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Assessment of Nutritional Value and Microbiological Safety of Food Waste for the Development of Balanced Feed Additives for Aquaculture

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ABSTRACT

This study aims to evaluate the nutritional value, microbiological safety, and residual levels of heavy metals in food waste to develop a balanced feed mixture for aquaculture. The study used four categories of food waste: fat-containing, bone, organic, and composite. The physicochemical composition of the samples was determined in accordance with international standards using modern analytical equipment. Microbiological safety was assessed by determining the total viable count (QMAFAnM), the presence of pathogens, and the content of lactic acid bacteria. The analyses revealed that the samples studied possessed high nutritional value but varied in their chemical composition. Fat-containing waste has the maximum energy value (443.91kcal) and a high proportion of lipids (25.88%), but also increases oxidation indices, requiring stabilization by antioxidants. Bone waste had the highest concentration of protein (43.18%) and macronutrients (Ca, P), making it a valuable source of minerals for fish feed. Organic waste contains a significant amount of carbohydrates (87.26g/kg), but their potential utilization requires enzymatic treatment to enhance digestibility. Composite waste combines a balanced ratio of proteins, fats, and carbohydrates, although there is a need to control oxidation processes. Microbiological analysis did not reveal the presence of pathogenic microorganisms, and the presence of lactic acid bacteria may improve digestion in fish. The assessment of heavy metal content revealed that the concentrations of Pb, Cd, As, and Hg did not exceed the maximum permissible limits established by international regulations, indicating that the tested waste is safe for use in feed. The results prove the great potential of using food waste as a feed additive for aquaculture. However, its effective application requires standardization of raw materials, quality control at all processing stages, and the development of preservation technologies to prevent oxidation and loss of nutritional value. Further research will focus on optimizing processing methods and assessing the impact of such feeds on fish growth, health, and productivity.

Keywords: Aquaculture, Food waste, Feed additives, Sanitary indicators, Sustainable development, Safety.

INTRODUCTION

Amid the rapid growth of the world population and the constant need to ensure food security, the rational use of food waste acquires special relevance (Bugubayeva et al. 2024; Rozhkova et al. 2025). One promising direction for processing such waste is its use as an alternative feed raw material in the agro-industrial complex (Truong et al. 2019; Torok et al. 2021), which would aid in reducing the environmental load and costs of feed production for animals, birds, and fish, providing more sustainable and profitable farming systems (Zheldybayeva et al. 2025).

Traditional methods of food waste utilization, such as landfilling and incineration, are fraught with serious environmental and economic problems (Kobilova and Shingisov 2024; Saparov et al. 2024). Studies show that food waste has considerable nutritional value, containing high levels of proteins, fats, carbohydrates, and minerals (Pakhomov et al. 2022). That said, its use in animal and fish feed requires a comprehensive safety assessment, considering microbiological risks and the content of potentially hazardous substances (Kamalieva et al. 2020).

The incorporation of food waste into fish feeds is actively explored in various countries, including the USA, Japan, South Korea, and China. Experimental data demonstrate that, if technological standards are met,

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such feeds can successfully replace conventional ingredients, providing high nutritional value and safety (Bektursunova et al. 2022). In the Netherlands, it is a traditional practice to utilize by-products from the food industry in animal production. This provides an effective way to process organic residues from restaurants and food production into feed ingredients, reducing dependence on conventional feed and environmental impact (Alekhin et al. 2014). A similar trend can be seen in Russia. New veterinary regulations introduced since 2021 authorize the processing of moderately hazardous biological waste into animal feed and feed additives (Yerzhanova et al. 2025). This opens more opportunities to utilize food waste in feed production, reducing landfill volumes and boosting the efficiency of resource use. The experience of these countries shows that the rational use of secondary resources makes it possible not only to reduce the environmental load but also to reduce dependence on traditional sources of raw materials for feed.

In Kazakhstan, the problem of processing food waste effectively is becoming urgent. The development of aquaculture has created the need for safe and cost-effective feeds based on local resources that would reduce import dependence and increase the environmental sustainability of fish farming (Ulyanov et al. 2024). As of today, the country has 14 enterprises engaged in fish feed production with a total capacity of 136 thousand tons per year. The use of food waste in feed production is still in the early stages, although some enterprises are already taking steps in this direction. The Government of the Republic of Kazakhstan is also taking measures to support aquaculture. In 2021, the Fishery Development Program for 2021–2030 was adopted, aimed at increasing fish production and improving the infrastructure of the industry (Government of the Republic of Kazakhstan, 2021).

As argued by Georganas et al. (2020), processing food waste into animal feed has a double advantage, it contributes to food security and increases the nutritional value of livestock products due to the biologically active compounds contained in the waste.

However, successful implementation of such initiatives requires comprehensive research to assess the nutritional value and safety of processed food waste and to develop technologies for its effective use in aquaculture feed production (Baidalina et al. 2024; Sarsembayeva et al. 2025).

The present study aims to comprehensively assess the nutritional value and microbiological safety of food waste to develop a feed mixture for aquaculture in Kazakhstan. This work includes an analysis of key parameters, including protein, fat, carbohydrate, and mineral content, as well as an evaluation of microbiological parameters and the presence of potentially hazardous compounds.

MATERIALS AND METHODS

Research objects and sampling methodology

The study analyzed various types of food waste generated in the canteens of the enterprises of the Nefte Stroy Servis LTD LLP. The waste was classified by origin and physical and chemical properties into four main categories:

Sample 1 — fat-containing waste consisting of used vegetable and animal fats, margarine, leftover fatty sauces, mayonnaise, and fatty broths and gravy.

Sample 2 — bone waste, including bones, cartilage, seafood shells, and egg shells.

Sample 3 — organic food waste made up by uneaten meals, porridge, vegetable and fruit leftovers, dairy products, and bakery products.

Sample 4 — composite waste, a blend of several types of food waste, such as leftovers from cooked dishes containing bones, fat, and flour products simultaneously.

Sampling was carried out in strict compliance with the regulated national and international standards. The samples were collected from kitchen work areas, temporary storage areas, and waste disposal areas. Each sample was placed in a sterile container marked with information on the type of waste and the time and place of collection. The collected samples were transported to the laboratory under controlled temperature conditions to prevent microbiological changes. The samples were collected three times, considering the temporal and technological factors of waste accumulation.

Preparation of samples

Sample preparation was carried out in the laboratory of the Department of Veterinary Sanitation at Kazakh National Agrarian Research University. Before any laboratory tests, all food waste samples underwent pre-treatment. First, the samples were dried at 60°C in a ShS-80-01 SPU drying cabinet (Smolenskoye Special Technological Construction Bureau for Software Control Systems, Russia) to constant mass, which minimized the impact of moisture on the analysis. Next, the dried samples were ground to a uniform consistency in an LZM-M2 laboratory mill (LaborKomplekt, Russia), which ensured their homogeneity and the reproducibility of subsequent measurements. For further analysis, the samples were homogenized to ensure a uniform distribution of the components in the sample.

Analysis for chemical composition of food waste

The physicochemical composition of the samples of various types of food waste was studied in an accredited laboratory of the Research Institute of Food Safety at Almaty Technological University, following the established methods regulated by state and international standards.

Total protein content was identified as described in GOST 13496.4-2019 (Federal Agency for Technical Regulation and Metrology 2019) by the Kjeldahl method based on determining the nitrogen content in the sample. Fat content was determined according to GOST 13496.15-2016 (Federal Agency for Technical Regulation and Metrology 2016) with an SOX606 Soxhlet extractor (Hanon Instruments, China). Determination of carbohydrate content was carried out according to GOST 34134-2017 (Federal Agency for Technical Regulation and Metrology 2017) by the chromatographic method using an Agilent Technologies 1200 high-performance liquid chromatograph (Agilent Technologies, USA).

Ash content was determined according to GOST 32933-2014 (Federal Agency for Technical Regulation and Metrology 2014) by burning dried samples in an ECPS-10 SPU mod. 4005 muffle furnace (Smolenskoye STCB SCS, Russia) at 550°C to complete the removal of organic substances and then weighing the remnants. Moisture content was established as per GOST R 54951-2012 (Federal Agency for Technical Regulation and Metrology 2012b) using a ShS-80-01 SPU drying cabinet (Smolenskoye STCB SCS, Russia).

The acid value of fat in the food waste samples was determined per GOST 13496.18-85. A portion of the sample (5.0g) was dissolved in 50mL of ether-alcohol mixture (1:1) and titrated with 0.1n KOH solution in the presence of phenolphthalein to a stable pink coloring. The volume of KOH was recorded and used to calculate the acid value. The results were expressed in mg KOH/g to one decimal place (USSR State Committee for Standards 1985). The peroxide value of fat was determined according to GOST 31485-2012. A portion of the sample (5.0g) was mixed with a solution of acetic and chloroform acids, then a solution of potassium iodide was added, and the resulting mixture was kept in the dark. The released iodine was titrated with 0.01n sodium thiosulfate solution in the presence of starch until discolored. The result was expressed in mmol of active oxygen per 1kg of fat (Federal Agency for Technical Regulation and Metrology 2012c).

Energy value was calculated based on the content of proteins, fats, and carbohydrates according to GOST 32195-2013 using physiological coefficients: 1g protein — 4kcal, 1g of fat — 9kcal, 1g of carbohydrates — 4kcal. Total calories were calculated as:

$$EV\ (kcal) = (P \times 4) + (F \times 9) + (C \times 4)$$

where: P — protein content (g), F — fat content (g), C — carbohydrate content (g) per 100g of product.

Determination of mineral composition

Mineral composition was determined according to established standards: iron (Fe), copper (Cu), zinc (Zn), calcium (Ca), magnesium (Mg), sodium (Na), silicon (Si), nickel (Ni), potassium (K), and selenium (Se) — according to GOST 32343-2013 (Federal Agency for Technical Regulation and Metrology 2013a) with a KVANT-Z-ETA-T atomic absorption spectrometer (KORTEK LLC, Russia); aluminum (Al) — as per GOST 30178-96; phosphorus (P) — by the photometric method according to GOST 9794-2015; iodine (I) and nitrogen (N) — through titrimetric analysis according to GOST 31660-2012.

Total microbiological contamination

The total Quantity of Mesophilic Aerobic and Facultative Anaerobic Microorganisms (QMAFAnM) was determined according to GOST 10444.15-94 (State Committee of the Russian Federation for Standardization and Metrology 1994) by sowing on nutrient media and then counting colony-forming units (CFU) per 1g of the product using a Scan 100 semi-automatic colony counter (Interscience, France). Coliform bacteria were determined through incubation in selective media as per GOST 31747-2012 (Federal Agency for Technical Regulation and Metrology 2012d). *Escherichia coli* was detected on Endo's medium and Levine agar following GOST 30726-2001 (State Committee of the Russian Federation for Standardization and Metrology 2001). *Proteus spp.* was detected using high-lactose media according to GOST 28560-90 (USSR State Committee for Product Quality Management and Standards 1990a). *Enterococcus spp.* was detected in selective media and identified by biochemical properties under GOST 28566-90 (USSR State Committee for Product Quality Management and Standards 1990b). *Pseudomonas* was cultivated on Cetrimide agar and Agar King-B as per GOST R 54755-2011 (Federal Agency for Technical Regulation and Metrology 2011). *Salmonella spp.* was detected on selective media (bismuth sulfite agar, Endo's medium) following GOST 31659-2012 (Federal Agency for Technical Regulation and Metrology 2012e). *Listeria monocytogenes* was identified as per GOST 32031-2012 (Federal Agency for Technical Regulation and Metrology 2012a). *Clostridia* were detected under anaerobic conditions on Wilson-Blair medium according to GOST 29185-91 (USSR Committee for Standardization and Metrology 1991). *Staphylococcus aureus* was identified by sowing on egg yolk salt agar following GOST R 52815-2007 (Federal Agency for Technical Regulation and Metrology 2007). Finally, mold fungi and yeasts were determined by sowing on Sabouraud agar and wort agar as described in GOST 10444.12-2013 (Federal Agency for Technical Regulation and Metrology 2013b).

Determination of heavy metal residues in the samples

The residual amounts of heavy metals, i.e., lead (Pb), cadmium (Cd), arsenic (As), and mercury (Hg), in the food waste samples were determined according to GOST 30178-96 (State Committee of the Russian Federation for Standardization, Metrology and Certification 1996). For this purpose, the samples were pre-treated with acids to convert the metals into soluble forms. The samples were then analyzed on a KVANT-Z-ETA-T atomic absorption spectrometer (KORTEK LLC, Russia). The obtained data were compared with the established limits.

Statistical data processing

The obtained data were subjected to a variation analysis performed in Microsoft Excel 2019. The validity of the results was tested using variation statistics and Student's t-test. The detected differences were deemed statistically significant at $P \geq 0.05$.

RESULTS

Physicochemical parameters of food waste samples

In the course of the study, a thorough analysis of food waste was conducted to systematize it by its physicochemical characteristics (Table 1). The parameters included the mass fraction of moisture, the content of proteins, fats, and carbohydrates, as well as the acid and peroxide values of fat and energy value.

Sample 1 (fat-containing waste) is marked by the highest mass fraction of fat at 25.88% ($P \geq 0.05$), significantly surpassing organic and composite waste. The content of carbohydrates (38.01g/kg) is the lowest among the considered groups. The mass fraction of protein amounts to 40.56%, was slightly inferior to bone and composite waste. Ash content (9.77%) indicates a low content of mineral substances. The high acid (53.15mg KOH/g, $P \geq 0.05$) and peroxide values (78.01mmol/kg, $P \geq 0.05$) point to the active development of oxidation processes, indicating reduced freshness and the potential risk of rancidity, which limits direct application without preventive measures. Energy value (443.91kcal) is the highest among the samples due to the high concentration of lipids.

Table 1: Physicochemical parameters of food waste samples

Indicator	Food waste sample			
	1 (fat-containing)	2 (bone)	3 (organic)	4 (composite)
Mass fraction of moisture, %	6.15±0.08	7.08±0.09	6.44±0.08*	6.82±0.09*
Mass fraction of ash, %	9.77±0.11	9.05±0.10*	9.91±0.13	10.05±0.15
Mass fraction of protein, %	40.56±0.53	43.18±0.59*	41.66±0.55	43.65±0.61
Mass fraction of protein in terms of dry matter, %	43.22±0.61	46.47±0.67*	44.53±0.64	46.84±0.64
Mass fraction of fat, %	25.88±0.33*	24.32±0.30	22.59±0.27	21.77±0.25
Mass fraction of fat in terms of dry matter, %	27.57±0.36	26.17±0.34	24.14±0.31	23.36±0.32
Carbohydrate composition, g/kg	38.01±1.23	23.36±1.21	87.26±2.11*	56.3±1.52*
Acid value of fat, mg KOH/g	53.15±0.61*	50.27±0.55	54.65±0.63*	57.96±0.63*
Peroxide value of fat, mmol/kg	78.01±0.55*	77.42±0.84	74.98±0.81*	77.48±0.91*
Energy value, kcal	443.91*	440.35*	418.70	422.28
* — P≥0.05				

* Shows a significant difference within a row.

Bone waste (Sample 2) shows significant differences from other categories of food waste in several parameters. First, it has the highest mass fraction of protein, 43.18% (P≥0.05), owing to the presence of collagen and structural proteins. This figure exceeds the protein content of organic waste (41.66%) and fat-containing waste (40.56%) but is slightly inferior to composite waste (43.65%). In terms of fat content (24.32%), bone waste holds an intermediate position. The ash content of bone waste is 9.05% (P≥0.05), which is indicative of a high mineral content, but is lower than that of composite waste (10.05%) and fat-containing waste (9.77%) because of the higher concentration of inorganic compounds in mixed waste. Although the ash content of organic waste is not specified, given that they are predominantly of plant origin, it can be lower. The carbohydrate content in bone waste (23.36g/kg) is the lowest across the groups, which can be explained by the absence of plant impurities. The carbohydrate component (23.36g/kg) is minimal due to the absence of plant components. The acid (50.27mg KOH/g) and peroxide values (77.42mmol/kg) indicate a relative stability of the lipid fraction. The energy value (440.35kcal) is among the highest due to the large proportion of proteins and fats. The energy value of bone waste reaches 440.35kcal due to the high concentration of proteins and lipids.

Sample 3 (organic waste) is predominantly made up of plant components with an addition of dairy and cereals. A distinguishing feature of this group is the maximum content of carbohydrates — 87.26g/kg (P≥0.05). The mass fraction of protein (41.66%) is comparable to that of other waste groups, yet the fat content (22.59%) remains moderate, falling behind samples 1 and 2. Moisture content is 6.44% (P≥0.05). The acid (54.65 mg KOH/g) and peroxide values (74.98mmol/kg) indicate medium intensity of oxidation (P≥0.05), which characterizes the lipid fraction as relatively stable. The energy value of organic waste amounts to 418.70 kcal.

Composite waste demonstrates a balanced content of protein (43.65%), fat (21.77%) and carbohydrates (56.3 g/kg) (P≥0.05). Its energy value (422.28kcal) corresponds to a moderate calorie content, which results from the optimal ratio of all macronutrients. Moisture content is around the average (6.82%) for the tested samples. The acid and peroxide values are the highest among all groups, reaching 57.96mg KOH/g and 77.48mmol/kg (P≥0.05), respectively, and indicate more intensive oxidation processes.

Macro- and micronutrient content in different food waste samples

Investigation of the mineral composition of food waste is an important stage in developing effective and environmentally safe feed additives for fish. Table 2 presents the obtained data on the content of macro- and microelements in the four groups of food waste.

The content of calcium ranged from 6,703.66±82.22mg/100g (Sample 1) to 7,009.61±98.15mg/100g (Sample 2) (P≥0.05). The highest concentration of Ca is recorded in bone waste, which is associated with the presence of bone tissue rich in hydroxyapatite. The highest content of magnesium is detected in sample 1 (74.90±0.99mg/100g) and the lowest in 2, averaging at 61.48±0.83mg/100g (P≥0.05). Sodium content falls in the range of 160.31±1.81 to 170.14±2.56mg/100g (P≥0.05), with the highest level found in sample 2 (bone waste). Phosphorus is the highest in sample 2 as well (3389.35±48.19mg/100g), while the lowest value (3,257.19±42.34mg/100g) is observed in composite waste (Sample 4). The greatest amount of potassium is detected in organic waste, where it averages at 978.19±17.03mg/100g. Silicon content reaches its peak in fat-containing waste (25.75±0.26mg/100g), while the lowest level is recorded in sample 4 (20.22±0.13mg/100g).

Considering trace element composition, the highest concentration of iron is found in sample 2 (5.76±0.08mg/100g), which is owed to the high content of hemoglobin and myoglobin in bone tissues. Average copper content ranges from 0.083±0.001mg/100g to 0.097±0.002mg/100g, and the highest amount of this element is observed in organic waste (Sample 3). Zinc reaches its maximum concentration in composite waste (2.94±0.05mg/100g). Nickel content fluctuates in the range of 0.011±0.0002–0.025±0.0005mg/100g, the maximum level observed in composite waste (Sample 4). Iodine levels range from 0.021±0.0003mg/100g (Sample 3) to 0.039±0.0005mg/100g (Sample 1) (P≥0.05).

Thus, the mineral composition of food waste varies, which should be considered when developing technologies for its utilization and possible use as secondary raw materials.

Microbiological parameters of different food waste samples

The conducted microbiological analysis (Table 3) shows that the studied food waste samples do not contain pathogenic and opportunistic microorganisms, such as

Table 2: Mineral composition of food waste samples

Element, mg/100 g	Food waste sample			
	1	2	3	4
Macroelements				
Ca	6,703.66±82.22	7,009.61±98.15*	6,914.27±89.49	6,983.45±90.78*
Mg	74.90±0.99	72.18±0.93	61.48±0.83*	67.09±0.87
Na	163.19±1.95	170.14±2.56*	160.31±1.81*	166.75±2.18
P	3,315.22±47.17	3,389.35±48.19	3,276.77±42.68	3,257.19±42.34
K	961.27±15.71*	955.92±11.05*	978.19±17.03	909.64±10.93
Si	25.75±0.26	24.73±0.35	23.92±0.24	20.22±0.13
Microelements				
Fe	5.45±0.08	5.76±0.08*	5.52±0.07	5.03±0.07
Cu	0.088±0.0009	0.083±0.001	0.097±0.002*	0.094±0.001*
Zn	2.26±0.04	1.77±0.02	1.93±0.04	2.94±0.05
Ni	0.018±0.0003	0.023±0.0004	0.011±0.0002	0.025±0.0005
I	0.039±0.0005*	0.027±0.0003	0.021±0.0003	0.033±0.0004*
* — P≥0.05				

* Shows a significant difference within a row.

Table 3: Microbiological parameters of different food waste samples

Indicator	Food waste sample			
	1	2	3	4
QMAFAnM, CFU/g	8×10^1	9×10^1	8×10^1	8×10^1
Lactic acid bacteria, CFU/g	4×10^1	1×10^1	2×10^1	5×10^1
Coliform bacteria, per 0.1 cm^3 of the product	Not found	Not found	Not found	Not found
Escherichia coli, CFU/g	Not found	Not found	Not found	Not found
Proteus, CFU/g	Not found	Not found	Not found	Not found
Enterococcus, CFU/g	Not found	Not found	Not found	Not found
Pseudomonas aeruginosa, CFU/g	Not found	Not found	Not found	Not found
Salmonella, per 25 cm^3 of the product	Not found	Not found	Not found	Not found
Listeria monocytogenes, CFU/g	Not found	Not found	Not found	Not found
Sulphite-reducing Clostridia, CFU/g	Not found	Not found	Not found	Not found
Staphylococcus aureus, CFU/g	Not found	Not found	Not found	Not found
Mold, CFU/g	Not found	Not found	Not found	Not found
Yeast, CFU/g	4	4	4	4

Escherichia coli, Proteus spp., Enterococcus spp., Pseudomonas aeruginosa, Salmonella spp., Listeria monocytogenes, Clostridium perfringens and *Staphylococcus aureus*. This proves the sanitary safety of the tested raw materials and the lack of contamination with potentially dangerous bacteria.

Total viable count (QMAFAnM) varied in the range of $8\times10^1-9\times10^1$ CFU/g, which is permissible for organic food substrates. The presence of lactic acid microorganisms in the range of $1\times10^1-5\times10^1$1 CFU/g suggests their possible origin from dairy products or plant waste components containing fermented substrates. The highest number of lactic acid microorganisms is found in sample 4 (5×10^1 CFU/g), which may be attributed to the combined composition favoring the development of these bacteria. The absence of mold fungi and low yeast levels indicates adequate waste quality and the absence of conditions for the active development of fungal microflora.

Overall, the microbiological parameters of the analyzed food waste samples testify to their sanitary safety and potential suitability for use as fish feed additives, subject to further evaluation of the stability of their microbiological composition during storage and processing.

Analysis of the residual content of heavy metals and toxic elements in food waste

The study of heavy metal and toxic element residues in the food waste samples (Fig. 1) revealed the presence of lead (Pb) and cadmium (Cd) in the tested samples, while arsenic (As) and mercury (Hg) were not detected.

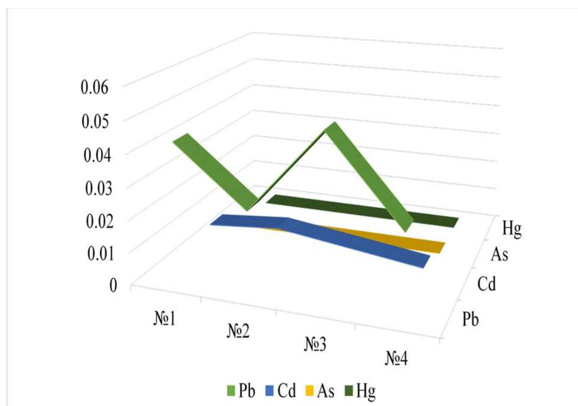

Fig. 1: Diagram of the analysis of residual concentrations of heavy metals and toxic elements in the food waste samples.

Lead content varied in the range of 0.025-0.051mg/kg (P≥0.05), with its highest concentration recorded in organic waste (Sample 3), and the lowest in bone and composite waste (Samples 2 and 4). Cadmium concentration was the lowest among all the detected elements, falling in the range of 0.005-0.011mg/kg (P≥0.05), the highest content found in sample 2. Importantly, the detected lead and cadmium levels do not exceed the threshold limit values (TLVs) set for feed additives and feed raw materials. This confirms the safety of the examined waste and its potential suitability for further use as feed additives for fish.

DISCUSSION

The results of our study of the physicochemical and mineral composition of food waste indicate its significant potential as an alternative source of nutrients, although the variability of composition calls for strict control and standardization. As noted by Mo et al. (2019), the use of fermented feed components from food waste increases the nutrient assimilation rate of fish and contributes to the improvement of their growth and productivity. The quality of raw materials and processing methods are crucial factors. Recent reviews show that targeted microbial fermentation of heterogeneous food residues consistently improves digestibility and palatability while reducing anti-nutritional factors in aquafeeds, leading to better growth and health outcomes in fish (Siddik et al. 2024). In parallel, ensilaging/fermentation of fish and mixed food wastes can curb lipid oxidation and stabilize waste-derived lipids; lactic-acid bacteria and organic acids are particularly effective, though antioxidant control may still be required for storage (Maksimenko et al. 2024). These findings align with our elevated oxidation indices in fat-rich fractions and support standardizing pretreatments (fermentation/ensilaging + antioxidant management) before inclusion in aquaculture feeds. Establishing such processing controls within national guidelines would improve batch-to-batch consistency and safety.

Our analysis of food waste showed significant differences in physicochemical characteristics due to the features of the initial raw materials. Sample 1 (fat-containing waste) is characterized by a high mass fraction of fat (25.88%) and the greatest energy value (443.91kcal), which agrees with the conclusion of Potapov et al. (2017) that fat-containing waste from the food industry is high in calories and can be utilized in animal and fish feed with appropriate treatment. However, the high acid (53.15mg KOH/g) and peroxide values (78.01mmol/kg) point to active oxidation processes, which may reduce the quality of the lipid fraction and necessitate stabilization with antioxidants (Zhang et al. 2020). Bone waste (Sample 2) was the highest in protein (43.18%) due to its high content of collagen and other structural proteins. This observation is consistent with a study by Islam et al. (2023) reporting that bone residue contains a significant amount of protein but has lower digestibility than muscle tissue. Organic waste (Sample 3) was notable for its highest carbohydrate content (87.26g/kg) due to it being mainly plant-based. This result is corroborated by Shurkhno et al. (2014), who note that organic food waste from plant raw materials contains a significant amount of fiber, starches, and simple sugars, which may limit its use as the main source of protein. Composite waste (Sample 4) was found to be balanced in protein (43.65%), fat (21.77%), and carbohydrates (56.3g/kg), making it a promising feed additive option. However, high acid and peroxide values are indicative of intensive oxidation processes. This is consistent with the findings of Raak et al. (2017) that mixtures of different food waste, especially those containing lipid components, are prone to oxidation during long-term storage. Recent studies similarly show that illumination can accelerate lipid oxidation in lipid-rich seafood during frozen storage (Jensen et al. 2023) and that nitrogen-modified atmosphere storage can slow oxidation in high-oil matrices (Ma et al. 2024).

The analysis of the mineral composition of the samples showed great variability in the content of macro- and microelements, which should be considered when developing feed rations. Bone waste showed the highest content of calcium and phosphorus. Calcium and phosphorus are key components in mineral metabolism and bone tissue formation in animals and birds, especially in the early stages of development (Lall and Kaushik 2021).

Microbiological analysis demonstrated a satisfactory sanitary condition of the samples. Total viable count (QMAFAnM) fell within 8×10^1–9×10^1CFU/g, satisfying Codex Alimentarius regulations (Negash 2020). The absence of pathogenic microorganisms (*Escherichia coli, Salmonella spp., Listeria monocytogenes, Staphylococcus aureus*) evidences the safety of food waste for use in fish feeding. The presence of lactic acid bacteria (1×10^1–5×10^1CFU/g) may indicate partial fermentation of organic components, which could be beneficial for digestion in fish, as probiotic microorganisms can improve nutrient absorption (Ringø et al. 2020). Here, it is worth highlighting the conclusion of Abilkhadirov et al. (2021) that established that the addition of functional feed additives with lactic acid bacteria improves digestion in carp fish, increasing the feed conversion ratio.

Finally, the analysis of residual concentrations of heavy metals and toxic elements in food waste is of key importance for assessing their safety and suitability for fish feed. Lead is one of the most toxic metals that can accumulate in the bodies of hydrobionts, affecting their physiological processes, including reproduction and growth (Titov et al. 2020). In our study, lead content ranged 0.025–0.051mg/kg. Cadmium is also a highly toxic element that can accumulate in biological tissues and cause metabolic disorders in fish (Lapirova 2014; Liu et al. 2022). In the samples, its concentration was within 0.005–0.011mg/kg, the highest content recorded in sample 2 (bone waste). Importantly, the observed concentrations of lead and cadmium do not exceed the maximum permissible concentrations established for feed raw materials and feed additives. Per technical regulations, the maximum permissible levels of these metals in feed and feed additives are 5mg/kg for lead and 0.5mg/kg for cadmium (Government of the Republic of Kazakhstan, 2008).

Conclusion

Our analysis of the nutritional value and microbiological safety of food waste confirms its significant potential as an alternative raw material for the production of feed additives in aquaculture. The study demonstrates that different categories of food waste have high nutritional value, but their composition varies considerably, calling for strict quality control and standardization.

Thus, our results give evidence of the great potential of using food waste as a feed additive in aquaculture. However, to introduce this technology into industrial production, standards for raw material quality control and detoxification methods need to be developed. Further research will focus on improving food waste processing technologies to maximize the preservation of nutritional value while minimizing contaminants.

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Data Availability: The data will be available upon request from the corresponding author.

Ethics Statement: The study did not involve live animals or human participants. All procedures for sampling, handling, and laboratory analysis of food waste were carried out in strict accordance with national and international veterinary and sanitary regulations to ensure biosafety and environmental protection.

Author’s Contribution: NS: Conceptualization, methodology design; AZh: Data collection, laboratory analysis; TB: Project administration, interpretation of results; SSh: Validation of microbiological analysis and critical revision of the manuscript; TA: Data curation, preparation of figures and tables; PI: review, and technical guidance on veterinary and sanitary aspects. All authors participated in revising the manuscript and approved the final version for submission.

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