439	0.027	−0.006	−0.032	0.297	−0.340
b* value	−0.280	0.269	−0.425	−0.187	0.436	0.311	0.378	0.529	−0.465	1.000	0.976	−0.181	−0.042	−0.218	−0.043	0.513
c* value	−0.262	0.247	−0.416	−0.174	0.423	0.292	0.370	0.510	−0.439	0.976	1.000	−0.355	0.004	−0.225	−0.039	0.495
h* value	0.011	0.027	0.091	0.056	−0.109	−0.008	−0.050	−0.118	0.027	−0.181	−0.355	1.000	−0.301	0.054	0.140	0.120
Moisture (%)	0.380	−0.248	0.428	−0.184	−0.386	−0.315	−0.459	−0.344	−0.006	−0.042	0.004	−0.301	1.000	−0.044	−0.457	−0.376
Fat (%)	−0.186	0.055	−0.228	0.187	0.241	0.296	0.199	−0.082	−0.032	−0.218	−0.225	0.054	−0.044	1.000	−0.382	0.155
Ash (%)	0.102	−0.109	0.086	−0.035	−0.230	−0.289	0.065	−0.045	0.297	−0.043	−0.039	0.140	−0.457	−0.382	1.000	−0.121
Protein (%)	−0.620	0.385	−0.599	0.194	0.515	0.696	0.621	0.772	−0.340	0.513	0.495	0.120	−0.376	0.155	−0.121	1.000

Figure 2

Hierarchical cluster analysis of physicochemical, nutritional, and mineral parameters of Nile tilapia after brining.

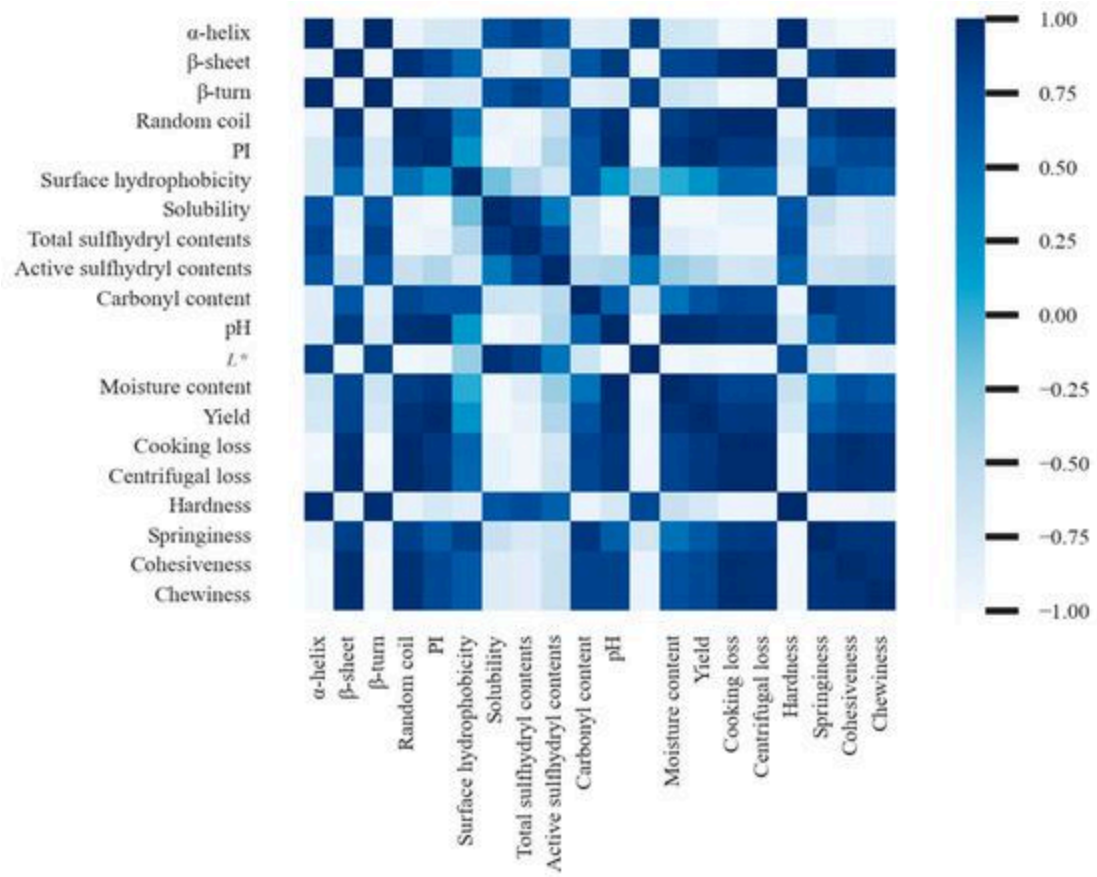


Figure 3

Principal Component Analysis (PCA) of Physicochemical, Nutritional, and Microbiological Characteristics of Nile Tilapia (*Oreochromis niloticus*) Subjected to Different Brining Treatments.