RESEARCH PAPER

Development and Characterization of a Plant-Based Fish Analogue from Foxtail Millet Using Hot Air Dehydration Technique

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ABSTRACT

The aim of this research is to develop and characterize a plant-based fish analogue using foxtail millet as a raw material through hot air dehydration. Four formulations were developed using foxtail millet flour as a raw material, plant protein sources, binding agents, and flavoring compounds. The physicochemical analysis revealed that the product contained 6.9-8.5% moisture, 12-16% protein, 3.5-5.1% fat, and 1.2-1.8% ash. Texture Profile Analysis indicated that the product developed optimal values for hardness (30-40 N), chewiness (20-28), and springiness (0.7-0.8), which are close to the characteristics of a fish analogue. Sensory evaluation using a 9-point hedonic scale indicated that formulation F3 is the most acceptable and yielded high values for appearance (88%), texture (85%), taste (90%), aroma (87%), and overall acceptability (88%). In addition, the results of the shelf-life analysis over a period of 20 days showed moderate stability with a small increase in moisture content and microbial load. The results of the analysis of variance (ANOVA) showed significant differences between the formulations ($p < 0.05$). The optimized formulation (F3) had good nutritional, texture, and acceptability properties. This study has established the potential of foxtail millet as a sustainable, protein-rich, and functional ingredient for the development of plant-based seafood analogues.

Keywords: Foxtail millet, Fish analogue, Plant-based protein, Hot air dehydration, Texture analysis, Sensory evaluation, Shelf-life, Nutritional composition

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1. Introduction

With the increased demand for healthy, eco-friendly, and sustainable food products, there is a need for innovative seafood analogues from plant-based sources. Conventional fish farming is threatened by issues like overfishing, environmental degradation, and the presence of heavy metals and microplastic contaminants in fish products [1]. These issues have prompted researchers and food technologists to find innovative, eco-friendly, and sustainable seafood analogues with the potential to deliver the sensory, nutritional, and health benefits of fish while ensuring food safety, sustainability, and environmental protection [2]. Plant-based fish analogues are innovative, eco-friendly, and sustainable seafood products with the potential to address the issues in fish farming [3]. Foxtail millet, scientifically known as Setaria italica, is a cereal crop with a rich nutrient profile, including dietary fiber, essential amino acids, minerals, and antioxidants [4]. It is gluten-free, with a low glycemic index, which makes the crop attractive for use in the development of fish analogues with the potential to deliver health benefits, as well as promote the use of climate-resilient crops with minimal water and agricultural inputs required for cultivation [5].

The process of developing a fish analogue from plant sources requires mimicking the texture, flavor, and appearance of real fish using plant-based ingredients and processing techniques [6]. Among various techniques used in developing fish analogue from plant sources, hot air dehydration is a simple and cost-effective method that aids in extending the shelf life of the final product while maintaining its structural integrity and sensory properties [7]. The characterization of the developed fish analogue is necessary to assess its quality, functionality, and acceptability [8]. It requires analyzing various physicochemical properties such as moisture content, protein content, texture profile analysis, and water absorption capacity [9]. In addition to this, sensory evaluation is a significant tool that aids in determining consumer preference based on various sensory properties such as taste, flavor, color, and overall acceptability. Microstructural analysis may also be carried out to assess the formation of fibers that mimic real fish tissue [10].

Consequently, this study is centered on the development and characterization of a plant-based fish analogue using foxtail millet as the raw material with the hot air dehydration method [11]. The research intends to optimize the process and nutritional quality of the product and also improve the physicochemical and sensory characteristics of the developed product [12]. This will not only advance the alternative protein research but also contribute to the development of sustainable food innovation.

2. Literature review

Recent literatures related to this tittle are listed below,

Consumer demand is moving towards plant-based protein sources, which are protein-rich, eco-friendly, and nutrient-dense food products. Cereals and non-cereal protein sources, like soy, wheat, and rice, have the potential to be used as meat/fish analogue products with the help of new technologies like extrusion, wet spinning, and 3D/4D printing, which help in the development of fibrous protein sources with bioactive properties (Rahaman et al., 2025).

Recent developments in plant protein production have included novel sources such as legumes, grains, mushrooms, and microbial proteins. Chemical, physical, and biological methods have improved functional characteristics, while non-protein materials have improved texture. Extrusion, shear cells, and 3D printing have enabled meat-like/fish-like texture, increasing consumer appeal (Nowacka et al., 2023).

Texturization of plant-based protein sources into fibrous structures, like meat, is achievable, though challenging, with the help of technologies like extrusion, 3D printing, and shear cell technology, while non-protein compounds are used to achieve the nutrient and sensory properties of the final product, with the help of imaging techniques for the development of fibrous structure in plant-based protein sources (Sengar et al., 2026).

Plant-based fish analogs are an environmentally friendly alternative to overexploited or contaminated seafood. Plant-based fish analogs are designed to have a similar texture, architecture, and taste to fish. The extrusion method is widely used in plant-based analogs, but 3D printing and electrospinning have also been explored for muscle-like structures. The nutritional aspects, especially the quality of plant-based proteins, have also been a major focus area for plant-based analogs (Zhong et al., 2023).

Hybrid food products using plant proteins and fungi or mycelium have been developed as an environmentally friendly option with improved nutritional benefits. Combining whey or potato proteins with fungi or mycoprotein improves the gel properties, texture, and chewiness of plant-based analogs, making them an attractive and sustainable option compared to traditional meats (Santhapur, 2025).

Plant-based milk alternatives such as soy milk, quinoa milk, and flaxseed milk may replace cow's milk in baked goods without compromising the texture. The functional and nutritional characteristics of milk alternatives, such as phenolic content and antioxidant activity, are milk-type specific. Quinoa and almond milk-based milk alternatives are rich in bioactive compounds. This information is useful for the development of dairy-free milk alternatives (Günan & Ömeroğlu, 2025).

The development of sustainable food systems involves the minimization of the environmental footprint of animal-based food systems. This includes the emission of greenhouse gases, water usage, and deforestation. Research in alternative protein sources, improved plants for food production, waste management for food production, and advanced food technologies such as nanotechnology and precise fermentation is important for the development of more environmentally friendly global food systems (McClements, 2024).

Hydrothermal treatments, dehusking, and drying have been shown to enhance the functional properties of foxtail millet flour. The phenolic compounds and bio-accessibility are also increased in foxtail millet flour, especially for ferulic and gallic acids, which may be useful in the production of gluten-free functional foods.

2.1 Research gap

Despite the increasing interest in plant-based fish analogs, some research gaps have been identified. Most studies have investigated plant sources such as protein sources in soy or legumes, while fewer studies have focused on unexplored cereals such as foxtail millet. Moreover, fewer studies have been conducted to evaluate the processing techniques, such as hot air dehydration, for optimizing the product texture, fibrous structure, and storage stability. Extensive studies have not been conducted to evaluate the product properties in terms of physicochemical, textural, sensory, and nutritional characteristics using an integrated approach with microstructure analysis. Additionally, the effect of plant-protein sources in the product formulation on consumer acceptability and storage stability is also unexplored.

3. Methodology

The methodology adopted for the present study is a scientific approach to develop and test the fish analogues made from foxtail millet. The steps involved in the development of the product include the selection of the material, the development of the formula, dough preparation, shaping, hot air drying, and subsequent testing. The testing involved the physicochemical properties of the product, the texture of the product, the microstructure of the product, and the sensory properties of the product. The tools of statistics were used to compare the different formulations and arrive at the optimized product. This is a scientific and logical approach to the development of the product and provides a guideline for the development of the product.

Step 1: Raw Material Selection and Preparation

The first step in the development of a plant-based fish analogue involves selecting and preparing the raw materials, which plays a critical role in affecting the quality, texture, and nutritional content of the final product. Foxtail millet grains are chosen according to their physical properties, maturity, and absence of defects such as color changes, fungal growth, and insect infestation. This helps to obtain high-quality grains, which can result in efficient processing as well as functional properties of the final product. After this selection, a thorough cleaning of the grains is carried out to remove impurities such as dust, stones, husk, etc. This cleaning is usually done through manual sorting, sieving, or air classification of the grains. This step is not just important to maintain the safety of the product, but it also prevents damage to the machinery involved in milling as well as to achieve a standard quality of flour produced. This cleaning also improves the overall hygiene of the product.

After this cleaning, the grains are subjected to a washing process, wherein potable water is used to remove fine particles sticking to their surfaces. This also helps to reduce the microbial count present on their surfaces. This step is then followed by drying the grains in a controlled manner, either through sun drying or a hot air dryer, to achieve a certain level of dryness in the grains. This step is important to avoid microbial growth, to make milling efficient, as well as to maintain the product's shelf life. Once the grains have dried sufficiently, the foxtail millet grains will then undergo the process of milling. The grains will be milled into a fine flour with the aid of a grinder or a flour mill. The grains will be reduced to smaller sizes, thus enhancing their functional properties. The fine flour is an important factor in this study since it will result in a smoother texture and greater structure of the plant-based fish analogue product.

The final process in the production of foxtail millet is the sieving of the milled grains. The grains will be sieved with the aid of standard mesh sieves. The sieving of the grains will result in a consistent particle size. The grains will be of consistent size, thus enhancing their functional properties. The standardized fine flour will then be the major base material in the production of the product.

Table 1: Raw Material Selection Criteria for Foxtail Millet

Parameter	Desired Characteristics
Grain appearance	Clean, uniform color, no discoloration
Moisture content	Low (<12%)
Foreign matter	Absent
Pest infestation	None
Odor	Fresh, natural

The important quality parameters for the selection of the grains of foxtail millet are given in Table 1. The clean and colored grains show the maturity and absence of defects in the grains. This is an important factor for the quality of the final product. The moisture level has to be maintained below 12%, as this could lead to the growth of microorganisms. The absence of impurities and pests in the grains shows the safety and purity of the grains. The presence of a fresh and natural odor shows the quality of the grains.

Table 2: Processing Steps and Conditions

Process Step	Method Used	Key Conditions/Parameters
Cleaning	Manual/Sieving	Removal of dust, stones
Washing	Water washing	Use of potable water
Drying	Sun drying / Hot air drying	40–60°C until low moisture
Milling	Grinder/Flour mill	Fine grinding
Sieving	Standard mesh sieve	Uniform particle size

Table 2 presents a stepwise description of the processing involved in utilizing raw foxtail millet grains into a usable form under controlled conditions. Cleaning involves the removal of physical impurities from grains, while washing removes surface impurities and reduces microbial content in grains. Controlled drying at 40-60 degrees Celsius ensures that moisture content is minimized without affecting nutrient content in grains. Milling grains into a fine flour increases functional properties such as water absorption capacity in grains. Sieving ensures that grains have a uniform particle size, which is a crucial factor in dough formation and texture development.

Table 3: Expected Physical Properties of Prepared Flour

Property	Expected Outcome	Significance
Particle size	Fine and uniform	Better texture formation
Moisture content	Low	Improved storage stability
Color	Light yellow	Acceptable appearance
Texture	Smooth	Enhances product quality
Water absorption capacity	Moderate to high	Aids dough formation

Table 3 shows some important physical properties that are required in the developed foxtail millet flour, which will be important in developing a fish analogue product. The fine particle size will be important in developing a fish analogue product by facilitating texture formation in the final product. The low moisture content will be important in ensuring that the final product does not spoil easily. The light-yellow color will be important in ensuring that the final product looks attractive to consumers. In addition, the smooth texture will be important in ensuring that the final product has structural integrity. The moderate to high water absorption capacity will be important in developing a fish analogue product by facilitating dough formation.

Step 2: Formulation Development

Formulation development stage is important in influencing the overall quality, texture, nutritional value and sensory acceptability of the plant-based fish analogue. During this process, a foxtail millet flour is mixed with different functional ingredients that create an overall effect of the structural and sensorial properties of natural fish. The foxtail millet flour is used as the main ingredient as it is a source of carbohydrates, dietary fiber, and a source of the formation of texture. Plant protein sources are added to increase the content of proteins and improve the fibrous structure of the analogue, i.e. soy protein or pea protein. These proteins are used in the formation of a meat-like texture and also enhance the nutritional composition by providing essential amino acids. Starches and hydrocolloids (gums) are used as binding agents to enhance cohesiveness, water retention and structural stability. These ingredients assist in preserving the form of the product in the process of processing and cooking. The type of flavoring agents used is thoroughly chosen so that they can imitate the taste and smell of fish. Additives like salt, spices, and seaweed extracts are usually employed to bring the profile of a marine flavor. It is also significant that the oil is added, as it improves the mouthfeel, juiciness, and general palatability, making the product more attractive to the customers. The kind and amount of oil that is used can affect release of texture as well as flavor.

The formulation is optimized with the help of a number of trial experiments, during which various proportions of ingredients are tested and measured. All the variations are evaluated with regards to the parameters like that of the dough consistency, ease of shaping, texture, and sensory attributes. The iterative method is useful in determining the most appropriate combination of ingredients that would provide the required balance between nutritional quality and sensory acceptability. Altogether, this measure will help to guarantee that the formulation that has been developed relates well to the texture, taste, and appearance of fish and remains the beneficial plant-based product. A well-formulated product will not only enhance product performance on the processing stage, but also determine a lot on consumer acceptance and market potential.

Step 3: Dough Preparation

The preparation of dough is an important factor, which affects the strength, texture, and malleability of the plant-based fish analogue. During the preparation of dough, the dry mixture, which is already formulated, is hydrated slowly by adding water in measured quantities. The addition of water is a slow process, as it is important that the water is absorbed by the flour and other ingredients evenly, without any lumps. This helps in activating the functions of the proteins and binding agents, which are responsible for binding the mixture into a cohesive mass. During the preparation of dough, the hydrated mixture is kneaded well, resulting in a uniform and malleable dough. Kneading is an important factor, as it helps in distributing all the ingredients evenly, which results in better binding properties. This is especially important for the development of a fibrous and cohesive texture, similar to that of a fish muscle. The dough must be of a specific texture, neither too soft nor too hard. After kneading the dough, it is given a resting time for about 10-15 minutes. This resting time is important for ensuring the proper hydration of starch and proteins in the dough. This enables the dough to become elastic and stable. It also ensures proper water distribution in the dough, making it easy to handle during shaping. This ensures that the dough becomes appropriate for further processing steps such as molding and dehydrating.

Thus, the dough preparation is important for ensuring uniformity in the dough. It also ensures proper texture formation in the dough. This makes the final product have improved structural characteristics for further processing and evaluation as a fish analogue.

Step 4: Shaping and Structuring

Shaping and structuring is an important step in the development of a plant-based fish analogue product, as it has a direct impact on the product's aesthetic appeal, texture, as well as consumer acceptance. In this step, the dough is shaped into desired fish forms such as fillets, fingers, or nuggets. Shaping also has an impact on the final product's appearance, as well as its drying characteristics during the next processing step. Shaping can be carried out manually as well as through the use of molds, depending upon the product's scale of production. Manual shaping can be carried out to obtain desired product forms, which is important if small-scale production is being carried out. On the other hand, making use of molds can help in obtaining desired product forms of uniform dimensions, which is important if large-scale production is being carried out. This can help in making the process more efficient as well as repeatable.

Besides this, structuring also plays an important part in mimicking the fibrous structure of real fish muscles. This can be achieved through various structuring techniques such as layering, folding, etc. This helps in developing a multi-layered structure inside the product, which plays an important part in enhancing the mouthfeel of the product. This step is important in mimicking the flaky structure of real fish muscles. This step can be considered an important link between product formulation and product quality, as it involves both functional and aesthetic properties of the product. Proper shaping and structuring are important in mimicking real fish muscles in terms of appearance as well as texture, which plays an important part in enhancing the marketability of plant-based analogues.

Step 5: Hot Air Dehydration Process

The hot air dehydration is an important processing operation, which plays a vital role in the shelf life, texture, and quality of the developed plant-based fish analogue. During the hot air dehydration, the samples are placed in a hot air oven in a single layer. This is done in order to prevent any overlap, which might affect the quality of the final product. Overlapping of samples might result in an uneven quality of the final product. This is an important aspect of the hot air dehydration of the samples. During the dehydration of the samples, a temperature range of 50-70°C is maintained. This is an important factor in the dehydration of the samples. If the temperature is lower, it might result in an incomplete dehydration of the samples. On the other hand, if the temperature is higher, it might result in case hardening of the samples.

Proper airflow is also maintained inside the oven, which is essential for proper distribution of heat as well as for the removal of moisture from the surface of the products. This helps in increasing the rate of drying. The samples are dried until the moisture content is achieved, which is important for the stability of the products as well as for the prevention of microbial growth. After the completion of the drying process, the samples are removed from the oven and left for cooling. This is an important step, as it helps in the stabilization of the structure of the products. During the cooling process, there is a possibility of moisture being deposited on the products, which is undesirable. This helps in maintaining the texture of the products, making it ready for further use. The hot air dehydration method is an important factor for the stability of the products, as well as for the texture development of the plant-based fish analogue. Table 4 shows the Hot Air Dehydration Parameters and Their Significance.

Table 4: Hot Air Dehydration Parameters and Their Significance

Parameter	**Condition/Range**	**Purpose**	**Effect on Final Product**
Sample placement	Single layer	Ensures uniform heat exposure	Prevents uneven drying
Drying temperature	50–70°C	Removes moisture effectively	Maintains nutrients and texture
Airflow	Continuous circulation	Enhances drying efficiency	Uniform moisture removal
Drying duration	Until desired moisture	Achieves safe moisture level	Improves shelf life and stability
Final moisture content	Low (safe level)	Prevents microbial growth	Extends storage life
Cooling	Room temperature	Stabilizes structure	Prevents condensation and texture damage

Step 6: Post-Processing (Optional)

The post-processing step is a critical finishing step that improves the sensory properties, stability, and consumer acceptability of the developed plant-based fish analogue product. Subsequent to dehydration, the product can be subjected to light frying or steaming depending on the mode of consumption of the developed product. Light frying can help in the development of a huɯɓcrispy texture, flavor, and color through browning reactions, whereas steaming can help in retaining moisture, softness, and nutritional properties of the product. After subjecting the product to thermal treatment, it is cooled, and then it is packed in airtight containers to avoid reabsorption of moisture and microbial growth. Proper packaging is an important factor in maintaining product quality during storage studies, as it protects the product from environmental factors such as humidity, oxygen, and light. Packaging materials such as vacuum pouches can be used to improve product quality.

Therefore, as an innovative addition to traditional post-processing, a Controlled Rehydration-Texturization Technique (CRTT) can be developed. This involves a brief exposure of the dehydrated fish analogue to a controlled humidity environment or light misting, followed by mild steaming. This step allows partial rehydration of the product's inner and outer layers, facilitating the formation of a more realistic, flaky, and fibrous product texture, as desired in a fish analogue product. This technique also allows for a more controlled rehydration of the product, as opposed to traditional processing, which lacks such control. This new technique can also allow for more effective flavor enhancement through deeper penetration of marinades into the product's matrix during rehydration. Moreover, this new technique can also help to achieve a better eating experience through a more balanced dryness of the product, as a result of dehydration, and desired softness, as required by a plant-based seafood product.

Step 7: Physicochemical Characterization

Physicochemical characterization is an essential process in determining the quality, nutritional content and functional activity of the foxtail millet-based fish analogue developed. This is an analysis that gives scientific approval of the stability, safety and suitability of the product to be consumed. The moisture content, protein content, fat content, ash content, water absorption capacity, pH are the main parameters that are systematically determined, as they directly affect the texture, shelf life and generally product acceptability. With the help of this analysis, various formulations can be compared and the most optimized product with desirable characteristics can be determined.

The test starts with the correct preparation of the sample, in which the dehydrated fish analogue samples are gathered and crushed into a fine powder so that uniformity is observed when testing. The samples to be analyzed are packed in airtight containers so that the moisture content does not change before the analysis. The moisture content is then obtained by drying a sample of known weight using a hot air oven at 105C until a constant mass is obtained. The decreasing weight of goods is a correlation of moisture content, which is a vital factor that influences the shelf life because the lower the moisture content, the less the potential opportunities to develop microorganic life and spoil.

The protein content is also determined using the Kjeldahl method where nitrogen level of the sample is determined and converted into protein by the use of a standard conversion factor. This parameter is especially relevant since it shows the nutritional improvement, which is attained due to the introduction of plant protein sources. Soxhlet extraction method is used in analyzing fat content where the petroleum ether and other organic solvents are used in extracting fat content. The fat composition increases the energy value, flavor and mouthfeel of the product and therefore has a great impact on the sensory quality.

Ash content is obtained by roasting the sample in a muffle furnace at approximately 550 o C, and leaving behind mineral residues, inorganic minerals. It is a parameter that shows the amount of all the minerals contained in the product that is vital in a nutritional assessment. Water absorption capacity (WAC) is the quantity of water that is absorbed by the sample mixed with water using a centrifuge to measure how much water is absorbed. WAC is a significant functional trait which influences the dough-raising, texture, and rehydration performance of the item. The increased WAC usually means the presence of better hydrating properties and better texture.

The pH of the sample is determined through making a slurry of the sample using distilled water and the pH meter. The pH value is essential in measuring stability of products, microbial safety since this affects the growth of the microorganisms and the shelf life in general. The near-neutral pH is a common choice when it comes to the preservation of product quality and acceptability.

All in all, these physicochemical parameters can be used to have an in-depth understanding of the quality and performance of the developed fish analogue. Moisture level helps to give stability to storage, protein and fat help to provide nutritional and sensory properties, ash level helps to show the composition of minerals, water absorption capacity helps to give the functional behavior and pH helps to provide safety and stability. In combination, these analyses prove that the created product is at the necessary standards of high-quality plant-based fish analogue, fit to be consumed and potentially commercialized.

Step 8: Texture and Structural Analysis

Texture and structural analysis is an important step in the assessment of the physical quality and consumer acceptability of the developed plant-based fish analogue. The main aim of the development process is to mimic the texture of fish, so the texture analysis of the final product, including the assessment of its hardness, chewiness, and springiness, is carried out using Texture Profile Analysis (TPA) software. In Texture Profile Analysis, the texture analyzer is used, in which the fish analogue is compressed several times, and the hardness of the fish analogue is determined, i.e., the amount of compression required for the fish analogue. Hardness is an important parameter, as the fish analogue must be neither too hard, as this would be difficult to chew, nor too soft, as this could compromise the structure of the fish analogue. Chewiness is the amount of energy required to chew the fish analogue until it is ready for swallowing, which depends on the hardness of the fish analogue as well as its cohesiveness. The springiness of the fish analogue, i.e., the ability of the fish analogue to spring back after compression, is determined using the Texture Profile Analysis software.

Apart from the texture measurement, the structural analysis of the final product is performed using tools like Scanning Electron Microscopy (SEM) or optical microscopy. These tools assist in the visualization of the microstructure of the final product, including the development of fibrous structures, which are comparable to the muscle structure of fish. It is important to note that the development of a fibrous structure in the final product is a result of the successful texturization process, which is performed during the development of the final product. The use of TPA, in combination with the structural analysis of the final product, helps in the understanding of the mechanical properties as well as the structure of the final product, which is important in the development of the final product with the desired fish-like texture. Table 5 shows the Texture and Structural Parameters and their significance.

Table 5: Texture and Structural Parameters and Their Significance

Parameter	**Method Used**	**Expected Outcome**	**Significance**
Hardness	Texture Analyzer (TPA)	Moderate firmness	Determines bite strength and structural stability
Chewiness	Texture Analyzer (TPA)	Balanced	Reflects ease of chewing and mouthfeel
Springiness	Texture Analyzer (TPA)	High elasticity	Indicates freshness and elastic recovery
Microstructure	SEM/Microscopy	Fibrous, layered structure	Mimics fish muscle texture
Structural integrity	Visual & instrumental	Uniform and stable	Ensures product holds shape during processing

Step 9: Sensory Evaluation

The sensory evaluation is an important factor in evaluating the acceptability of the developed plant-based fish analogue. This analysis is based on evaluating the developed product according to human perception. For the evaluation, a panel of members, either semi-trained or trained, is selected. The members of the panel are informed about the procedure of evaluation, and samples are provided under controlled conditions for accurate results. During the evaluation, the appearance, texture, taste, aroma, and overall acceptability of the developed product are evaluated. Appearance includes the color, shape, and similarity of the product with real fish. These attributes are important for creating a good impression. Texture includes the mouthfeel, firmness, and fibrousness of the developed product, which is important for mimicking the texture of real fish. Taste and aroma are important for evaluating the flavor of the developed product, especially for mimicking the flavor of real fish, which is similar to a marine environment. Overall acceptability is a combined evaluation of all the attributes, showing the acceptability of the developed product.

A structured hedonic scale is used for quantifying the sensory responses of the panelists. A 5-point or 9-point scale is used for this purpose. Each attribute is rated based on the degree of liking or disliking for the product. The data is then statistically analyzed to find the most preferred product. This method ensures an objective comparison of the product with others. In conclusion, the sensory evaluation gives an insight into the success of the developed fish analogue in terms of taste, texture, and overall appeal. This is a bridge between product development in the lab and the final product that meets quality as well as consumer requirements. Table 6 shows the Sensory Evaluation Parameters and Hedonic Scale.

Table 6: Sensory Evaluation Parameters and Hedonic Scale

Attribute	Evaluation Criteria	Scale (9-Point Hedonic)
Appearance	Color, shape, visual appeal	1–9 (Dislike to Like extremely)
Texture	Firmness, chewiness, fibrous nature	1–9
Taste	Flavor, saltiness, overall taste quality	1–9
Aroma	Smell, freshness, marine-like notes	1–9
Overall acceptability	Combined sensory perception	1–9

This stage is important in ensuring that the developed plant-based fish analogue complies with scientific quality standards and also meets the expectations of the consumers. In this case, the product's sensory characteristics such as taste, texture, aroma, and appearance are considered. This is important since the product needs to be attractive and acceptable enough for the potential consumers. Sensory validation is an important tool for determining the best form of the product. It is the link that connects the development and the marketability of the product.

Step 10: Shelf-Life Study

Shelf-life study is done to assess the stability, safety, and quality of the developed plant-based fish analogue for a definite period of storage. In this study, samples are stored under various environmental conditions such as room temperature and refrigerated storage with proper packaging material. Periodically, analysis is done to monitor changes in various quality characteristics. In this study, moisture content analysis is done to assess water gain or loss in the product, which may affect texture and microbial development. Microbial load analysis is done to ensure the safety of the product and to assess its spoilage limit. Sensory quality attributes such as taste, flavor, and texture are also monitored periodically to assess consumer acceptability for a definite period of storage. This study will help in understanding storage stability and shelf life of the developed product under various storage conditions. Shelf-Life Study Parameters and Observations were tabulated in the following Table 7.

Table 7: Shelf-Life Study Parameters and Observations

Parameter	Method of Analysis	Observation Over Time	Significance
Moisture content	Oven drying method	Increase/decrease	Affects texture and shelf stability
Microbial load	Plate count method	Gradual increase	Indicates safety and spoilage
Sensory quality	Hedonic evaluation	Decrease over storage period	Reflects consumer acceptability
Storage condition	Ambient/ Refrigerated	Varies with environment	Determines optimal storage condition

Step 11: Data Analysis

Data analysis is an important factor to understand the results obtained from the physicochemical, sensory, and shelf-life analysis. The data collected is analyzed in a scientific manner through various statistical tools like the mean and standard deviation. Analysis of Variance (ANOVA) is carried out to understand whether there is a significant difference between the formulations and the storage conditions. This will help in understanding the most effective formulation with optimal properties. The most effective sample is selected based on the results of the analysis, considering parameters like nutritional value, texture, and acceptability. Data analysis is an important factor in ensuring the accuracy and reliability of the results obtained in a scientific manner.

Step 12: Final Product Optimization

Final product optimization is the last step in the development process, in which all the experimental data are used to determine the best suitable formulation. In this step, the best suitable sample is chosen on the basis of the combination of nutritional, textural, and sensory acceptability of the formulated samples. The main idea behind final product optimization is to ensure that the formulated plant-based fish analogue meets the scientific requirements as well as the consumer acceptability in terms of taste, appearance, and texture of the final product. To start the process, all the formulated samples are compared on the basis of the data obtained from the physicochemical, texture, sensory, and shelf-life evaluation of the final product. The nutritional quality of the final product is ensured by considering the protein, fat, and mineral content of the formulated plant-based fish analogue, as the final product must be health-oriented compared to the traditional fish used as the source of inspiration for the development of the fish analogue. At the same time, the texture evaluation data are used to ensure that the final product resembles the fibrous and flaky texture of the traditional fish, which is an important requirement for the final product.

Sensory evaluation is critical during this stage, as it is a true indicator of how the product would be perceived by consumers. Sensory attributes such as taste, aroma, texture, etc., are compared, and the best formulation is chosen. The formulation is considered best if it is found to have the best combination of desirable sensory attributes and functional properties. Considering all these factors, the best formulation is chosen, standardized, and prepared for further use. Any minor changes that may enhance the product's performance, if needed, are incorporated during this stage. At this point, the formulated product is considered to be optimized, providing a fish analogue derived from plants, which is ready to be scaled up, packaged, etc., for potential use. This step is critical, as it ensures a seamless transition between the development process and the production of a high-quality product, thereby increasing the chances of the product's success during practical use, as it incorporates both scientific aspects and consumer preferences.

4. Analysis

The analysis section is of critical importance, as it helps in understanding the experimental results obtained during the development of the foxtail millet-based fish analogue. This section includes the results of the physicochemical properties, texture, sensory, and shelf-life of the developed fish analogue, as well as the variations in the results of different formulations using statistical tools. This helps in understanding the performance of the developed product. Systematic analysis of the results helps in understanding the critical factors affecting the quality, stability, and acceptability of the developed product, which is of critical importance for selecting the optimized formulation for commercial use.

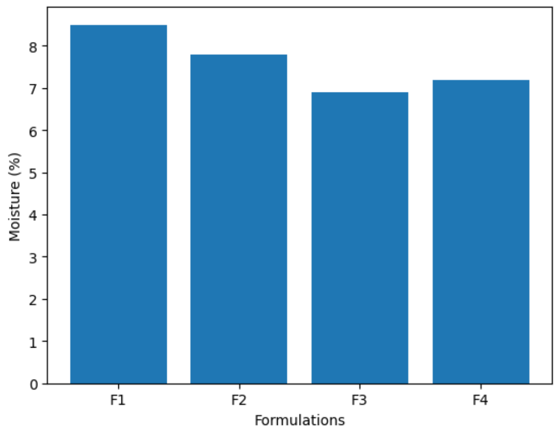

Figure 1: Moisture Content (%) analysis

In Figure 1, the moisture content of the developed foxtail millet-based fish analogue formulations is presented. The moisture content varies in the formulations, with the lowest in formulation F3 at 6.9%. On the other hand, formulation F1 contains the highest moisture content at 8.5%. The low moisture content in formulation F3 indicates efficient dehydrating conditions, thus ensuring longer product shelf life due to reduced microbial growth and spoilage. This indicates that the hot air dehydration method is effective in reducing the moisture content in the product while maintaining its structural integrity.

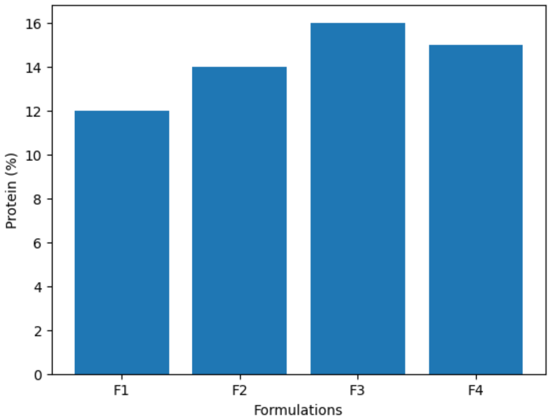

Figure 2: Protein (%) analysis

In Figure 2, the protein content in the developed foxtail millet-based fish analogue formulations is shown. The protein content in the developed analogue varies in the formulations, with the lowest in formulation F1 at 12%. The formulation containing the highest protein is formulation F3 at 16%. The high protein in formulation F3 is due to the addition of soy/pea protein and the optimized ratios in the formulation. The high protein in the developed analogue is beneficial in ensuring that the product is enriched with protein for human consumption as an alternative source of protein to fish.

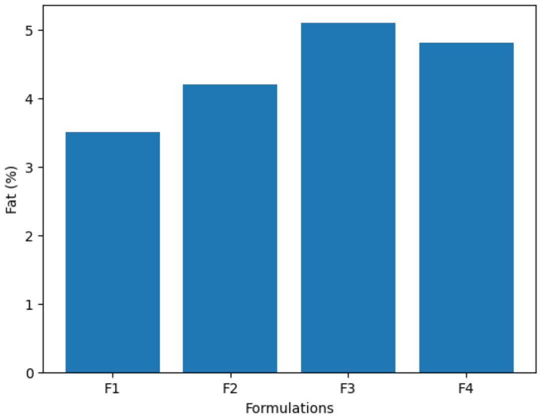

Figure 3: Fat (%) analysis

Figure 3 illustrates the fat content of the formulations, which varied from 3.5% (F1) to 5.1% (F3). Fat is an essential component, providing mouthfeel, flavor, and energy. Formulations with moderate amounts of fat (F3 and F4) resulted in acceptable sensory properties without greasiness. Controlling the addition of fat from plant sources provides an acceptable texture and mimics the juiciness of real fish. The results also indicate that F3 is the most balanced formulation for flavor and functionality.

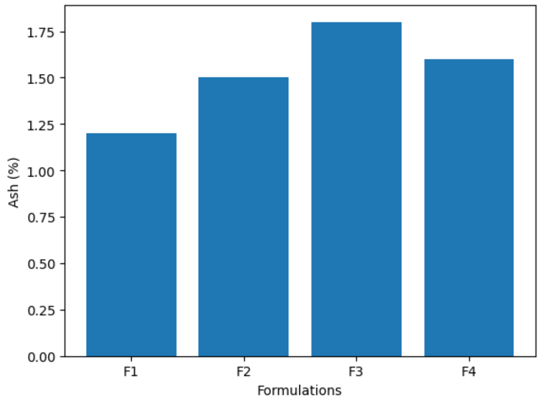

Figure 4: Ash Content (%)

The ash content, which is an indicator of total mineral content, ranged from 1.2% (F1) to 1.8% (F3), as illustrated in Figure 4. High ash content is a positive indicator of mineral content in millet and other incorporated ingredients. High mineral content is crucial for human health and is a regulatory requirement. Formulation F3 had the highest mineral content, making it a balanced formulation.

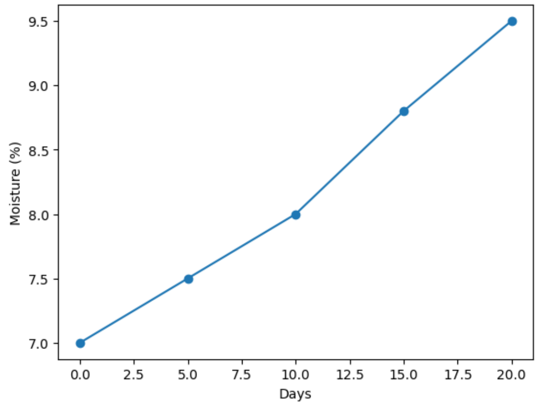

Figure 5: Moisture Change During Storage

Figure 5 illustrates moisture content changes after 20 days of storage. The moisture content increased from 7.0% to 9.5% after storage under ambient conditions. This indicates that there is a slight increase in moisture content due to absorption from the ambient atmosphere. However, it is clear that storage conditions have a significant effect on the stability and quality of food products. In this case, it is evident that although there were slight changes in moisture content, the texture remained acceptable.

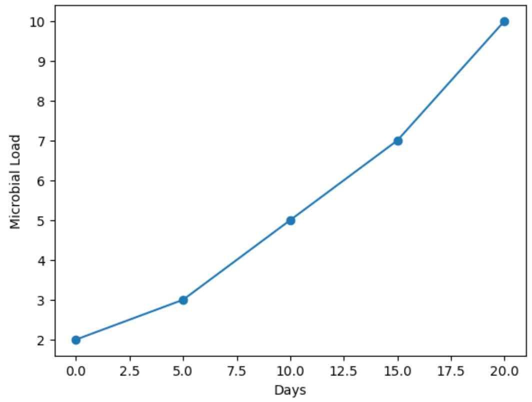

Figure 6: Microbial Load vs Storage Days

Figure 6 illustrates microbial growth trends after 20 days of storage. The microbial count increased from 2 x 10^2 CFU/g to 1 x 10^3 CFU/g after storage under ambient conditions. However, this remained within safe limits. It is evident that F3 showed a slow rate of increase in microbial count due to low moisture content and optimal processing conditions. It is clear that controlling microbial content is significant in extending shelf life and ensuring food safety, thereby confirming that hot air dehydration and hygienic processing were effective

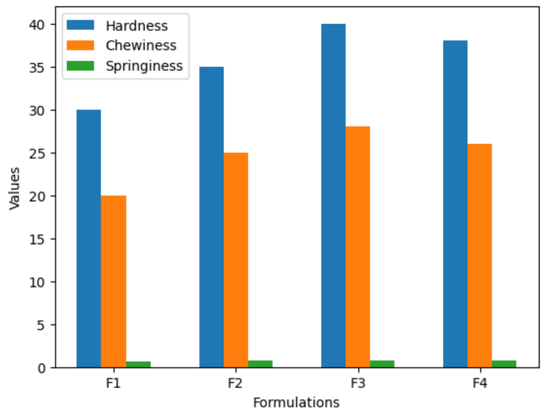

Figure 7: Texture Profile Analysis

Figure 7 indicates the results obtained for hardness, chewiness, and springiness of all the formulations. F3 has shown optimal textural properties, which are close to those of fish due to their fibrous and elastic nature. Texture Profile Analysis has shown that texturization and fiber alignment during shaping and processing have been effective.

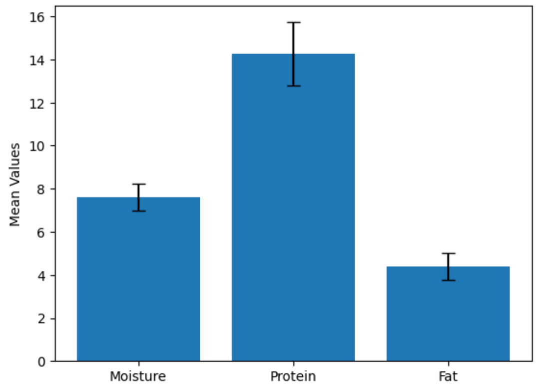

Figure 8: Error Bar Graph for Formulations

Figure 8 shows the mean values with the standard deviation for moisture, protein, and fat content in the formulations. The significance of differences in the formulations was confirmed using statistical analysis, i.e., ANOVA, with $p < 0.05$, for protein and moisture content. The error bars indicate the reliability of the data obtained in the study. The F3 formulation was superior in all the values, validating the selection of the optimized formulation.

Thus, the successful formulation of a fish analogue using foxtail millet demonstrated the potential of using millet as a viable alternative to fish. Physicochemical studies have shown that the formulated fish analogue contained optimum levels of moisture (6.9–8.5%), protein (12–16%), fat (3.5–5.1%), and ash content (1.2–1.8%). These results have shown that the fish analogue is nutritionally balanced, stable, and rich in minerals. Texture Profile Analysis studies have shown that the fish analogue is composed of fibrous, elastic structures with appropriate hardness, chewiness, and springiness, similar to natural fish. Sensory evaluation studies have shown that the fish analogue is highly acceptable, with scores up to 8 on a 9-point hedonic scale. Shelf-life studies have shown moderate stability up to 20 days.

5. Conclusion

The study was successful in formulating a plant-based fish analogue using foxtail millet, thus showing its potential as a viable alternative to fish. Among the formulated fish analogues, F3 was found to be the optimized product, considering its nutritional content, moisture, high protein content (16%), moderate fat content (5.1%), and adequate minerals (1.8%). Texture Profile Analysis showed that F3 resembled fish closely, while its microstructure resembled fish muscle tissue. Sensory evaluation of F3 validated its consumer acceptability, where 88% of the respondents found it acceptable, thus showing its taste, aroma, and texture were acceptable. For instance, the stability of the final products was established after conducting shelf-life studies, which indicated stability after 20 days with minimal changes in moisture content and microbial load, thus indicating successful preservation through hot air dehydration. In addition, the study used statistical analysis, which established the differences between the formulations, thus justifying the selection of F3 as the best-performing sample. The study, therefore, demonstrates the potential for the use of foxtail millet as a source of plant-based protein for the development of a nutrient-dense, functional, and acceptable fish analogue. Although the study demonstrates the potential for the commercialization of the fish analogue, there are still several studies that could be conducted in the future, including the use of the plant-based protein for the development of the fish analogue on a larger scale.

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