Revista Brasileira de Engenharia de Pesca

Cidade Universitária Paulo VI – Avenida Lourenço Vieira da Silva 1.000 – São Luís/MA.
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Edição 17, Vol. 1, 2026.

SCIENTIFIC AND TECHNOLOGICAL ASPECTS OF CONSERVATION AND PROCESSING OF TILAPIA FILLETS

ASPECTOS CIENTÍFICOS E TECNOLÓGICOS DA CONSERVAÇÃO E DO PROCESSAMENTO DE FILÉS DE TILÁPIA

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Citação: SILVA, R. E. S.; SILVA, W. B.; PORTO, T. S.; SHINOHARA, N. K. S.; OLIVEIRA FILHO, P. R. C. (2026). Scientific and technological aspects of conservation and processing of tilapia fillets. Revista Brasileira de Engenharia de Pesca, 17(1), 333-366.
https://doi.org/10.18817/repesca.v17i1.4572

Recebido: 24 May 2026
Revisado: 19 July 2026
Aceito: 21 July 2026
Publicado: 21 July 2026

Resumo

A rápida expansão da produção de tilápia e a crescente demanda por filés intensificaram a necessidade de tecnologias eficazes de conservação e processamento. Este estudo analisou o panorama científico e tecnológico dessas tecnologias, identificando tendências, lacunas e oportunidades de inovação. Os dados foram coletados no Scopus, no Instituto Nacional da Propriedade Industrial (INPI) e no Espacenet, utilizando os termos "filé de tilápia" OU "filés de tilápia". Foram analisados, no total, 418 artigos científicos e 179 documentos de patentes. Os resultados mostraram que a China liderou tanto a produção científica quanto a atividade de patenteamento. Ao mesmo tempo, o Brasil apresentou forte produção científica, mas atividade de patenteamento limitada, indicando uma baixa conversão do conhecimento científico em proteção tecnológica. Além disso, a maioria das patentes concentrou-se no desenvolvimento de novos produtos e em estratégias de processamento de valor agregado. Ao mapear técnicas de conservação, inovações tecnológicas e lacunas de pesquisa, este estudo fornece informações para apoiar a inovação e a sustentabilidade na cadeia produtiva da tilápia.

Palavras-chaves: Inovação; Patentes; Métodos de conservação; Prospecção tecnológica; Filés de tilápia.

Abstract

The rapid expansion of tilapia production and the growing demand for fillets have heightened the need for effective preservation and processing technologies. This study analyzed the scientific and technological landscape of these technologies, identifying trends, gaps, and opportunities for innovation. Data were collected from Scopus, the National Institute of Industrial Property (INPI), and Espacenet, using the terms "tilapia fillet" OR "tilapia fillets." A total of 418 scientific articles and 179 patent documents were analyzed. The results showed that China led both scientific production and patenting activity. At the same time, Brazil demonstrated strong scientific output but limited patenting activity, indicating a low conversion of scientific knowledge into technological protection. In addition, most patents focused on developing new products and value-added processing strategies. By mapping preservation techniques, technological innovations, and research gaps, this study provides information to support innovation and sustainability in the tilapia production chain.

Keywords: Innovation; Patents; Preservation methods; Technological prospecting; Tilapia fillets.

Introduction

Tilapia are freshwater fish belonging to the family Cichlidae, order Cichliformes, and genus *Oreochromis*, and are native to Africa and the Middle East. Among the farmed species, the Nile tilapia (*Oreochromis niloticus*) stands out as the most widely produced worldwide, while *Oreochromis aureus*, *Oreochromis mossambicus*, and their hybrids are also significant for aquaculture (El-Sayed and Fitzsimmons, 2023; Samaddar et al., 2024).

Figure 1. Adult Nile tilapia (*Oreochromis niloticus*), the main species cultivated worldwide and the primary raw material for fillet production.
Source: Adapted from Vajargah, 2021

Tilapia has become one of the most important species in global aquaculture. Originally from Africa, it is currently farmed in more than 120 countries, especially in China, Indonesia, Egypt, Brazil, and the Philippines (Charo-Karisa, 2024). Tilapia farming has been successful due to excellent market acceptance, nutritional and sensory quality, and ease of production (Oliveira et al., 2024).

Global tilapia production reached 5.3 million tons in 2022, making it the fourth most farmed aquatic species worldwide. In Brazil, tilapia is the leading cultivated fish species, accounting for about 68% of the country's total farmed fish production in 2024, surpassing 662 thousand tons (Peixe BR, 2024; FAO, 2024). Among commercialized tilapia products, fillets are the most preferred by consumers for their convenience and versatility in preparation (Andoh-Odoom et al., 2024).

High tilapia production is associated with favorable biological characteristics, notably their strong environmental tolerance, which is based on flexible osmoregulation, metabolic plasticity, and robust endocrine responses to stress. The gills are the primary interface for ionic balance and gas exchange, undergoing structural and molecular remodeling in response to challenges posed by salinity and alkalinity (Vajargah, 2021; Angadi, 2024).

These characteristics, combined with advances in genetic improvement, nutrition, disease management, and farming systems, have contributed significantly to increased productivity, fillet yield, and the quality of tilapia products. In addition, the development of technologies for processing, filleting, refrigeration, freezing, packaging, and value addition has increased the efficiency of the production chain, reduced post-harvest losses, and facilitated the production of fillets with higher quality and longer shelf life (Prado-Toledo et al., 2022; Jiang et al., 2023).

Studies aimed at preserving tilapia fillets are increasingly seeking new approaches and technological resources to preserve the nutritional components, quality, and bioactive compounds in fish, and to extend the shelf life (Presenza et al., 2023; FAO, 2022).

To understand the innovation profile of research and technological progress focused on products such as tilapia fillets, analyzing articles and patents is a valuable tool that provides a comprehensive overview of the field. In addition, it enables the monitoring of existing and emerging technologies in a given field of study, allowing for the evaluation of new opportunities and avoiding the duplication of existing ideas, inventions, or processes, as well as the waste of time and resources (Santos et al., 2024). To do this, articles and patents are collected from databases and analyzed by main technologies, inventors, countries, and institutions, thus providing a basis for decision-making (Da Silva et al., 2021).

Patents play an important role in the innovation process by supporting research and development (R&D) in a given technological area and facilitating the acquisition and protection of intellectual property. Furthermore, studying patents helps companies develop business and strategic transactions by providing data to analyse competitors, understand a given technological area, access patent applicability, and identify potential alliance partners in research and development (Barbosa et al., 2023).

Scientific articles are fundamental to the advancement of knowledge and innovation, contribute to the development of new technologies, and strengthen the theoretical basis of a given scientific field. The analysis of articles in a field of interest allows for the identification of emerging trends, knowledge gaps, methodological advances, and topics of greater relevance, in addition to providing input for the direction of other studies (Ebidor and Ikhide, 2024).

However, information regarding the global evolution of scientific research and technological innovation related to the preservation and processing of tilapia fillets remains fragmented. Therefore, the following research question guided this study: How have scientific research and technological innovation related to the preservation and processing of tilapia fillets evolved worldwide, and what trends, gaps, and opportunities can be identified through the analysis of scientific articles and patent documents? To answer this question, this study aimed to identify the main trends, technological advances, gaps, and opportunities related to the preservation and processing of tilapia fillets by analyzing scientific articles and patent documents, with emphasis on preservation techniques, product development, and differences in technological maturity among leading and emerging countries.

Material and Methods

The data collection and analysis are presented in figure 2. The Scopus database was used to collect scientific articles. The search was performed using the words "tilapia fillet" OR "tilapia fillets" in the title, abstract, and keyword fields. As an inclusion criterion, only scientific articles were considered, excluding conference papers, conference reviews, book chapters, and reviews. After initial screening, all articles were analyzed to assess how research on tilapia fillets was distributed across the temporal evolution of publications, topics covered, and countries of origin.

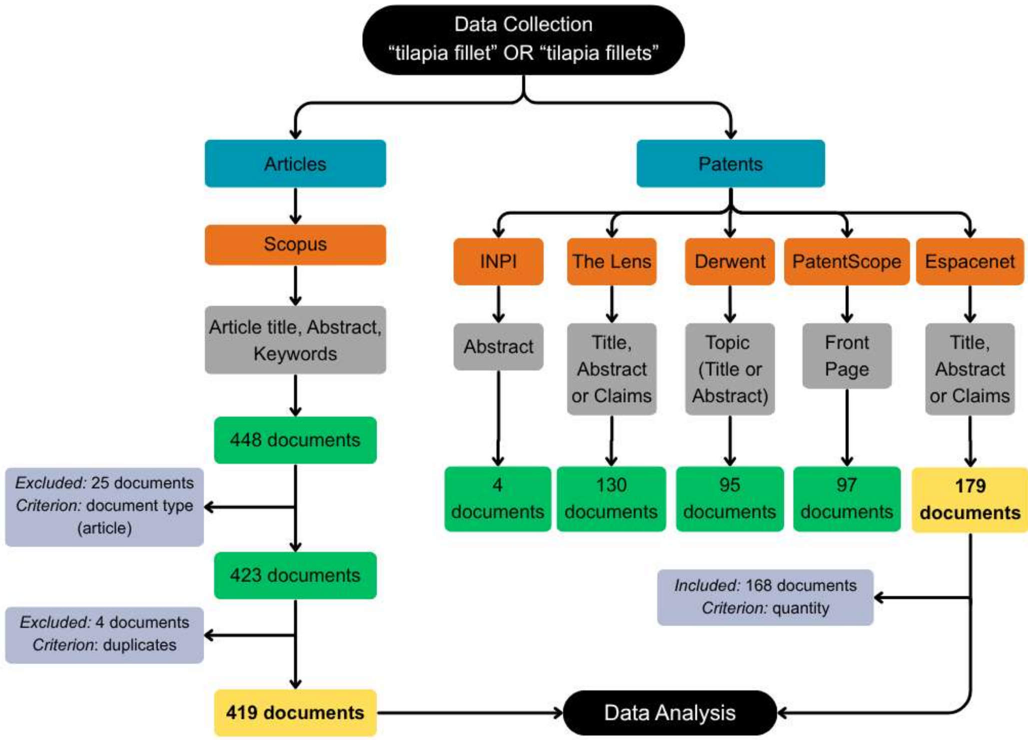

Figure 2. Methodological steps for collecting and analyzing documents.

To collect patents related to the study topic, the following databases were consulted: The Lens, National Institute of Industrial Property (INPI), PatentScope (WIPO), Derwent Innovations Index, and Espacenet. The search was performed using the keywords "tilapia fillet" OR "tilapia fillets" in the following fields: title, abstract, and claims (The Lens and Espacenet); abstract (INPI); front page (PatentScope); and title or abstract (Derwent). The database that presented the largest number of documents available for virtual access was selected for the collection and analysis of patents (Espacenet).

Espacenet was selected as the exclusive patent database because it provides broad international coverage and enables the retrieval of patent documents from multiple national and regional patent offices through a unified search platform. Unlike searches restricted to a single national patent office, Espacenet allows the identification of patent families and related documents across jurisdictions, reducing the risk of counting the same invention multiple times as independent national applications. The database also provides access to bibliographic information, publication data, priority information, applicants, inventors, classifications, and patent family relationships, which are essential for the technological landscape analysis conducted in this study.

The documents exported to Microsoft Excel, containing 418 articles and 179 patents, were examined and presented in the form of tables and graphs. For patents, records over time, technological classification according to IPC (International Patent Classification) codes, and the identification of the main inventors were analyzed.

The scientific articles were evaluated according to the temporal evolution of publications, main research topics, and geographical origin of authors and institutions. In addition, the contents of the documents were analyzed based on the titles, abstracts, and keywords to identify trends, advances, and gaps in the field studied. The analysis was organized into four analytical dimensions: (i) main research themes; (ii) methodological trends; (iii) main scientific advances; and (iv) knowledge gaps. Within these dimensions, the articles were grouped according to the predominant focus of the study, including conservation technologies, food safety, nutritional quality, thermal processing, environmental sustainability, edible coatings, natural antioxidants, metabolomics, contaminant detection, and life-cycle assessment. The categorization was performed by the authors using a predefined analytical framework. Each article was assigned according to its predominant research objective and methodological contribution. When a study addressed more than one theme, the main category was determined based on the primary objective of the research, while secondary contributions were incorporated into the synthesis of methodological trends and scientific advances. The identification of knowledge gaps was based on the comparison between the research approaches, technologies, and outcomes reported in the most cited studies, with particular attention to aspects that remained insufficiently integrated or insufficiently validated, such as industrial-scale application, economic feasibility, sustainability assessment, consumer acceptance, and multidisciplinary evaluation.

Results e Discussion

Overview of scientific literature

This section examines the findings of 418 scientific articles on the preservation and processing of tilapia fillets.

Production of publications and temporal trends

Scientific research on the conservation and processing of tilapia fillets has grown significantly over the years, as illustrated in Figure 3A. Between 1994 and 2025, scientific output showed a Compound Annual Growth Rate (CAGR) of approximately 11.43%, reflecting an increase from 1 to 30 publications during that period. This result indicates significant and sustained growth in scientific interest in the topic over the past three decades.

The first study was published in 1994, and until 2007, the number of publications remained low, reflecting the early stage of research development in the area. From 2008 onwards, publications gradually increased, indicating greater scientific involvement with the topic, which may be linked to the strengthening of tilapia farming and the growing demand for quality control, safety, and improvements in preservation and processing techniques (FAO, 2022). From 2018 onwards, the growth in the number of articles was even greater, driven by advances in new preservation technologies, such as active packaging, modified atmosphere, and edible coatings (Yu et al., 2020; Kilinç and Kilinç, 2022; Dehghani et al., 2018). Another factor that may have contributed to the increase in publications in this area was the global concern with waste utilization and the adoption of sustainable practices in the production chain (Cooney et al., 2023).

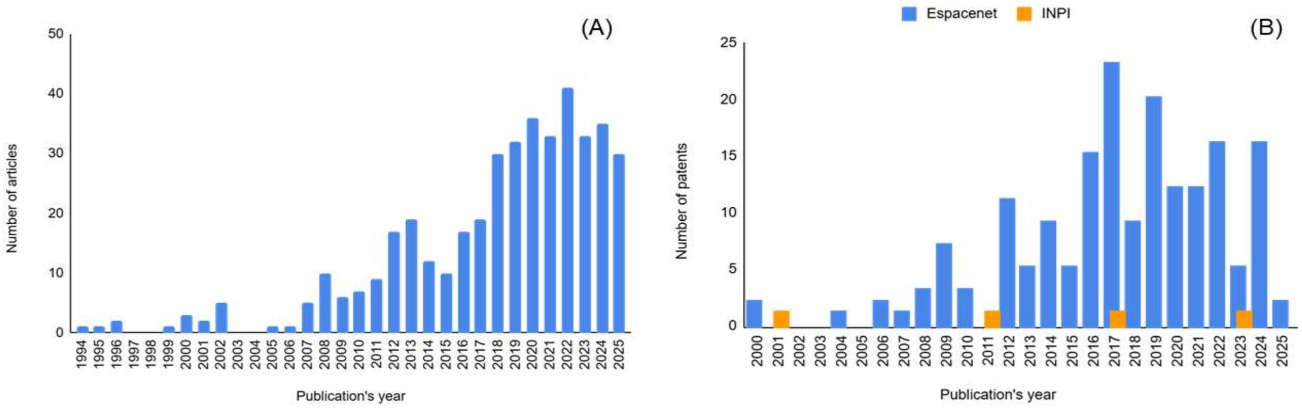

Figure 3. Research trends in tilapia fillet studies. (A) Number of articles over time. (B) Number of patents over time.

The temporal distribution of patents from Espacenet revealed a nonlinear trend in technological activity related to tilapia processing and preservation. Between 2000 and 2007, patent activity was low and sporadic, with a maximum of two patents per year. Starting in 2008, there was a general trend toward expansion, although marked by annual fluctuations, notably in 2012, with 11 patents, and especially during the 2016–2019 period. The highest number of patents was recorded in 2017, with 23 patents, followed by 20 patents in 2019. Activity remained relatively high between 2020 and 2022, with 12, 12, and 16 patents, respectively. Following a decline in 2023, a further recovery was observed in 2024, with 16 patents.

Despite these fluctuations and periods of heightened technological activity, the CAGR calculated between 2000 and 2025 was 0%, because the number of patents in the initial and final years remained the same, with two patents in both years. This result should be interpreted with caution, as the CAGR considers only the values at the extremes of the series and therefore does not adequately represent the intermediate dynamics observed. Thus, although the compound growth between the starting and ending points is zero, the annual distribution shows that there was a significant expansion in patent activity over the period, especially starting in the mid-2010s, when the highest levels of technological output were observed.

A comparison of the two curves suggests a mismatch between the expansion of scientific knowledge and its conversion into patent-protected technologies. While scientific output showed positive and sustained compound growth, patent activity did not show net growth between the starting and ending years of the series. However, the CAGR for patents must be interpreted in conjunction with their annual distribution, since technological activity showed significant fluctuations over the period, including peaks of 23 patents in 2017 and 20 in 2019. Therefore, the 0% CAGR does not indicate a lack of technological development but solely reflects the fact that the initial and final values of the series are equal.

Taken together, the comparison shows that scientific development occurred in a more continuous and growing manner, while technological activity exhibited a more irregular pattern and was concentrated in certain periods. This difference may indicate opportunities to strengthen knowledge transfer and intellectual property protection, especially through closer collaboration between universities, research centers, and companies.

Thematic areas and approaches

Of the total of 418 articles, the main themes addressed were conservation methods (Zhao et al., 2019a; Alsaggaf et al., 2017; Duan et al., 2011; Zhao et al., 2019b; Wei et al., 2021), quality control (Limbu et al., 2018; Sarker et al., 2016; Zhang et al., 2012; Li et al., 2021), and assessment of environmental impacts during the tilapia fillet production chain (Pelletier and Tyedmers, 2010) (Table 1).

Table 1. Analytical synthesis of the main research trends and knowledge gaps identified in the most cited studies on tilapia fillets indexed in the Scopus database (March 1994–August 2025).

Aspect analyzed	Synthesis of the most cited articles
Main research themes	Conservation technologies, food safety, nutritional quality, thermal processing, and environmental sustainability.
Methodological trends	Predominance of experimental studies evaluating preservation technologies, edible coatings, natural antioxidants, thermal processing, metabolomics, analytical methods for contaminant detection, and life cycle assessment. Recent studies increasingly combine multiple analytical techniques to assess physicochemical, microbiological, nutritional, and environmental quality.
Main scientific advances	Development of preservation strategies that improve shelf life and product quality, adoption of sustainable feed ingredients, application of rapid analytical methods for food safety, and incorporation of environmental assessments into the tilapia production chain.
Knowledge gaps identified	Limited integration of preservation technologies with sustainability assessments; few studies evaluating the industrial-scale application and economic feasibility of emerging preservation methods; scarcity of multidisciplinary studies simultaneously addressing food safety, nutritional quality, consumer acceptance, and environmental performance.

Food safety has been a concern in major studies on tilapia fillets, as the use of antibiotics and contaminating chemical compounds can cause adverse systemic effects in fish and pose potential risks to human health (Limbu et al., 2018). Therefore, methods for detecting prohibited residues in fish products are applied for monitoring, quality control, and food safety (Zhang et al., 2012).

The nutritional quality of tilapia fillets has been the focus of many studies, which, by exploring the lipid composition and behavior of the fatty acid profile, have found good results in replacing fish oil with microalgae of the genus *Schizochytrium* sp. in the diet (Sarker et al., 2016) and chemical and nutritional changes in the processing of fillets subjected to different thermal methods, where the type and intensity of heating are significant factors (Li et al., 2021).

More recent studies have introduced innovative techniques using natural and sustainable preservatives, such as biopolymers, phenolic compounds, and edible coatings to preserve the quality and safety of fillets during storage (Zhao et al., 2019a;

Alsaggaf et al., 2017; Zhao et al., 2019b). In addition, improved processing methods, such as vacuum impregnation with gelatin and natural antioxidants, facilitate and intensify the incorporation of bioactive compounds into tilapia fillets (Zhao et al., 2019a; Zhao et al., 2019b).

The oldest preservation methods involve combining traditional techniques such as hot air drying and microwaving fresh fillets to reduce water activity and slow down deterioration reactions. As a result, the synergy between the different types of heating optimizes the total drying time compared to hot air drying alone, making it a promising alternative for increasing industrial productivity (Duan et al., 2011).

The sustainability of fillet production is assessed in terms of the environmental impacts of the production chain, comparing frozen tilapia fillets from intensive aquaculture systems with fillets farmed in lakes and nurseries, demonstrating significant differences in greenhouse gas emissions, energy use, and feed conversion efficiency (Pelletier and Tyedmers, 2010).

In recent years, studies have sought to improve traditional methods, such as freezing, which can cause deterioration in the texture of fillets over time during storage. Given this, combining polyphenols can inhibit the negative effects on texture and, at the same time, provide longer shelf life for tilapia fillets (Wei et al., 2021).

With the advancement of research, there has been a shift in the scientific literature on tilapia fillets, moving from approaches focused solely on technological stability and increased shelf life to a broader vision that seeks innovation, food safety, nutritional quality, and sustainability. This shift reflects a consolidation of research efforts toward integrated approaches that combine preservation technologies with quality, safety, and sustainability requirements, reinforcing the importance of integrated approaches across the tilapia production chain.

Geographic distribution of the survey

China, Brazil, and the United States are the main countries responsible for developing studies on tilapia fillets (Figure 4). China has the highest number of publications, with 166 articles, followed by Brazil with 113 articles, and the United States with 29 articles. The geographic distribution of scientific output had a Gini index of 0.571, indicating a moderate to high concentration of article production among the countries analyzed. Although China had the highest scientific output, with 166 articles, other countries also contributed significantly to the development of knowledge in this field, including the United States, Thailand, Egypt, Mexico, and Taiwan. Compared to the distribution of patents, which had a Gini index of 0.879, scientific output showed greater international dispersion. This difference highlights that, although scientific knowledge on tilapia processing and preservation is relatively distributed among different countries, the transformation of this knowledge into patent-protected technologies remains highly geographically concentrated, particularly in China.

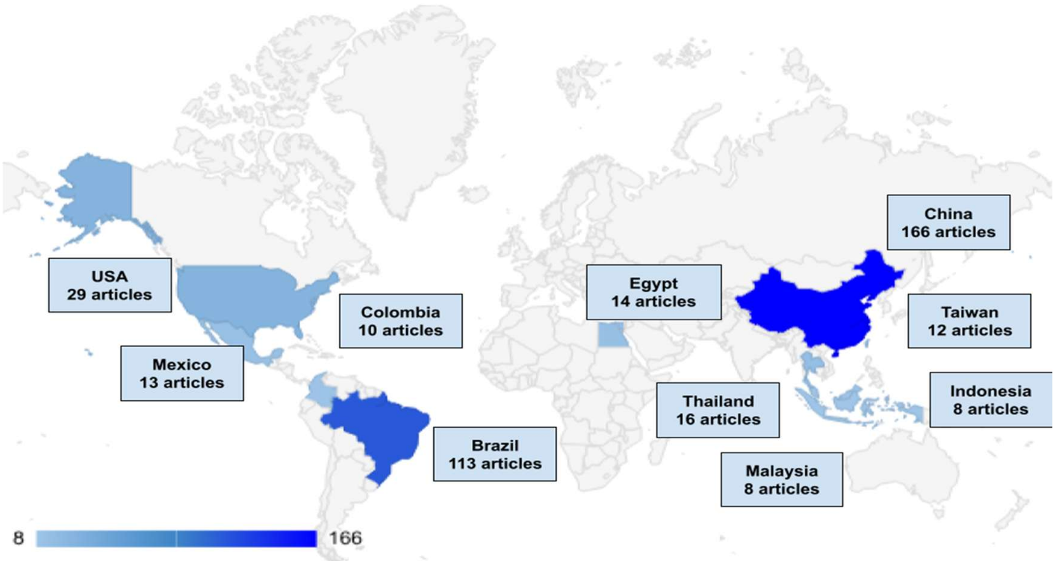

Figure 4. Number of articles on tilapia fillet(s) by country.

The strong performance of these countries may be related to the tilapia trade. China leads the world in tilapia production, and Brazil has shown large production volumes, being the main producer in the Americas and one of the largest outside Asia, while the United States is the largest importer of the species (Peixe BR, 2024; FAO, 2024).

The high availability of raw materials and market growth are driving investment in research and academic interest in areas such as processing, transportation, storage, preservation, and marketing, to provide safe products with a longer shelf life and good sensory acceptance (Pierozan et al., 2024; Afrin et al., 2023; Deepitha et al., 2021; Shahrier et al., 2023). In the United States, scientific interest is focused on monitoring the quality and safety of products intended for American consumers (Guan et al., 2024; Chu et al., 2021).

To ensure high-quality fishery products with an extended shelf life, facilitating distribution among countries, recent studies have explored the use of seaweed extracts in the preservation of tilapia fillets and other species, under both refrigerated and frozen conditions, demonstrating significant improvements in product quality and stability during storage (Afrin et al., 2023; Deepitha et al., 2021; Shahrier et al., 2023).

Although the high availability of raw materials and the economic importance of tilapia farming contribute to stimulating scientific research, these factors alone do not fully explain China's leadership in scientific production. This prominent position is also associated with the country's National Innovation System, which has been strengthened through sustained investments in research and development (R&D), strategic public policies, and the expansion of scientific infrastructure over recent decades. Government initiatives promoting applied research and collaboration among universities, research institutes, and industry have enhanced knowledge generation and accelerated scientific advances in strategic sectors, including aquaculture and food technology. Therefore, China's high scientific output reflects not only the scale of its aquaculture industry but also an innovation-oriented environment that supports research development and knowledge production (OECD, 2023).

Having reviewed the scientific literature, the article next examines technological innovations and patent activity related to tilapia fillet preservation and processing.

Technological landscape (patent analysis)

This section delves into the 179 patent filings to explore technological developments and innovations in tilapia fillet conservation and processing.

Patent filing trends over time

After searching for patents in international databases (Espacenet, Lens, Derwent, and PatentScope), Espacenet has the largest collection of documents related to tilapia fillets (179 patents). In Brazil, a search for national data by the National Institute of Industrial Property (INPI) resulted in four patents on the subject.

Regarding the distribution of patent publications over the years, it can be observed that the first patents on tilapia fillets were published in 2000, with a peak of 23 patents in 2017, followed by a gradual decline and sharp fluctuations in subsequent years (Figure 3B).

The high number of patents registered in 2017 may be related to the expansion of aquaculture, which accounted for 46.8% of global fish production in 2016, compared to 25.7% in 2000 (FAO, 2018). This rapid growth has increased interest among industry and research centers in protecting new industrial solutions. In this context, China stood out as the leading patent filer during the period, highlighting its strategy of innovation and strengthening of the aquaculture chain (WIPO, 2023).

However, patents lag behind publications, indicating that technological development and its conversion into intellectual property still do not keep pace with scientific progress.

The distribution of articles reveals consistent growth in scientific production over the last two decades (Figure 3A), with a more pronounced increase since 2012 and a peak between 2020 and 2022, which is in line with the continuous growth of global aquaculture and the consolidation of tilapia as one of the main species in production (FAO, 2018).

International patent classification (IPC) analysis

Patents are categorized by IPC codes (International Patent Classification), distributed across various technological fields based on their content or technological function (Oliveira et al., 2022). The most frequent IPC classes among tilapia fillet patents belong to Section A (Human needs), which includes Classes A22 (Slaughtering, meat treatment, and processing of poultry or fish) and A23 (Food, non-alcoholic beverages, and their treatment or preparation) (Figure 5).

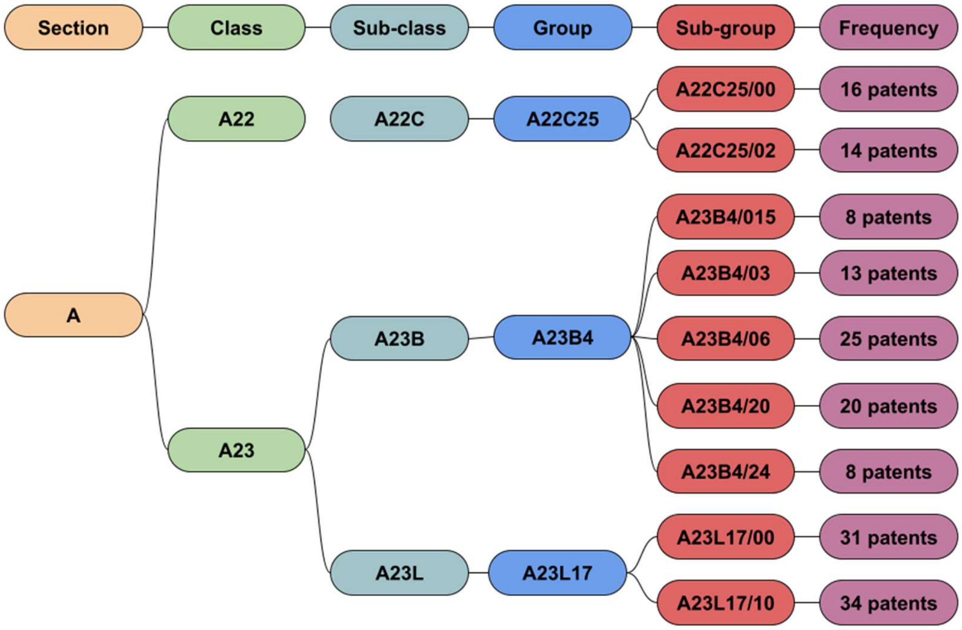

Figure 5. Main IPC codes involving tilapia fillets in patents published between 2000-2025.

Of particular note is the A23L17/10 subgroup, which was covered by 31 patents. According to the descriptions of the WIPO IPC codes, it is classified in Section A (Human needs), Class A23 (Foodstuffs, non-alcoholic beverages, and their treatment or preparation), Subclass A23L (Foodstuffs, foodstuffs or non-alcoholic beverages not covered by Subclasses A21D or A23B-A23J; their preparation or treatment, preservation of foodstuffs or foodstuffs in general), group A23L17 (seafood; fish products; fish meal; fish substitutes; their preparation or treatment) and subgroup A27L17/10 (fish meal or powder; granules, agglomerates or flakes). Examples include the patents applied for by inventors Huawei et al. (2023) (CN117281236A), in which the invention discloses a crispy tilapia fillet food and the method of preparation, as well as the patent produced by Xu et al. (2018) (CN108740840A) in which they proposed a method of manufacturing seasoned and deep-frozen pieces of tilapia fillets.

This was followed by code A23B4/06, which had the second-highest frequency in patents. According to the WIPO IPC codes, this corresponds to Section A (Human needs), Class A23 (Food, non-alcoholic beverages and their treatment or preparation), Subclass A23L (Food, foodstuffs or non-alcoholic beverages, not covered by subclasses A21D or A23B-A23J; their preparation or treatment, food or foodstuff preservation in general), Group A23B4 (General methods for preserving meat and sausages, fish or fish products), and Subgroup A23B4/06 (Freezing; Subsequent thawing; Cooling). This subgroup includes patents such as the one developed by Jiangqiu et al. (2015), which involves a method for extending the refrigerated shelf life of tilapia fillets using chitosan, and another patent produced by Li et al. (2009), which proposes a methodology for maintaining freshness of tilapia fillets with air-regulated freezing temperature, in which the fish are packed in containers containing a mixture of gases (50-80% CO_2 and 20-50% N_2) and stored at freezing temperature (-8°C to -2°C).

The predominance of codes A23L17/10 and A23B4/06 reveals progress in the industrialization of tilapia, with a focus on processing into ingredients and products with higher added value and the improvement of preservation technologies, reinforcing the search for quality, safety, and extended shelf life.

Geographical and origin analysis of patents

Examining the origins of the primary applicants, it was found that nine countries were responsible for publishing documents (Figure 6). China stands out as the largest patent filer, with 159 patents, highlighting its technological leadership in the aquaculture sector. Next are the Philippines with 9 patents, the United States with 3 patents, Germany and Russia with 2 patents each, while Canada, Mexico, Luxembourg, and the United Kingdom each have 1 patent.

The geographic concentration of patent activity was quantified using the Gini Index, which yielded a value of 0.879. This result highlights a highly unequal distribution of patents among the countries analyzed, close to the upper limit of concentration for this indicator. This high level of inequality is explained primarily by China's dominance, which accounted for 88.8% of the identified patent documents, while the other countries each accounted for less than 5%. Therefore, the high Gini Index quantitatively confirms the strong geographic concentration of technological innovation related to tilapia processing and preservation, indicating that the development of patent-protected technologies is concentrated in a few countries and, in particular, in a single dominant technology hub.

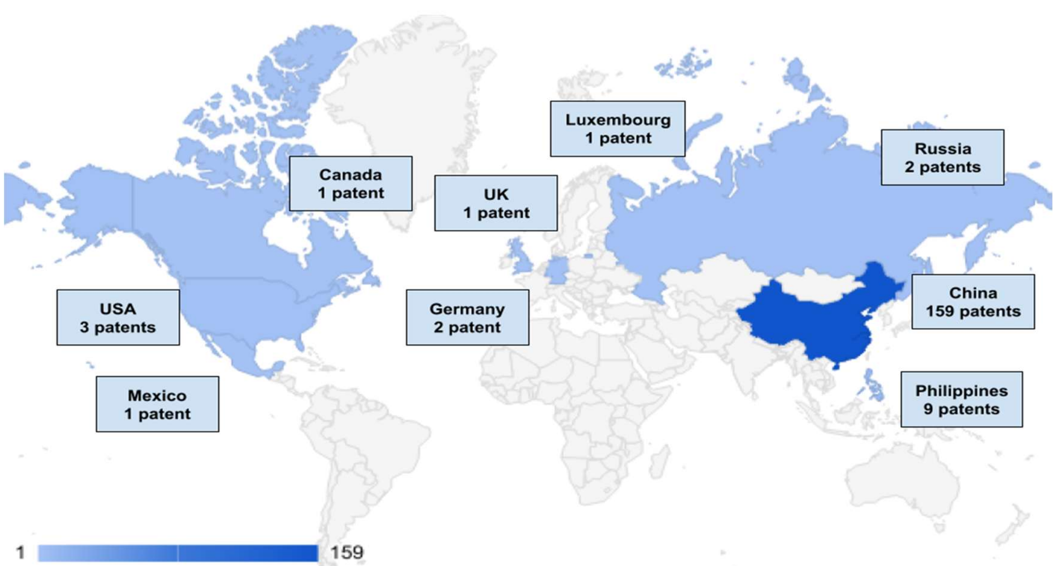

Figure 6. Distribution of patents according to country of origin.

It is observed that Asian countries lead in patent production, which may be related to the large-scale production of this fish on the continent. However, other important tilapia producers in the context of Latin America, Brazil, and Mexico (FAO, 2024) have four patents and one patent pending, respectively (Figures 6 and 3B).

Furthermore, there is a contrast between scientific output and technological output by country. While China leads in both, Brazil and the United States have a high number of articles but low patent production, suggesting that the generation of scientific knowledge does not always translate into intellectual property protection. This scenario may be associated with factors such as innovation culture, incentive structure, intellectual property policies, and industrial maturity, indicating that productive capacity is not the only determinant of technological development in the sector.

The discrepancy between scientific output and patent activity indicates that knowledge generation does not necessarily lead to technological innovation. While China leads both scientific publications and patent filings, its performance reflects an innovation ecosystem that promotes technology transfer, university–industry collaboration, and the commercialization of research outcomes, facilitating the conversion of scientific knowledge into protected technologies (Chen et al., 2024; Li et al., 2024).

In contrast, despite Brazil's significant scientific production in aquaculture, its patent output remains limited. This disparity suggests that the main challenge lies not in scientific capacity but in the effective transfer of knowledge to the productive sector. Therefore, technological competitiveness depends not only on research productivity but also on mechanisms that strengthen intellectual property protection and technology transfer (Cohen et al., 2025; WIPO, 2024).

Of the patents available on Espacenet, 78 organizations responsible for publishing patents on tilapia fillets were identified, of which 49 are private companies, 19 are institutions, and 10 are individuals (Table 2).

Table 2. The main organizations responsible for publishing patents related to tilapia fillet in the Espacenet database.

Organization	Country	Number of patents
Fujian Fuming Food Co Ltd	China	14
Univ Hainan	China	11
South China Sea Fisheries Res Inst, Chinese Acad Fishery Sciences	China	9
Fujian Mingfa Aquatic Product Dev Co Ltd	China	8
Guangdong Gourmet Aquatic Co Ltd	China	6

Univ Guangdong Ocean	China	6
Hainan Qinfu Foods Co Ltd	China	5
Zhanjiang Full Fresh Aquatic Product Ltd Company	China	5
Maoming Hongye Aquatic Products Co Ltd	China	4
Univ Guangxi	China	3

The organization that leads in patent production is Fujian Fuming Food Co., Ltd. (14 patents), a private company in the food production and sales and catering services sector. Its innovation strategy focuses on developing technologies for the industrial processing of tilapia fillets, especially automated devices and equipment to improve production, quality, and environmental sustainability (Yang et al., 2019a; Yang et al., 2019b; Yang et al., 2019c).

Hainan University stands out as the leading public institution involved in patent publication, with 11 patents related to tilapia. Its technological strategy focuses on the development of methods for preserving and assessing the quality and safety of fish, with an emphasis on advanced analytical tools and physical-chemical monitoring techniques (Feng et al., 2019; Lin and He, 2014; Yonghuan et al., 2022).

Thus, it is observed that private companies and independent inventors seek to protect solutions focused on productive efficiency, market competitiveness, and adding value to the final product. Meanwhile, public institutions have a greater interest in developing analytical methods and quality control. This differentiation highlights both the industrial interest in optimizing processes and strengthening commercial positioning, and the role of universities in generating knowledge applied to monitoring the quality of tilapia-derived products.

Furthermore, these findings highlight opportunities to strengthen technology transfer mechanisms, expand university–industry collaboration, and encourage intellectual property protection, particularly in countries where scientific production has not yet been proportionally translated into technological innovation, such as Brazil. Such actions can improve the conversion of scientific knowledge into technological innovation within the tilapia production chain.

Brazilian overview of tilapia fillet patents

Analyzing the national patent landscape involving tilapia fillets, four invention patents were found published in the database of the National Institute of Industrial Property (INPI) (Table 3). It was observed that two of them were registered by Brazilian federal universities, both with similar purposes: the manufacture of a smoked “mortadella-type” product made from mechanically separated meat from freshwater fish, including tilapia. The main difference between these patents is the formulation: while the one filed in 2016 (Bartolomeu and Waszczynskyj, 2011) describes the development of a new product, the one filed in 2017 (Martins et al.,

2017) presents improvements in the composition, reducing the amount of fat, sodium, and additives compared to the previous one. In addition to these, a patent published in 2003 (Braeger et al., 2001) was also identified, referring to a method and apparatus for filleting fish, and a more recent one, from 2023 (Gonçalves et al., 2023), related to the use of recombinant synthetic DNA to increase muscle mass in tilapia, highlighting the diversity of technological approaches in the sector.

Table 3. Patents available in the INPI national database.

Title	Year of deposit	Year of publication	Status	Depositor	Type of patent	IPC
Recombinant synthetic DNA for muscle mass increase in tilapia	2023	2025	Deposited	Federal University of Pelotas/Brazil	Invention Patent	C12N 15/16
Production of smoked mortadella-type sausage made from mechanically separated meat - freshwater fish MSM, with reduced fat, sodium, and additive content.	2017	2019	Deposited	Federal University of Campina Grande/Brazil	Invention Patent	A23L 17/00
Manufacturing process for smoked sausage "mortadella type" made with mechanically separated meat - freshwater fish MSM and dietary fiber	2011	2016	Deposited	Federal University of Paraná/Brazil	Invention Patent	A23L 17/00
Method and apparatus for filleting fish	2001	2003	Granted	Nordischer Maschinenbau Rud. Baader GmbH + Co. KG/Alemanha	Invention Patent	A22C 25/16

The granted patent was filed by the German company Baader (Braeger et al., 2001), a global company responsible for manufacturing innovative machines for the food processing industry. The patent makes it possible for machines to be used in the filleting process so that extensive manual processing is not necessary. The process suggests that before the filets are scaled from the ribs, the ventral folds are trimmed using a machine to remove parts that reduce the quality of the filet, while finishing cuts are made in order to adapt to the relatively rigid rib profiles.

The International Patent Classification (IPC) was established through the Strasbourg Agreement in 1971, which provides for a hierarchical system of universal symbols to group patents and utility models according to the different areas of technology to which they belong (WIPO, 2022). The code under which the Brazilian documents are classified, "A23L 17/00" refers to "Food products from the sea; Fish products; Fish meal; Fish egg substitutes; Preparation or treatment thereof," while the Baader company's patent "A22C 25/16" involves documents associated with "Fish processing; Removal of fish bones; Filleting of fish". The patent published in 2023 was classified as "C12N 15/16", which covers mutation or genetic engineering technologies; DNA or RNA related to genetic engineering; vectors, such as plasmids, and their isolation, preparation, or purification; use of their hosts; recombinant DNA technology; DNA or RNA fragments and their modified forms; genes encoding animal proteins; and hormones. This classification shows that, unlike the others, the focus of the invention is not on fish processing but on the application of molecular biotechnology to aquaculture, demonstrating a significant advance in the technological diversity of patents related to tilapia.

Focus of patented innovations

Based on patent information extracted from the Espacenet database, the patents were grouped according to the type of innovation (Figure 7). The documents filed seek to develop technological solutions focused on three main areas: processing methods, conservation techniques, and new products.

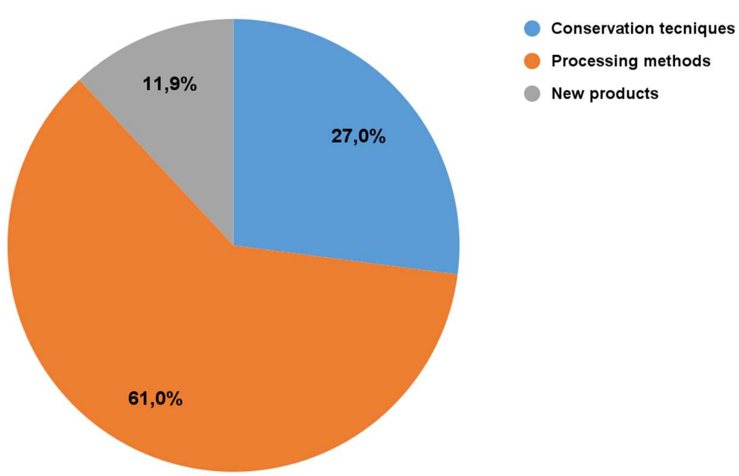

Figure 7. Patent's classification based on innovation type.

Most patents involve the development of tilapia processing methods. These innovations include filleting machines (Kjær et al., 2020), packaging (Zhou and He, 2020), cleaning and drying devices (Yang et al., 2020), waste recovery processing (Wang et al., 2023), and advanced detection methods for quality control (Chen and Lin, 2018). This set of technologies demonstrates the industry's interest in increasing operational efficiency, reducing losses, and ensuring the safety and quality of the final product.

The second most common theme addressed by patents is preservation techniques designed to extend the shelf life of fillets, preserving flavor, aroma, and texture while maintaining quality and freshness. These include the use of coatings with chitosan solutions at different molecular weights (Jiangqiu et al., 2015), modified atmosphere (Tang et al., 2020), combined irradiation and freezing strategies (Yang et al., 2023), and a combination of drying, surface sealing with hot oil, and pectin application before freezing (Sun et al., 2019). These trends show progress toward more sustainable and natural preservation approaches, in line with market demand for products with fewer chemical additives, as well as meeting the logistical need to preserve fish quality throughout the production chain.

The third group highlights the development of products derived from tilapia fillets, such as ready-to-eat smoked fillets (Xiaoling et al., 2012), tea-flavored tilapia fillet snacks (Shen et al., 2016), devices for producing breaded tilapia fillets (Zhou and He, 2021; Zhou et al., 2020), and functional formulations (Zolotokopova et al., 2021). These patents reflect the strategy of adding value to the product and diversifying consumer niches, positioning tilapia as a versatile protein capable of competing in high-value-added markets.

In general, the patents analyzed present technological advances directly related to the current needs of the tilapia production chain, addressing challenges such as extending shelf life, ensuring microbiological safety, improving production performance, and expanding the product portfolio, thereby improving the competitiveness and sustainability of tilapia products.

Comparative analysis: scientific research vs. patent innovation

Tilapia production has increased recently due to its ease of cultivation and success in the commercial market as fillets, thanks to the nutritional and sensory qualities of its composition. However, the same composition contributes to negative factors such as oxidative and microbial deterioration, which can be avoided during cultivation, processing, transportation, and storage.

So, the articles and patents seek to promote viable solutions to keep the entire tilapia production chain safe, as well as technological improvements in some stages of the fillet production process and thus produce quality fillets, applying production technologies and promoting adaptations according to the soil and climatic conditions in the countries of traditional production, among these places, we highlight the southern and southeastern regions in Brazil, which through publications in Brazilian journals and patents, show the strength and innovation in the production of new products from tilapia processing waste.

Favero Neto et al. (2024) portray the importance of fish welfare in captivity to improve meat quality. This study uses environmental enrichment by adding objects to provide environmental stimuli, thereby improving the activities of captive fish and meeting their physiological, behavioural, and psychological needs. This treatment resulted in improved water retention capacity and a better fatty acid profile in tilapia meat.

Tilapia are commonly fed aquafeeds formulated with vegetable oils because of their lower cost; however, this practice reduces the deposition of long-chain omega-3 fatty acids, particularly EPA and DHA, in the fillets. Recent studies focused on dietary supplementation strategies to improve the nutritional quality of tilapia meat. Marine-derived ingredients, such as fish oil and *Schizochytrium* sp. microalgae, consistently enhance EPA and DHA levels due to their direct supply of these fatty acids (Stoneham et al., 2018; Duarte et al., 2021; Jorge et al., 2022). Alternative feed ingredients, including fermented coffee husk meal and thraustochytrid oil, have also shown promising results, demonstrating the growing interest in more sustainable and cost-effective lipid sources (Fitria et al., 2020; Davies et al., 2022). More recently, combinations of vegetable and marine oils have emerged as a strategy to balance production costs with improvements in the fatty acid profile of fillets (Perez-Velazquez et al., 2024).

These findings indicate a shift from conventional feed formulations toward nutritional strategies that simultaneously enhance fillet quality, support sustainable aquaculture, and meet consumer demand for healthier products.

During the processing of tilapia fillets, any preservation method can be applied, from the simplest technology, such as thermal processing (Pongsetkul et al., 2022), to the most advanced, such as high-intensity ultrasound (Ugalde-Torres et al., 2024), when it is estimated that the characteristics of the product will be maintained for longer until it reaches the consumer, including the transportation and storage stages. It was observed that the most widely used method is cold, either refrigeration or freezing, a method used from ancient times to the present day (Uddin et al., 2017).

However, products preserved by freezing are susceptible to damage, such as surface burning and oxidation (Vanhaecke et al., 2010). To eliminate this, a new preservation approach uses a combination of supercooled storage and ice glazing. The latter consists of applying a layer of ice containing additives such as essential oils, chitosan, or catechin compounds (He et al., 2018).

Both scientific research and patents use cold chain preservation as the predominant method for extending shelf life, often supplemented by edible coatings with natural extracts or essential oils. These biofilms consist of edible coatings made from polysaccharides, which are used alongside essential oils or natural extracts as antioxidants and/or antimicrobials (Hai et al., 2022; Noghani et al., 2024). These innovative techniques based on traditional methods reveal a common priority among academia and industry, due to their proven efficiency, economic viability, and ability to integrate with new conservation technologies.

Recent studies have focused on the application of non-thermal technologies that have also been developed. Liu et al. (2025) used cold sterilization methodologies, such as plasma-activated water (PAW), ozone water (OW), and slightly acidic electrolyzed water (SAEW), which proved to be effective as an antibacterial mechanism in tilapia fillets. Wang et al. (2022) analyzed the effect of cold plasma, and the results demonstrated that the method was effective in inhibiting bacterial growth without significantly negatively affecting the quality characteristics of tilapia fillets.

In addition, the use of extracts from alternative sources of antioxidant and bioactive compounds with a focus on extending the shelf life of tilapia fillets, as in Shahrier et al. (2023), who applied algae extracts and analyzed their effectiveness during refrigerated storage, in which a delay in bacterial growth, inhibition of ammonia formation, and other secondary products of lipid oxidation were observed, thus maintaining the quality of fish fillets for a longer period and providing good sensory characteristics. Similarly, Dulal et al. (2023) evaluated the impact of water lily extracts on frozen tilapia fillets and observed that this plant showed potential as an antioxidant and antimicrobial, with effective reduction of lipid oxidation, delay in microbial growth, and improvement in the overall sensory attributes of frozen Nile tilapia fillets.

Another topic that is frequently discussed scientifically and technologically is new tilapia fillet products, such as breaded tilapia fillets (Albergaria et al., 2022), mortadella, nuggets and sausages prepared using mechanically separated meat from tilapia filleting (Bacelar et al., 2021; De Freitas et al., 2022), tilapia fillets flavored with coconut milk (Jing, 2016), semi-dried tilapia (Chaijan et al., 2017), chorizo (Ramirez, 2020), tilapia sausage type forged cooked ham (Carolina, 2022), tilapia pickle with moringa leaf powder (Akter et al., 2025a; Akter et al., 2025b), dedicated to offering the market new product possibilities. Furthermore, like Nile tilapia, its waste residues can have high nutritional value, with high-biological-value proteins, vitamins, unsaturated fatty acids, and low cholesterol levels (Love et al., 2022).

Despite extensive academic research on natural preservatives such as algae and plant extracts, few patents address their industrial-scale applications. This suggests either technological or regulatory barriers to commercialization, or untapped opportunities for innovation transfer.

On the other hand, patents dominate tilapia fillet processing techniques, with the implementation of improved devices for process automation. However, these technologies are rarely addressed in scientific literature, which indicates that industrial innovation has advanced in mechanical and automation solutions without equivalent academic monitoring, possibly due to companies' interest in protecting technologies that increase production efficiency and ensure competitive advantage in the market.

These differences suggest that, while academia deepens its understanding of product quality and preservation, the private sector leads the technological modernization of processing systems, revealing gaps that can be filled through joint research and technology transfer initiatives.

Gaps, challenges, and opportunities for innovation

Although scientific literature shows significant growth in the development of active and intelligent packaging, the number of patents filed in this area is still low. Researchers have extensively explored the use of smart systems capable of monitoring food quality, especially through pH-sensitive indicators. These systems use natural dyes that react to chemical changes associated with spoilage, usually consisting of a solid matrix incorporated into a pH-sensitive pigment (Yong and Liu, 2020).

The function of these indicators is to detect early changes in acidity, one of the main parameters related to freshness and microbiological safety. In the early stages of deterioration, changes in pH cause color changes in the sensor or in the packaging itself (Zubova et al., 2024). In addition, the production of volatile metabolites such as amines, ammonia, carbon dioxide, diacetyl, and hydrogen sulfide can also generate distinct chromatic responses, providing clear and direct information about product quality even before the package is opened.

For food safety reasons, chemical dyes have limitations on their use, which makes natural pigments more suitable. Among them, anthocyanin stands out for its non-toxic nature, wide acceptance by consumers, and low environmental impact (Khezerlou et al., 2023). This flavonoid pigment acts as a visual indicator of chemical and microbial changes, in addition to providing antioxidant and antimicrobial properties, contributing to the extension of food shelf life (Zubova et al., 2024).

Despite this significant scientific progress, little of this knowledge has been converted into patent applications, particularly within the aquaculture sector and with regard to tilapia fillets. This technological gap indicates opportunities for developing and protecting innovative solutions in active and intelligent packaging. However, the successful development and commercialization of these technologies depend not only on scientific advances but also on effective innovation systems, technology transfer mechanisms, and collaboration among universities, research institutions, and industry. For researchers, this creates opportunities for interdisciplinary innovation; for industry, it enhances competitiveness and product diversification; and for policymakers, it highlights the need for incentives and targeted funding to accelerate the translation of research into commercially viable technologies.

Therefore, aligning scientific research and technological innovation is essential to strengthen the competitiveness and sustainability of the tilapia production chain, expanding the transformation of scientific knowledge into innovative products, and consolidating the sector's global presence.

The challenges associated with the use of edible coatings on seafood products include developing coatings that are compatible with different types of seafood products, as well as ensuring the safety and stability of the coatings over time. In addition, regulatory requirements related to food safety and packaging materials must be met (Bremenkamp and Sousa Gallagher, 2025).

The material used in edible coatings comes into direct contact with food, so the edible material must be generally recognized as safe (GRAS) by the US Food and Drug Administration (FDA) before it can be used. In addition, the use of approved natural plant extracts and essential oils causes few allergic reactions and has little toxic effect, depending on the dosage. Therefore, appropriate measures should be implemented to periodically verify the toxicity and allergic nature of extracts and essential oils (Paidari, 2021). In addition, the materials used in the formation of edible coatings must be food-grade and non-toxic, with appropriate hygienic processing practices, and must comply with Good Manufacturing Practices (GMP) standards (Priya et al., 2023).

Although much of this technical knowledge originates from Brazilian research, most of it is not translated into protected intellectual property or commercially available technologies. This reflects persistent barriers in technology transfer between universities and industry, reinforcing the need for stronger innovation policies, technology incubation programs, and incentives for patent protection and research commercialization.

A comparison between scientific output and patent activity also highlights a significant gap regarding the ability to convert scientific knowledge into technological innovation. Although countries such as Brazil have significant scientific output in the area of tilapia processing and preservation, this output is not proportionally reflected in the number of patents identified. In contrast, China exhibits both high scientific output and strong patent activity, suggesting the existence of an institutional environment more conducive to transforming scientific results into protected technologies.

This difference may be related to the consolidation in China of public policies aimed at integrating science, innovation, and industrial development. According to the Institute for Industrial Development Studies (IEDI, 2025), since 2006, the Chinese government has been strengthening domestic innovation capabilities through strategic plans, with key milestones including the "Made in China" initiative and the 14th Five-Year Plan, in which innovation was placed at the center of the country's development and modernization process. In this context, industrial parks play a strategic role as concrete spaces for linking research, technological development, industrial production, and the internationalization of Chinese technology.

The Chinese experience also highlights a systematic effort to shift the drivers of innovation from public research organizations to the industrial sectors, using public investment in R&D to expand companies' innovative capacity and improve the commercialization of basic and applied research results. This integration of science policy, public funding, industrial development, and intellectual property protection may help explain the high concentration of patents observed in China in this study.

A particularly relevant aspect is the focus of Chinese government R&D investments on activities directly related to experimental development, manufacturing, and production. According to IEDI (2025), approximately 85% of Chinese government spending on R&D is directed toward experimental development activities, in contrast to the greater concentration on basic or applied research observed in other contexts. This model highlights a close integration between support for innovation and industrial policy, favoring the transformation of scientific results into technological applications and marketable products.

Furthermore, country-level comparisons should be interpreted carefully because the country of origin of a patent may refer to different dimensions of the innovation system, including the applicant's country, inventor's country, priority country, or the jurisdiction in which protection was sought. These dimensions are not necessarily equivalent. Therefore, the geographic distribution reported in this study reflects the country attribution criterion applied in the Espacenet records and should not be interpreted as a direct measure of national innovative capacity without considering differences in international patenting strategies.

Conclusion

This study demonstrated that the scientific and technological development of tilapia fillet conservation and processing has expanded in response to the growth of aquaculture and the increasing demand for value-added products. The literature indicates a transition from conventional preservation methods, particularly refrigeration and freezing, toward integrated strategies involving edible coatings, natural extracts, essential oils, biopolymers, non-thermal technologies, and advanced processing methods. These approaches seek not only to extend shelf life, but also to preserve nutritional, physicochemical, sensory, and microbiological quality.

The analysis of 418 scientific articles and 179 patent documents revealed a clear asymmetry between scientific production and technological protection. China emerged as the leading country in both scientific output and patenting activity, whereas Brazil demonstrated substantial scientific productivity but limited patent activity. This finding indicates a gap in the conversion of scientific knowledge into protected technologies and commercial innovations. The patent landscape also showed a strong concentration on the development of processed and value-added tilapia products, demonstrating that technological innovation is increasingly directed toward diversification and increased economic value rather than solely toward raw fillet preservation.

Therefore, the answer to the research question is that the conservation and processing of tilapia fillets constitute a dynamic and increasingly technology-driven field, characterized by the integration of traditional preservation methods with natural, non-thermal, and value-added technologies. The main opportunities for innovation lie in the development of sustainable preservation systems, intelligent and active packaging, natural antimicrobial and antioxidant compounds, non-thermal processing, and technologies capable of valorizing by-products and improving the efficiency of the production chain.

For the tilapia production chain, these findings have direct implications for reducing post-harvest losses, extending shelf life, improving product safety and quality, facilitating distribution, and increasing the economic value of tilapia products. However, the consolidation of these innovations requires greater interaction between universities, research institutions, industry, and intellectual property systems, particularly in Brazil. Future research should therefore prioritize the validation of emerging technologies under industrial conditions, economic and environmental assessment, regulatory compliance, scalability, and the effective transfer of scientific knowledge into commercially viable technologies.

Acknowledgment

The authors would like to thank the Postgraduate Program in Food Science and Technology (PGCTA, UFRPE), the Coordination for the Improvement of Higher Education Personnel - Brazil (CAPES), Project No. 88887.707972/2022-00, and the FACEPE, Process No. APQ-0956-5.06/24 and Process No. BPP-0081-5.06/24.

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