

Review

Non-Conventional Ingredients for Tilapia (*Oreochromis* spp.) Feed: A Systematic Review

Christian David Zuluaga-Hernández¹, Carlos A. Hincapié^{1,*}  and Marisol Osorio² 

¹ Agroindustrial Research Group (GRAIN), Faculty of Agroindustrial Engineering, School of Engineering, Pontificia Bolivariana University, Medellín P.O. Box 050004, Colombia; christian.zuluaga@upb.edu.co

² Technology and Innovation Management Research Group, Centre for Basic Science, School of Engineering, Pontificia Bolivariana University, Medellín P.O. Box 050004, Colombia; marisol.osorio@upb.edu.co

* Correspondence: carlos.hincapie@upb.edu.co; Tel.: +57-604-448-83-88

Abstract: The objective of this systematic review was to identify and classify, from the available literature, non-conventional feed ingredients from terrestrial plants, animals, algae, and fungi which have been evaluated for their potential use for tilapia (*Oreochromis* spp.) production. For this purpose, 795 papers published in the Scopus and Web of Science databases between 2011 and 2021 were analyzed using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology. Data on the growth rate (GR) and effects on weight gain (WG), specific growth rate (SGR) and feed conversion ratio (FCR); digestibility; fatty acid profile (FAP) of the fish carcass; and the survival rate (SR) were compiled in databases and summary tables. The results were refined according to different criteria, obtaining 144 documents that were pertinent for an in-depth analysis. From those, we found that 50.7% evaluated terrestrial plants, 22.2% animals, 13.9% algae, 9% fungi, and the remaining, combinations of some of the above categories. From the summarized results we concluded that most of the non-conventional sources analyzed have a positive potential impact as alternatives for producing tilapia. Survival was the most evaluated parameter, while digestibility was the least evaluated parameter.



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Keywords: tilapia; nutritional supplement; PRISMA; fish feed

Key Contribution: This review provides a comprehensive overview of the results of more than a hundred evaluations that have been carried out on different non-conventional ingredients for feeding tilapia, offering a range of alternatives for fish farmers.

1. Introduction

Nowadays, animal production faces significant challenges arising from the need to reduce its negative environmental impact and effect on climate change. It also faces input scarcity and an increase in its prices, mainly due to the economic situation derived from the COVID-19 pandemic and the war in Ukraine. These conditions have increased the need to seek non-conventional, sustainable, and, hopefully, locally produced food sources that will reduce the costs and carbon footprint related to its production and transportation. In the case of aquaculture production, it is also necessary to minimize the use of raw materials from fishery to reduce their impact on marine ecosystems.

Global aquatic food consumption (excluding algae) grew at an annual average of 3.0% between 1961 and 2019, a rate that almost doubled the annual global population growth (1.6%) over the same period, with an annual per capita consumption of 20.5 kg in 2019. In the same year, aquatic food reached 17% of total animal protein and 7% of total protein consumed worldwide [1]. It is expected that, by 2030, 57% of fish will come from aquaculture, compared to 53% in 2018–2020. Likewise, it is estimated that by 2030, fish will remain critical to the global diet and play a key role in food security [2]. Nile tilapia

(*Oreochromis niloticus*) is the third in the production of aquaculture species worldwide (9%), closely preceded by grass carp (*Ctenopharyngodon idellus*) with 11.8%, and silver carp (*Hypophthalmichthys molitrix*) with 10% [3].

FAO [1] has proposed a new approach to aquaculture called “Blue Transformation”, which aims, among other things, to develop and adopt sustainable aquaculture practices and improve capacities to achieve a more efficient and resilient aquaculture industry. The search for non-conventional and sustainable sources of fish feed allows progress toward achieving these objectives.

This paper presents the results of a systematic review aimed at identifying and classifying different raw materials from terrestrial plants, animals, algae, and fungi not commonly used in commercial fish feeds which have been evaluated to determine their potential use as ingredients for tilapia feed. To summarize this concept, we will call them non-conventional feeds, as opposed to traditional sources as fishmeal, soybean, fish, or corn oils, among others. These, in some cases, may be considered unsustainable or, in other cases, may be difficult to access for countries that do not produce, and therefore, must import them. In this case, situations such as those that occurred during the pandemic and post-pandemic, to cite two examples, can mean a shortage of supplies than can lead to a crisis in livestock production, and, in this specific case, in tilapia production.

To carry out an analysis in adequate depth, we have limited the scope of this manuscript to biological categories and therefore do not include chemical or mineral materials. Additionally, we exclude bacterial-based food sources since, if included, the analysis would exceed the length that can be adequately contained in a single article. Based on the results obtained, the digestibility results and the effects of diets and supplements on the fish in terms of growth rate, fatty acid profile, and survival rate were analyzed.

2. Materials and Methods

A systematic review was carried out based on an adaptation of the PRISMA methodology [4]. Bibliographic searches allow establishing data availability in systematic reviews, which aims to select and collect qualitative and quantitative data that will be available for analysis and will be used to determine eligibility depending on the topic of interest.

This process must be rigorous and replicable to ensure a minimal bias in searches [5]. Moreover, systematic reviews and meta-analyses synthesize data from existing primary research, and well-conducted reviews offer a practical solution to the problem of keeping up to date in any field of interest [6].

The specific focus of this systematic review is on non-conventional feed sources for tilapia production. Thus, papers indexed in Scopus and Web of Science (WOS) databases were used as sources. In both databases, the search was carried out in the title, abstract, and keywords fields (TITLE-ABS-KEY), published from 1 January 2011 to 31 December 2021, in English, Portuguese, and Spanish.

The primary search term was “Tilapia”. It was applied in combination with any of the following: “nutrition”, “nutritional supplement”, “dietary supplement”, “dietary supplementation”, “nutritional supplementation”, “new ingredient”, and “insect”. In the Scopus database, particularly, the search was also limited by the type of paper: “ar” (reviewed articles), “re” (reviews), and “cp” (conference papers). However, it was impossible to limit the search by type of paper in the Web of Science database since the search engine does not have this option.

The search equations developed with the keywords of interest were as follows:

Scopus:

TITLE-ABS-KEY (tilapia AND (nutrition OR “nutritional supplement” OR “dietary supplementation” OR “dietary supplement” OR “nutritional supplementation” OR “novel ingredient” OR “insect”)) AND (LIMIT-TO (DOCTYPE, “ar”) OR LIMIT-TO (DOCTYPE, “re”) OR LIMIT-TO (DOCTYPE, “cp”)) AND (LIMIT-TO (PUBYEAR, 2021) OR LIMIT-TO (PUBYEAR, 2020) OR LIMIT-TO (PUBYEAR, 2019) OR LIMIT-TO (PUBYEAR, 2018) OR LIMIT-TO (PUBYEAR, 2017) OR LIMIT-TO (PUBYEAR, 2016) OR LIMIT-TO (PUBYEAR,

2015) OR LIMIT-TO (PUBYEAR, 2014) OR LIMIT-TO (PUBYEAR, 2013) OR LIMIT-TO (PUBYEAR, 2012) OR LIMIT-TO (PUBYEAR, 2011)) AND (LIMIT-TO (LANGUAGE, "English") OR LIMIT-TO (LANGUAGE, "Portuguese") OR LIMIT-TO (LANGUAGE, "Spanish")).

Web of Science:

(tilapia AND (nutrition OR "nutritional supplement" OR "dietary supplementation" OR "dietary supplement" OR "nutritional supplementation" OR "novel ingredient" OR "insect")).

Using the results obtained from the search equation for Scopus and Web of Science, repeated papers were first discarded, and then a preliminary selection was made by reading the titles and abstracts. Thus, those unrelated to the topics of interest were discarded. The exclusion criteria used for this were:

- The fish evaluated is not of the genus *Oreochromis* spp.
- The article is not related to diet or supplement evaluation.
- Only the effects of the ingredient on fish health were evaluated in the article.
- Only effects on reproduction or sexual reversion were evaluated in the article.

After articles were eliminated based on the above criteria, it was also necessary to remove one article that had been retracted. A subsequent more in-depth reading allowed to identify other aspects that made some articles less interesting regarding the research objective:

- The ingredients evaluated are not included in the scope of the study but are bacteria, minerals, or chemically synthesized compounds.
- The ingredients evaluated are conventional. In the context of this paper, the term "conventional ingredient" is used to refer to an ingredient traditionally used in the production of commercial fish feed. For example, soybean, corn, fishmeal, and fish oil, among others. After these deputation stages, a preliminary selection of articles dedicated to feeding based on terrestrial plants (*embryophytes*), animals, algae, fungi, and some industrial by-products was obtained. The procedure followed is outlined in Figure 1.

At the end, the papers that met the following criteria were selected:

- Raw material origin—the food source evaluated was algae, animal, fungus, plant, or insect.
- Raw material processing method—the type of raw material evaluated in the articles: by-product, excrement, seed, meal, cake, shell, bran, extract, oil, essential oil, leaves, powder, hydrolate, protein hydrolysate, the residue of slaughtering, syrup, and nanoparticles.
- Analyses carried out—the type of evaluation carried out in the study: growth, body composition, digestibility, feed conversion ratio, health, survival, food consumption, food cost, and sensory acceptance.

The selected articles were compiled in a database consisting of the following items: authors, title, year, country, affiliation, abstract, keywords, raw material origin, raw material processing method, analysis carried out, and food source. The purpose of the database was to identify and synthesize information of interest for the review. This information was also entered into VantagePoint software to obtain different qualitative and quantitative analyses.

Moreover, the resulting papers were used to create summary tables of findings related to the incidence of the supplement or diet evaluated on the fish growth, its survival, the ingredient digestibility, and the fatty acid profile of the fish at the end of the evaluation. To create the table regarding the evaluated ingredients' incidence on tilapia's growth rate, the results found in the reviewed papers related to weight gain (WG), specific growth rate (SGR), and feed conversion ratio (FCR) were recorded.

Following the PRISMA methodology, the presence of conflicts of interest and the sources of funding for the research were analyzed to establish whether they have any possible impact on the results obtained and to ensure the impartiality of the information.

Furthermore, it is essential to highlight that analyses in which no quantitative data were found were not included to avoid errors in the evaluation of the certainty of the evidence.

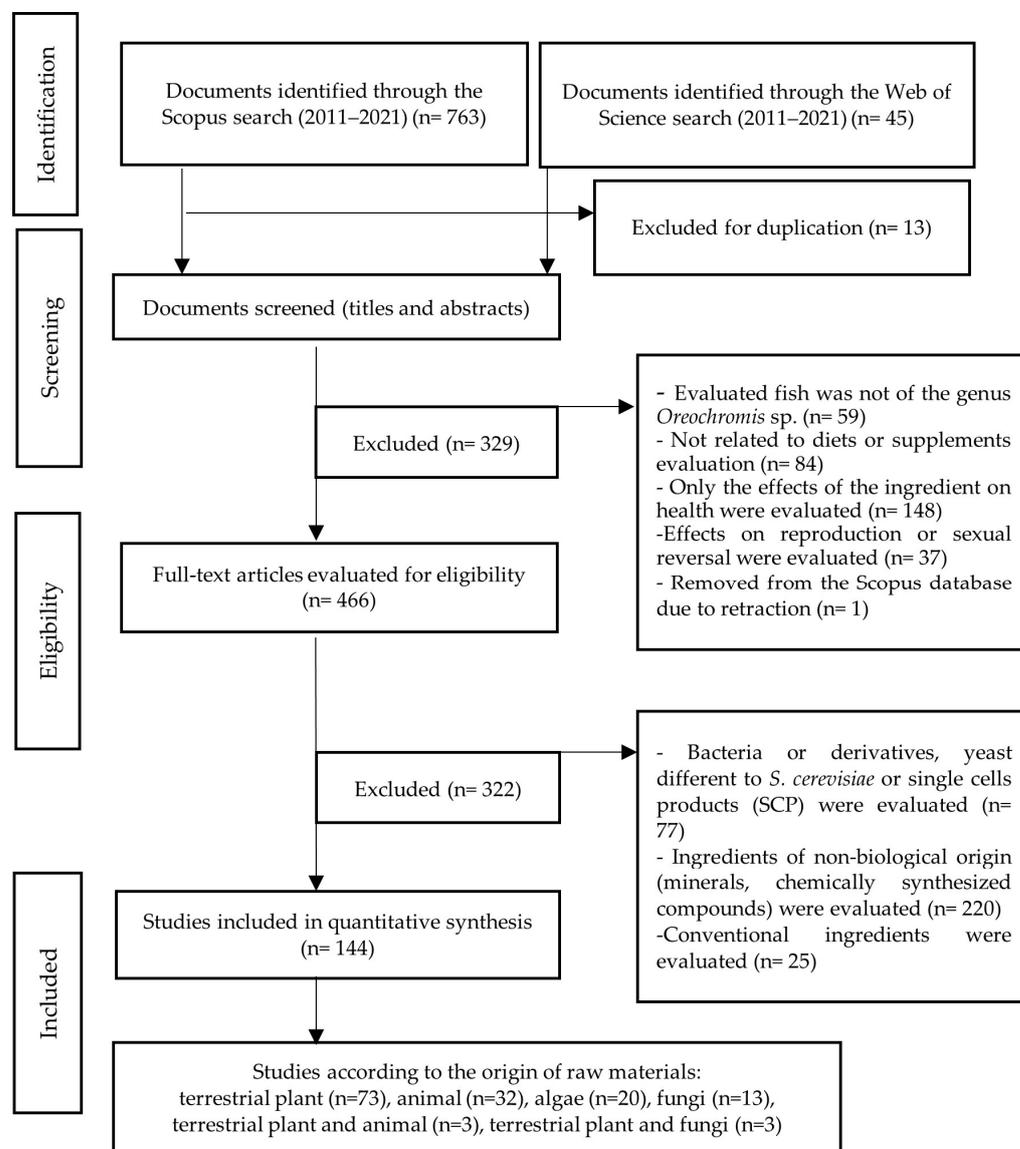


Figure 1. Document identification and selection flowchart. Source: Own elaboration.

Thus, tables and graphs were constructed to synthesize the information collected after examining the information grouped in these databases and the summary tables of findings. The most used way to analyze the different studies reviewed was to evaluate whether comparisons of the diets or supplements were made in relation to a commercial control and whether the highlight of this comparison showed a statistically significant difference (SSD) or not (No SSD). If there were differences, whether the diet or supplement evaluated had been superior (SSS) or inferior (SSI) compared to the control was recorded. The analysis of these sources in a disaggregated way, separating some of the feeding categories, allows us to go much deeper and bring up complementary data extracted from some of the other articles.

3. Results and Discussion

2.1. Analysis Criteria

As shown in Figure 1, with the equations for Scopus and WOS, 795 papers were obtained. A total of 651 were discarded for the various reasons mentioned above. Thus,

144 articles were finally obtained and classified according to the food source evaluated, resulting in 73 articles in the terrestrial plant category (50.7%); 32 in animal (22.2%); 20 in algae (13.9%); 13 in fungus (9.0%); 3 assessed terrestrial plant and animal (2.1%); and 3 evaluated terrestrial plant and fungus (2.1%).

The keywords most used by the authors of the reviewed papers can be seen graphically in the Word Cloud of Figure 2 as one of the results of VantagePoint software. These words largely coincide with the topics on which it was decided to delve in this review and confirm the correct choice of search terms.

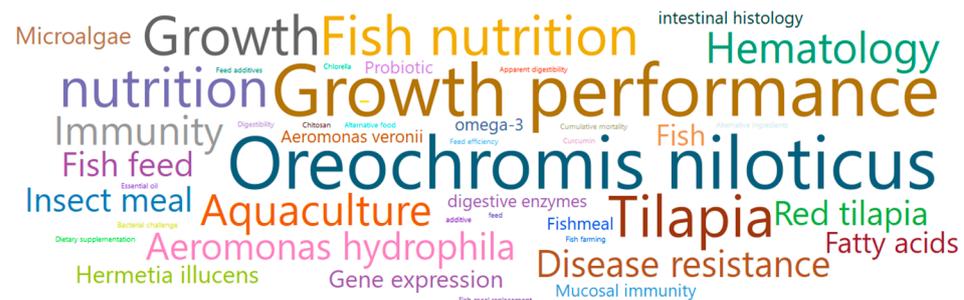


Figure 2. Keyword cloud of reviewed documents. Source: VantagePoint.

Figure 3 shows the number of publications per year according to the parameters previously defined for this review. A constant scientific production is noted from 2011 to 2017, with a small peak in 2014 and an increasing trend in publications starting in 2018. One possible explanation for this phenomenon is the increased interest in sustainability-related issues, which has been growing since the adoption of the Sustainable Development Goals in 2015 [7] proposed by the United Nations General Assembly. The search for alternative ingredients to those originating from industrial agriculture and industrial fishing point, among others, to objectives such as responsible production and consumption, underwater life, and life of terrestrial ecosystems.

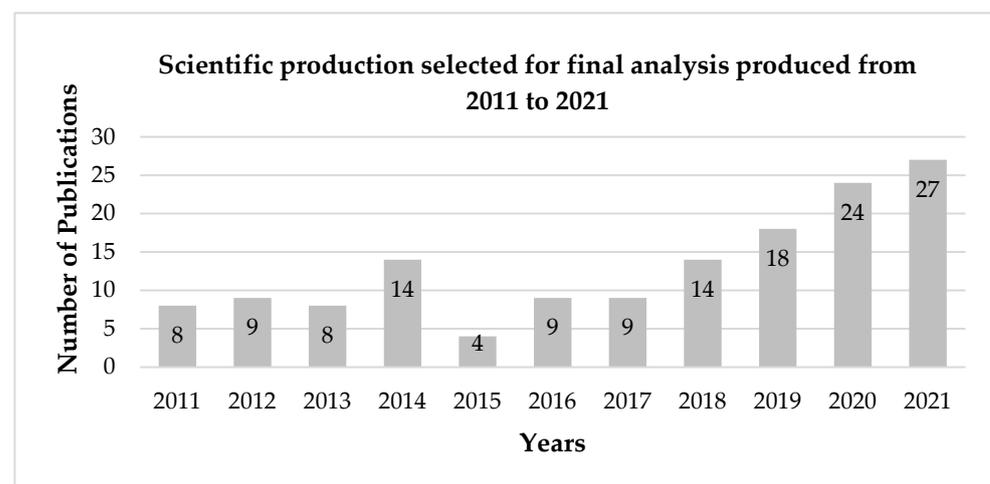


Figure 3. Scientific production selected for final analysis produced from 2011 to 2021. Source: Own elaboration.

On the other hand, when analyzing the country of affiliation of the authors of the papers evaluated, it was found that the country with the highest scientific production was Brazil, with 20.67% (43 publications), followed by Egypt, with 18.27% (38 publications), Thailand with 7.69% (16 publications), and China and Saudi Arabia, with 5.29% each (11 publications). Figure 4 shows the countries of the authors of the publications and the frequency of publications expressed in colors.

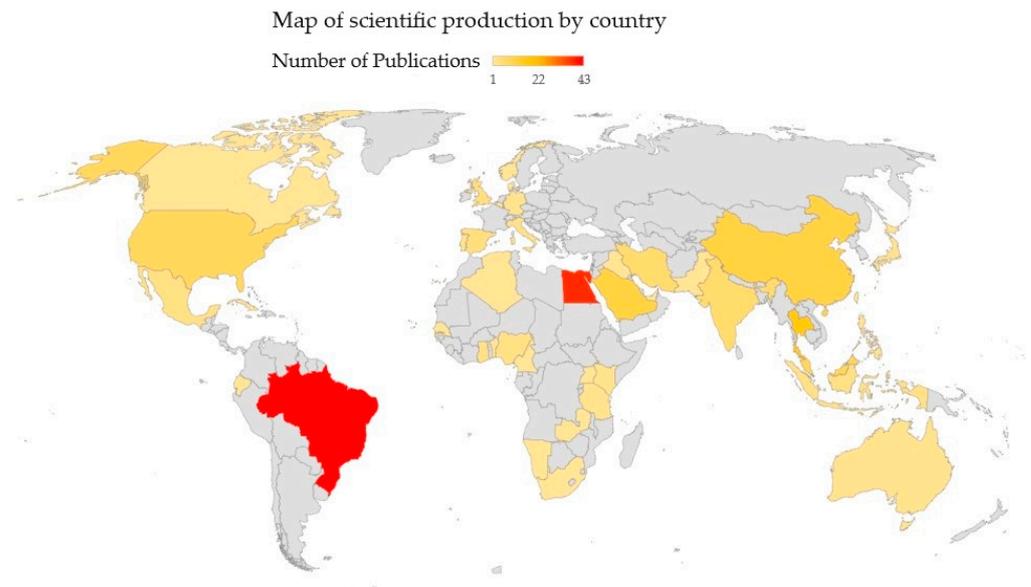


Figure 4. Number of documents per country. Source: Own elaboration.

2.2. General Considerations

The most frequently used experimental conditions were identified, to establish reference frameworks for new studies based on the existing literature. 75% of the reviewed research was conducted with *O. niloticus*, 13.19% with red hybrid (*O. niloticus* × *O. mossambicus*), 6.25% with GIFT (*O. niloticus* genetically modified), 4.87% with *O. mossambicus*, and 0.69% with *O. niloticus* × *O. aureus*.

Moreover, 61.81% of the studies tested supplements, 37.5% produced concentrated feeds that included the raw material studied, and 0.69% did not report any information on this matter. The review showed that 64.58% of the studies started with fish weighing between 0 and 20 g, 15.28% between 21 and 40 g, and 16.67% with fish weighing more than 40 g. The great majority of the papers, except for five (3.47%), reported the initial weight of fish as an essential element to be evaluated. The most frequent duration interval for the experiments was from 31 to 60 days (46.53%), followed by 61–90 days with 22.92%, and 30 days or less corresponds to 16.67%. The most frequent range of the number of individuals per tank was between 11 and 20, with 35.42%, followed by 21–30, with 25%, and 0 to 10, with 18.1%.

Some of the non-conventional ingredients found were used to replace fishmeal, soybean, or similar protein sources. Conventional fat sources such fish oil, soybean oil or corn oil were the aim of other significant number of papers. The improvement of immune system, nutrient availability, antimicrobial and antioxidant activities were other goals that were aimed to using ingredients as essential oils or plant extracts.

According to the amount of data, raw materials show the highest number of papers in the analyses considered in this evaluation. Some of those that stand out for the terrestrial plants' category are *Linum usitatissimum* L. and *Helianthus annuus* L., with the highest number of written articles, six and five publications, respectively. The next most frequent were *Salvadora persica* L. with 4, *Moringa oleifera* Lam. with three. In addition, there are *Cocos nucifera* L., *Astragalus membranaceus* Bunge, and *Olea europaea* L. with 2 evaluations each.

In the case of *L. usitatissimum*, *H. annuus*, *C. nucifera*, and *O. europaea*, extracted oil from these species was the most evaluated along with its impact on the growth and composition of the fish, especially on its fat content and fatty acid profile. For *S. persica*, its meal and its effect on the fish growth were evaluated. In *A. membranaceus*, the effects of polysaccharides extracted from the plant material on fish growth were evaluated. Also, its aqueous extract, in combination with that of other plants, was evaluated on growth and digestibility parameters.

The raw materials that stand out in the animal category are *Hermetia illucens* L. with 11 evaluations, followed by swine and poultry with 5 and 4 evaluations, respectively. Additionally, there is *Penaeus vannamei* Boone with 3 evaluations. In the fungi category, the highest number of mentions was obtained by *Saccharomyces cerevisiae* Meyen ex. Hansen, with 10 evaluations, and in the algae category, *Arthrospira platensis* Gomont stands out with 4 evaluations, most of them focused on growth and survival parameters.

Figure 5 shows the nine food sources with the highest number of mentions in the analyzed papers. 4 are terrestrial plants, 2 are of animal origin, 2 is algae, and 1 is fungi. It also shows that the Growth parameter reports the highest number of evaluations, followed by the Body Composition and Survival parameters.

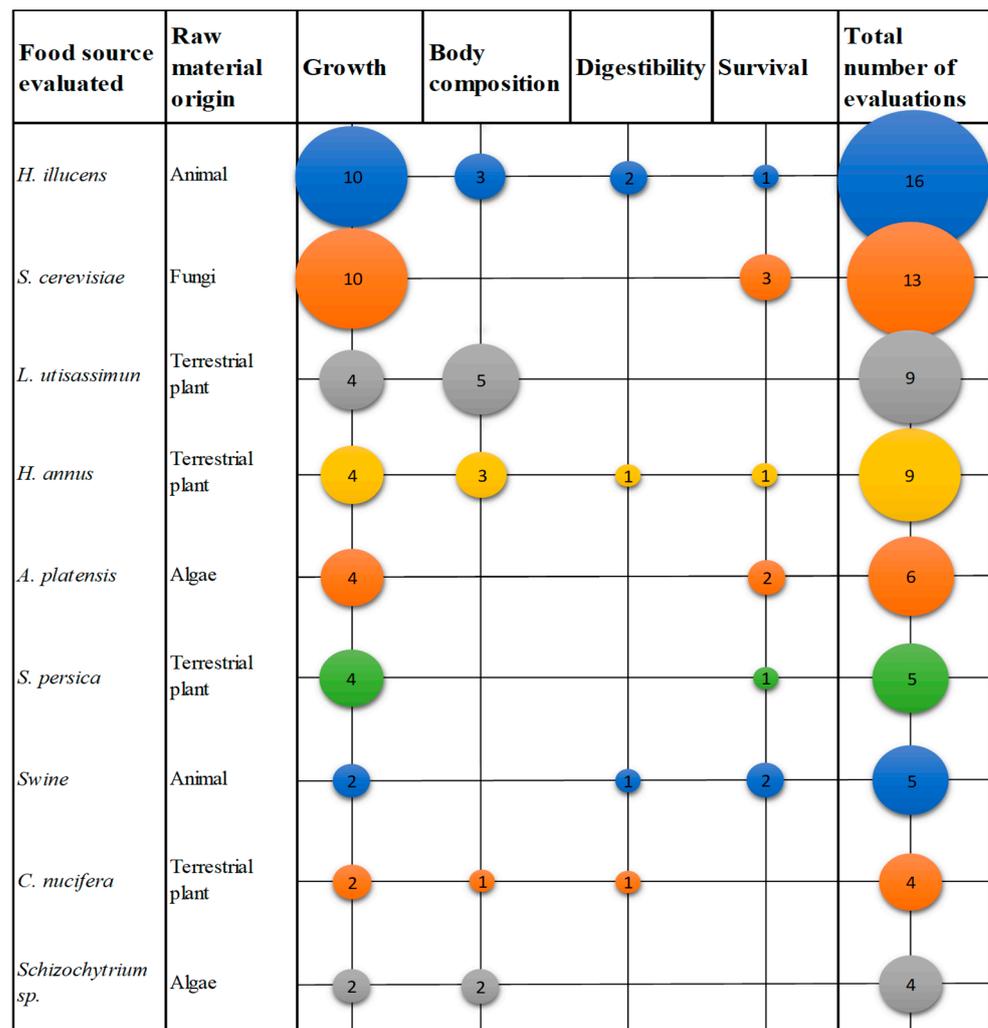


Figure 5. Food source evaluated with the highest number of tests performed in the reviewed documents. Source: Own elaboration.

2.3. Parameters Studied in Fish

2.3.1. Growth

Fish growth was evaluated in 86.1% (124 articles) of the total papers. The indicators analyzed were Weight Gain percentage (WG) (Equation (1)), Specific Growth Rate (SGR) (Equation (2)), and Feed Conversion Ratio (FCR) (Equation (3)). These indicators were obtained from the papers reviewed or calculated by the authors of this review based on the available information. The formulas used were as follows:

Growth Rate

Weight Gain Percentage (%WG)

$$WG(\%) = \frac{W_f - W_i}{W_i} \times 100\%, \quad (1)$$

Specific Growth Rate (SGR)

$$SGR(\% \text{ per day}) = \frac{\ln(W_f) - \ln(W_i)}{\text{number of days}} \times 100\%, \quad (2)$$

Feed Conversion Ratio (FCR)

$$FCR \left(\frac{g}{g} \right) = \text{Feed intake} \frac{g}{\text{Wet weight gain}(g)}, \quad (3)$$

where

W_i: initial weight

W_f: final weight.

According to the processing method of the raw materials and how they were added to each diet, 31 different categories were obtained. There were 142 mentions related to them from the 124 articles where growth indicators were evaluated. The main processing methods were meal with 38.1% (54 mentions), extracts of different types with approximately 12% (17 mentions), and essential oils and oils in general with 4.9% (7 mentions) each.

Data were organized according to the origin of the food evaluated for each diet. 64 of the papers reported diets based on terrestrial plants only (51.6%), 25 of animal origin (20.2%), 16 of algae (12.9%), and 14 of fungi (11.3%). In one of the studies, a plant and a fungus were simultaneously evaluated (0.8%). Four of the analyzed feeds are by-products (3.2%), one of which evaluated a digestate and another a meal, both from terrestrial plant and animal waste. Furthermore, one study includes residues from pasta production and another from bee pollen.

The articles that evaluated growth using terrestrial plants, either individually or in combination with another type of food source for tilapia were 67, which can be seen in Table 1 (54.0% of the total number of papers reviewed and 84.8% of the total number of papers that evaluated terrestrial plants). Regarding food sources from animals, algae, fungi, and by-products, it was reported that 48.4% (60 papers) were about growth, equivalent to 84.5% of the total number of papers where these types of food sources were evaluated (71 articles).

Table 1. Summary table of the different growth indicators evaluated in terrestrial plants as food sources with respect to commercial feeds. Source: Own elaboration.

Fish Species	Stage	Plant Species	Raw Material Processing Method	WG	SGR	FCR	Reference
n	F	<i>Allium cepa</i> L.	Meal	=	=	=	[8]
n	F	<i>Allium sativum</i> L.	Meal	=	=	=	[8]
n	F	<i>Arachis hypogaea</i> L.	Cake, Husk	=	=	=	[9]
n	F	<i>Azadirachta indica</i> A. Juss.	Seed extract	=	=	=	[10]
n	F	<i>Camellia sinensis</i> L. (30 days)	Extract	=↑	↑	↑	[11]
n	F	<i>C. sinensis</i> (60 days)	Extract	↑	=↑	↑	[11]
n	F	<i>Carica papaya</i> L.	Seed extract	↑	↑	↑	[10]
n	F	<i>Caryocar brasiliense</i> Cambess.	Peel, Meal	=	-	=	[12]
n	F	<i>Cinnamomum camphora</i> L.	Extract, Seed	↑	↑	↑	[10]
n	F	<i>Cinnamomum verum</i> J. Presl	Nanoparticles	↑	↑	=	[13]
n	F	<i>Citrus × sinensis</i> (L.) Osbeck	Extract	↑	=	=	[14]
n	F	<i>Citrus bergamia</i> Risso & Poit.	Oil	=↑	=↑	=↑	[15]

Table 1. Cont.

Fish Species	Stage	Plant Species	Raw Material Processing Method	WG	SGR	FCR	Reference
n	F	<i>C. nucifera</i>	Oil	=↑	=↑	=↑	[16]
n	F	<i>Cucurbita moschata</i> Duchesne	Seed meal	↑	↑	-	[17]
n	F	<i>Curcuma longa</i> L.	Hydrolate	=	=	=	[18]
n	F	<i>C. longa</i>	Curcumin	↑	↑	↑	[19]
n	F	<i>Cymbopogon citratus</i> (DC.) Stapf	Essential oil	↑	↑	↑	[20]
n	F	<i>Elephantopus scaber</i> L. (30 days)	Extract	↑	↑	↑	[21]
n	F	<i>E. scaber</i> (60 days)	Extract	=↑	=↑	=↑	[21]
n	F	<i>Euphorbia hirta</i> L.	Seed extract	↑	↑	↑	[10]
n	F	<i>H. annuus</i>	Seed meal	↑	↑	-	[17]
n	F	<i>Houttuynia cordata</i> Thunb.	Meal	=	=	=	[22]
n	F	<i>Ipomoea batatas</i> L.	Extract, Meal	=↑	=↑	=↑	[23]
n	F	<i>L. usitatissimum</i>	Seed extract	↑	=	=	[14]
n	F	<i>Lippia organoides</i> Kunth	Essential oil	=	-	=	[24]
n	F	<i>Lycium barbarum</i> L.	Meal	=↑	=↑	-	[25]
n	F	<i>Lycopersicon esculentum</i> Mill.	By-product, Meal	↓	↓	-	[26]
n	F	<i>Mangifera indica</i> L.	Meal	↓=	↓=	-	[27]
n	F	<i>M. oleifera</i>	Meal	↑	↑	↑	[28]
n	F	<i>M. oleifera</i>	Leaves	-	↑	=	[29]
n	F	<i>Pelargonium graveolens</i> L'Hér. ex Aiton	Extract	=↑	=↑	=↑	[20]
n	F	<i>Phoenix dactylifera</i> L.	By-product, Meal	↓	↓	-	[26]
n	F	<i>Pisum sativum</i> L.	By-product, Meal	↓	↓	-	[26]
n	F	<i>Rhizoclonium riparium</i> var. <i>implexum</i> (Dillwyn) Rosenvinge	Meal	=↑	=	↑	[30]
n	F	<i>S. persica</i>	Derived	=↑	=↑	=	[31]
n	F	<i>S. persica</i>	Meal	↑	=↑	=↑	[32]
n	F	<i>Theobroma cacao</i> L.	Meal, Husk	↓=↑	-	=↑	[33]
n	F	<i>Voandzeia subterranea</i> (L.) DC.	By-product, Meal	=↑	-	=↑	[34]
n	J	<i>A. membranaceus</i>	Polysaccharides	↑	↑	↑	[35]
n	J	<i>Cenchrus purpureus</i> (Schumach.) Morrone	By-product, Digestate meal	=	-	=	[36]
n	J	<i>C. nucifera</i> (28 °C)	Oil	↓	-	-	[37]
n	J	<i>C. nucifera</i> (22 °C)	Oil	↓=	-	-	[37]
n	J	<i>Cymbopogon flexuosus</i> (Nees) Will. Watson	Essential oil	=	=	=	[38]
n	J	<i>Glycine max</i> (L.) Merr.	Degummed soybean	=↑	=	=	[39]
n	J	<i>H. annuus</i> (28 °C)	Oil	↓	-	-	[37]
n	J	<i>H. annuus</i> (22 °C)	Oil	↓=	-	-	[37]
n	J	<i>H. annuus</i>	Seed, Cake	=	=	-	[40]
n	J	<i>Musa</i> ABB cv. Kluai “Namwa”	Fresh	↑	↑	↑	[41]
n	J	<i>Leucas aspera</i> (Willd.) Link	Meal	↓=↑	↓=↑	↓=↑	[42]
n	J	<i>L. usitatissimum</i>	Oil	=↑	=	=	[39]
n	J	<i>L. usitatissimum</i> (28 °C)	Oil	↓	-	-	[37]
n	J	<i>L. usitatissimum</i> (22 °C)	Oil	↓=	-	-	[37]
n	J	<i>Lippia sidoides</i> Cham.	Essential oil	=	=	=	[43]
n	J	<i>M. indica</i>	Meal	↓=	↓=	↓=	[44]
n	J	<i>Mentha arvensis</i> L.	Essential oil	↑	↑	=↑	[45]
n	J	<i>M. oleifera</i>	Leaves	=	=	-	[46]
n	J	<i>M. oleifera</i>	Seed	↑	↑	-	[46]
n	J	<i>Morus nigra</i>	Syrup	=↑	=↑	=↑	[47]
n	J	<i>Ocimum sanctum</i> L.	Extract	-	=	=	[48]
n	J	<i>G. max</i>	By-product: Okara	=	=	=	[49]
n	J	<i>O. europaea</i>	Cake	↑	↑	=↑	[50]
n	J	<i>O. europaea</i> (28 °C)	Oil	↓	-	-	[37]
n	J	<i>O. europaea</i> (22 °C)	Oil	↓=	-	-	[37]

Table 1. Cont.

Fish Species	Stage	Plant Species	Raw Material Processing Method	WG	SGR	FCR	Reference
n	J	<i>Origanum vulgare</i> L.	Dry leaves	=	=	=	[51]
n	J	<i>Oryza sativa</i> L.	Seed; Cake	=	=	-	[40]
n	J	<i>Phragmites</i> spp.	By-product, Digestate meal	=	-	=	[36]
n	J	<i>Piper nigrum</i> L.	Essential oil	=	=	=	[52]
n	J	<i>Pistacia vera</i> L.	Extract, Seed	=↑	=↑	=↑	[53]
n	J	<i>Portulaca oleracea</i> L.	Leaves	↓=	↓=	=	[54]
n	J	<i>Prosopis juliflora</i> (Sw.) DC.	Meal	=	-	=	[55]
n	J	<i>P. juliflora</i>	Meal	=	=	-	[56]
n	J	<i>S. persica</i>	Meal	=	=	-	[57]
n	J	<i>S. persica</i>	Meal	=	=	=	[58]
n	J	<i>Thymus vulgaris</i> L.	Essential oil	=	=	=	[43]
n	J	<i>Thymus zygis</i> L.	Essential oil	=	=	=	[43]
n	J	<i>Trigonella foenum-graecum</i> L.	Seed	=↑	=	-	[59]
n	J	<i>T. foenum-graecum</i>	Seed, Extract	=↑	=↑	-	[59]
n	J	<i>Uncaria tomentosa</i> (Willd.) DC.	Extract	=↑	-	=↑	[60]
GIFT	F	<i>Aloe vera</i> L.	Meal	=↑	=↑	=↑	[61]
GIFT	F	<i>Brassica napus</i> L.	Oil	=	=	=	[62]
GIFT	F	<i>Coriandrum sativum</i> L.	Seed oil	=	=	=	[62]
GIFT	F	<i>H. annuus</i>	Oil	=	=	=	[62]
GIFT	F	<i>L. usitatissimum</i>	Oil	=	=	=	[62]
GIFT	F	<i>Malus domestica</i> Borkh.	By-product, Meal	↓=↑	↓=↑	=↑	[63]
GIFT	F	<i>Ocimum gratissimum</i> L.	Essential oil	↓=↑	=↑	=	[64]
GIFT	F	<i>Zingiber officinale</i> Roscoe	Essential oil	↓=	↓=	↓=	[64]
m	F	<i>Pimenta dioica</i> (L.) Merr.	Seed meal	=↑	=↑	=↑	[65]
m	F	<i>Psidium guajava</i> L.	Leaves, Extract	=↑	=	=	[66]
m	J	<i>Cucurbita mixta</i> Pangalo	Seed, Meal	=↑	=↑	=	[67]
m	J	<i>Mucuna pruriens</i> (L.) DC.	Seed, Meal	↑	↑	=↑	[68]
m	J	<i>Stellaria media</i> L.	Meal	↓=	↓=	↓=	[69]
n × m	F	Unknown	Charcoal powder	=↑	=↑	=↑	[70]
n × m	J	<i>C. sinensis</i>	By-product	=	=	=↑	[71]
n × m	J	<i>Helianthus tuberosus</i> L.	Extract	↑	↑	↑	[72]
n × m	J	<i>Saccharum officinarum</i> L.	By-product, Meal	↓=	-	↓=	[73]
n × a	J	Mixture of <i>A. memembranaceus</i> , <i>Codonopsis pilosula</i> (Franch.) Nannf., <i>Eucommia ulmoides</i> Oliv., <i>Lonicera japonica</i> Thunb.	Extract	=↑	=↑	=↑	[74]

Note: Fish species: n: *O. niloticus*, m: *O. mosambicus*, n × m: red hybrid (*O. niloticus* × *O. mosambicus*), GIFT: *niloticus* GIFT (genetically modified), n × a: *O. niloticus* × *O. aureus*. Stage: F: Fingerling, J: Juvenile. Statistically significant superior (↑), statistically significant inferior (↓), no statistically significant difference (=) compared to control, no information was found in the corresponding parameter (-). WG: Weight gain, SGR: Specific growth rate, FCR: Feed conversion ratio.

Tables 1 and 2 summarize the results of the different analyses performed by the authors, comparing them statistically with the commercial control used. Moreover, the tilapia species and the growth stage of the fish on which the evaluation was performed were recorded. In these tables these acronyms were used: WG Weight gain, SGR Specific growth rate and FCR Feed conversion ratio. In Tables 1–6, an arrow up (↑) is used to denote “statistically significant superior”, arrow down (↓) denotes “statistically significant inferior”, and (=), “not statistically significant different” from control. When no information was found in the corresponding parameter in the specific source, a hyphen (-) was used. It is important to consider that, in some works, different concentrations were studied. In the case where the parameters have different statistical differences with respect to the control for different concentrations, this is expressed using more than one symbol. For example, “=↑” means that for the first group of concentrations, there is not statistically significant difference, and

in the second group of concentrations, the parameter is statistically significant superior with respect to control.

Table 2. Summary table of the different growth indicators evaluated in animals, algae, fungi, and by-products as food sources with respect to commercial feeds. Source: Own elaboration.

Fish Species	Stage	Raw Material Origin	Raw Material Processing Method	WG	SGR	FCR	Reference
Animal							
n	F	<i>H. illucens</i>	Meal	↓=↑	-	=	[75]
n	J	<i>H. illucens</i>	Meal	↓	↓	-	[76]
n	J	<i>Chrysomya putoria</i> Wiedemann	Meal	↓=	↓=	-	[76]
n	J	<i>Zophobas morio</i> Fabricius	Meal	=	=	-	[77]
n	J	<i>Spodoptera littoralis</i>	Meal	↓=	↓=	↓=	[78]
n	F	<i>Gryllus bimaculatus</i>	Meal	=↑	=	=↑	[79]
n × m	J	<i>H. illucens</i>	Oil	↓=↑	=	=	[80]
n × m	J	<i>H. illucens</i>	Meal	=	=	=↑	[81]
n	J	<i>H. illucens</i>	Meal	=	=	=	[82]
n × m	F	<i>H. illucens</i>	Excrement	=↑	-	-	[83]
n	J	<i>Penaeus monodon</i>	Shells	=↑	=↑	=↑	[84]
n	F	<i>H. illucens</i>	Meal	=	=	=	[85]
n	J	<i>H. illucens</i>	Meal	=	=	=	[86]
n	F	<i>H. illucens</i>	Meal	=	=	=	[87]
n	J	<i>Apis mellifera</i> L.	Propolis	↓=	↓=	=	[88]
n	F	<i>Cinereous cockroach</i>	Meal	=	=	=	[89]
n	J	<i>Tenebrio molitor</i>	Meal	↓	-	-	[90]
n × m	J	<i>Chrysomya megacephala</i>	Meal	=↑	=↑	=	[91]
n × m	F	<i>P. vancouverensis</i>	Shells	=	-	=	[92]
n × m	F	<i>P. vancouverensis</i>	Meal	↓=	-	=	[93]
n	-	<i>P. vancouverensis</i>	Shells	=↑	-	=	[94]
n	J	<i>A. mellifera</i>	Pollen	↑	↑	=	[95]
Algae							
n	-	<i>Dunaliella</i>	Fresh	↓↑	-	↓=	[96]
n	F	<i>Arthrospira platensis</i>	Meal	=↑	=↑	=↑	[97]
n	J	<i>Nannochloropsis oculata</i>	Meal	=↑	=↑	=↑	[98]
n	J	<i>A. platensis</i>	Nanoparticles	↑	↑	↑	[99]
n	F	<i>Caulerpa lentillifera</i>	Meal	=↑	=↑	-	[100]
n	J	<i>Chlorella vulgaris</i>	Meal	↓=↑	↓=↑	↓=↑	[101]
n	J	<i>Schizochytrium</i> sp.	Meal	=↑	-	=	[102]
n × m	F	<i>Enteromopha prolifera</i>	Meal	↑	=↑	=↑	[103]
n	F	<i>Nannochloropsis salina</i>	Meal	↓	↓	↓	[104]
n	-	<i>Gracilaria arcuata</i>	Meal	↓	↓	↓=	[105]
n	J	<i>Ulva clathrata</i>	Extract	=	=	=	[106]
n	J	<i>Schizochytrium</i> sp.	Dried whole cells	=↑	=	=	[107]
n × m	F	<i>A. platensis</i>	Meal	=↑	=↑	=↑	[108]
n × m	F	<i>Ulva fasciata</i>	Meal	↑	↑	↑	[109]
n	F	<i>Ascophyllum nodosum</i>	Meal	=	-	-	[110]
n × m	F	<i>A. platensis</i>	Meal	↓=↑	=↑	-	[111]
Fungi							
n	J	<i>S. cerevisiae</i>	Inactivated dry	=	-	=	[112]
n	J	<i>Aspergillus oryzae</i>	Cake	↑	↑	=↑	[50]
n × m	F	<i>Pleurotus pulmonarius</i>	Extract	=	=	↓	[113]
n	J	<i>S. cerevisiae</i>	Extract	↑	↑	↑	[114]
m	-	<i>S. cerevisiae</i>	Extract	↑	=↑	=↑	[115]
n	J	<i>Rhodotorula mucilaginosa</i>	Extract	=	=↑	=↑	[116]
n	J	<i>S. cerevisiae</i>	Meal	↑	↑	↑	[117]

Table 2. Cont.

Fish Species	Stage	Raw Material Origin	Raw Material Processing Method	WG	SGR	FCR	Reference
Fungi							
n	F	<i>Trichoderma reesei</i>	Fungi-degraded seed	=↑	-	-	[118]
n	-	<i>S. cerevisiae</i>	Meal	↑	↑	-	[119]
n	J	<i>S. cerevisiae</i>	Derived	=	=	=	[120]
n × m	F	<i>Pleurotus sajorcaju</i>	Meal	=	=	=	[121]
n	J	<i>S. cerevisiae</i>	Dried	=	-	-	[122]
GIFT	F	<i>S. cerevisiae</i>	Whole	-	-	↓	[123]
GIFT	J	<i>Aurantiochytrium</i> sp.	Meal	=	=	-	[124]
n	-	<i>S. cerevisiae</i>	Cell wall	↑	↑	↑	[125]
By-products							
n	-	Swine	Excrement	=	-	=	[126]
n	J	Poultry	Slaughter residues, Meal	=	=	-	[127]
n	J	Swine	Slaughter residues, Meal	=	=	-	[127]
n	J	Swine	Fat	↓=	↓=	↓=	[128]
n	F	<i>Oreochromis</i> spp.	By-product, Hydrolysate	↓=	-	-	[129]
n	J	Meat	Slaughter residues, Meal	=↑	-	-	[130]
n	J	Bone	Slaughter residues, Meal	=↑	-	-	[130]
n	J	Swine	Digestate meal	=	-	=	[36]
n	J	Cow	Digestate meal	=	-	=	[36]
n	F	Feathers poultry	Meal	↓	↓	-	[26]
n	J	Pasta	Waste	=	-	-	[131]

Note: Fish species: n: *O. niloticus*, m: *O. mosambicus*, n × m: red hybrid (*O. niloticus* × *O. mosambicus*), GIFT: *niloticus* GIFT (genetically modified). Stage: F: Fingerling, J: Juvenile. Statistically significant superior (↑), statistically significant inferior (↓), no statistically significant difference (=) compared to control, no information was found in the corresponding parameter (-).

Regarding growth, the most frequently evaluated plants were *H. annuus*, *L. usitatissimum*, and *S. persica* with four research each. *M. oleifera* with three, whereas *A. membranaceus*, *C. sinensis*, *C. nucifera*, *C. longa*, *M. indica*, *O. europaea*, and *P. juliflora* with two evaluations each.

It is noteworthy that studies with seed meal of *H. annuus* in 2013 and 2016 [40,62] showed no statistically significant differences (SSD) in Weight Gain and Specific Growth Rate concerning the control diet, while in a more recent study [17] the results were statistically significant superior (SSS). Supplementation with the oil of this plant reported a statistically significant inferior Weight Gain (SSI) compared to the control [37].

Trials with the seed extract of *L. usitatissimum* registered SSS weight gains compared to the control [14], while its oil did not show SSD compared to the control in the other reviewed evaluations [39,40,62]. In addition, *S. persica* meal recorded SSS results compared to the control in some of the evaluated diets [32], while the other evaluated diets did not record SSD compared to their respective controls [31,57,58].

In all cases where *M. oleifera* meal was evaluated, it recorded SSS results to the control [28]. When used as a seed, SSS weight gain and specific growth rate compared to the control were registered, while no SSD was found in these parameters when its ground and dried leaf was used [46]. In another experiment, leaves were supplemented in different percentages (4%, 8%, and 10%), registering results in weight gain SSS compared to the control, but without SSD in specific growth rate and feed conversion ratio [29].

In the two studies reviewed which *A. membranaceus* was evaluated, SSS results were obtained compared to the control. One included polysaccharide obtained from such plants in the diet [35], and the other used a mixture of aqueous extracts from four different plants, including the plant mentioned above [74]. The ethanolic extract of *C. sinensis* applied in diets registered SSS results compared to the control [42]. However, when it was added to the diet as green tea waste, no SSD occurred with the control [71].

It is also noteworthy that in two reviewed studies where *C. nucifera* oil was added to the diets, contrasting results were registered in the control, SSS in one [16] and SSI in the other [37]. Hydrolate of *C. longa* did not register SSD related to the control when added to the diets [18]. But when supplementation with curcumin was carried out, SSS were obtained [19].

In the two studies that evaluated diets containing mango meal (*M. indica*), SSI growth results were found compared to the control in most treatments [27,44]. The *O. europaea* cake showed significantly superior results to the control, while its oil recorded SSI results [37]. *P. juliflora* meal did not show SSD results to the control in the two works where it was evaluated [55,56].

An outstanding element is that in most of the studies, the plants evaluated yielded weight gains that were not statistically significantly different from the control or higher. This suggests that there are a significant number of plant sources that deserve further exploration and may be viable alternatives to replace conventional ingredients in tilapia feed.

It is striking that a significant number of these positive results have been obtained with extracts and essential oils. This observation and the conclusions drawn by many of the researchers suggest that the improvement in weight gain rates is due to an improvement in the immune system of fish, and microbiological and antioxidant activities.

The raw material from animals with the highest number of evaluations and increasing trend was the black soldier fly, *H. illucens*, with nine mentions. It was used as meal and oil. The effect of its excrement was also evaluated in one paper. It is interesting that, in two evaluations, one made with oil and the other with meal, SSS was registered when the inclusion percentage was the lowest in the diets evaluated, but SSI when the highest inclusion percentage was evaluated [75,80]. Likewise, it showed SSI in WG and SGR in a single diet where such raw material was used as a meal [76]. Furthermore, in a single case study with different evaluated diets SSS was reported in FCR [81].

The other mentions did not show SSD. *P. vannamei*, with three mentions, had SSI [93] when used as a meal but SSS when the shell was used [94]. The other raw materials from animals most frequently evaluated in the reviewed papers are analyzed in the by-product category.

In the algae category, *A. platensis* stand out with four evaluations, showed SSS in all growth parameters for some of the diets when it was used as a meal [97,108]. In one of the works, *A. platensis* was evaluated in nanoparticle form and showed SSS in all diets [99]. As a meal, in some diets it reported SSS and SSI for the WG parameter, and SSS for SGR in others [111]. Evaluations of dried cells [107] and meal [102] of *Schizochytrium* sp. reported SSS for the WG in some of the diets evaluated.

In the fungi category, *S. cerevisiae* had nine evaluations, in which its use as an extract stands out [114,115] with SSS in all diets. Also, SSS was observed when evaluated as a meal [117,119] in all parameters for which data were reported. It should be noted that SSS was reported in all growth parameters when the supplementation with *S. cerevisiae* cell wall was used [125].

The by-products from swine were mentioned four times. In this case, the only diet that showed differences from the control was the one that used pork fat [128], having SSI in all of the evaluated parameters. Diets containing bovine meat and bone as a slaughter residue meal [130] showed SSS in the WG parameter. Diets containing poultry feather meal [26] showed SSI in the WG and SGR parameters where they were evaluated.

Within these categories, most of the algae evaluated showed promising results, while in animals, *H. illucens* and *P. vannamei* showed the best results, although somewhat contradictory results among some studies. Within fungi, there are a significant number of promising results, with *S. cerevisiae* standing out. These results contrast with those obtained by the byproducts, since only those obtained with bone and meat slaughter residues obtaining outstanding results.

2.3.2. Fatty Acids Profile

This review also analyzed the impact of diets and supplements on the fatty acid profile of fish. It should be noted that, of the 144 papers initially reviewed, the fatty acid profile was evaluated in 13.2% (19 papers). Of these, 31.6% (6 papers) only reported data on the lipid profile of the diets fed to the fish, and 68.4% (13 papers) additionally reported the profile of the fish carcass at the end of the experiment. Two of them only reported the changes in the profiles at different moments of the experiment but not regarding a control diet, so they were not considered for this analysis. Therefore, for the fatty acid profile, 11 papers were analyzed. For terrestrial plants, five papers were found (45.5% of the 11 papers). Only oils of plant origin were evaluated in these papers, as reported in Table 3. For sources from animals, algae, fungi, and by-products, six articles were reviewed (54.5% of the 11 papers), which are summarized in Table 4.

For the preparation of Tables 3 and 4, only the data of the most relevant indicators of the fatty acid profile concerning the food source were extracted. The data reported for the fish carcass were analyzed according to their impact on human food.

Table 3. Summary table of the most relevant indicators of the fatty acid profile of the fish carcass after evaluation with supplements and vegetable oil diets. Source: Own elaboration.

Plant Species	<i>H. annuus, L. usitatissimum, C. nucifera, O. europaea</i>	<i>B. napus, Salvia hispanica L.</i>	<i>H. annuus, Perilla frutescens (L.) Britton</i>	<i>H. annuus, L. usitatissimum, B. napus, C. sativum</i>	<i>Borago officinalis L., Oenothera biennis L.</i>
Raw material processing method	Oil	Oil	Oil	Oil	Oil
Fish species	n	n	GIFT	GIFT	n
Stage	J	J	-	F	-
Omega 3	-	↑	↑*	=	↓*
Omega 6	-	↑	↓*	↓*	↑*
SFA	=	↑	=	=	=
MUFA	=	↑	↓*	=	=
PUFA	=	↑	↑*	=	=
LCPUFA	↓	-	-	=	-
Omega 3	-	↑	-	=	-
Omega 6	-	↑	-	↑*	-
n3/n6	↓	↑	↑*	=	↓
Reference	[37]	[132]	[133]	[62]	[134]

Note: SFA: Saturated fatty acids, MUFA: Monounsaturated fatty acids, PUFA: Polyunsaturated fatty acid, LC: Long Chain. Fish species: n: *O. niloticus*, GIFT: *niloticus* GIFT (genetically modified). Stage: F: Fingerling, J: Juvenile. Statistically significant superior (↑), statistically significant inferior (↓), no statistically significant difference (=) compared to control, no information was found in the corresponding parameter (-). * The difference was only present in some of the diets evaluated.

The most relevant result on the fatty acid profile of the fish was obtained when the diet with *B. napus* and *S. hispanica* oil was evaluated [132]. This is the only case among those reviewed in which a statistically significant increase in all of the evaluated indicators was registered compared to the control diet. In addition, it was the only diet in which saturated fatty acids (SFA) increased significantly, contrary to the other articles in which no SSD were observed with the control [37,62,133,134]. This is important since there is a direct relationship between SFA intake and the risk of developing diseases such as diabetes in humans. Thus, FAO recommends replacing SFA with polyunsaturated fatty acids (PUFA) to reduce the risk of coronary heart disease. Moreover, replacing SFA of animal origin with monounsaturated fatty acids (MUFA) of plant origin improves insulin sensitivity and glycemic control in type 2 diabetes [135].

In some of the diets that evaluated oils from *H. annuus* and *P. frutescens* [133], a significant decrease in MUFA and a significant increase in PUFA were reported regarding to the control. Both fatty acid groups are good for human consumption, as they help reduce the risk of cardiovascular diseases and strokes. The increase in PUFA helps to reduce the

concentration of LDL (low-density lipoproteins) cholesterol and the ratio of total cholesterol to HDL (high-density lipoproteins) cholesterol [135].

On the other hand, Omega-6 was significantly inferior to the control when *H. annuus* oil was used as a supplement. Similar results were found for diets that included *L. usitatissimum*, *B. napus*, *C. sativum* [62], and *P. frutescens* [133]. When diets that included *H. annuus* and *P. frutescens* [133], and *B. napus* and *S. hispanica* [132] were evaluated, statistically superior differences to the control in the ratio of Omegas n3/n6 were reported.

Regarding the LCPUFAs, diets that included *H. annuus*, *L. usitatissimum*, *C. nufifera*, and *O. europaea* [37] showed SSI contents compared to the control, however, when *H. annuus*, *L. usitatissimum*, *B. napus*, and *C. sativum* [62] were included in the diets, they did not report SSD. These fatty acids (mainly eicosapentaenoic acid 20:5n-3, EPA. and docosahexaenoic acid 22:6n-3, DHA) when come from oily fish diets, generally do not affect the concentrations of total cholesterol [135].

Table 4. Summary table of the most relevant indicators of the fatty acid profile of the fish carcass. Source: Own elaboration.

Raw Material Origin	Algae		Animal		Fungi	
Food source	<i>Schizochytrium</i> sp.	<i>N. salina</i>	<i>Schizochytrium</i> sp.	<i>H. illucens</i>	<i>T. molitor</i>	<i>Aurantiochytrium</i> sp.
Raw material processing method	Meal	Meal	Dried whole cell	Meal	Meal	Meal
Fish species	n	n	n	n	n	GIFT
Stage	J	F	J	F	J	J
Omega 3	↑	↑*	=	↓	↓*	↑
Omega 6	=	↓*	=	=	↑	=
SFA	=	↑*	↑*	=	↓	=
MUFA	=	↑*	↓*	=	=	=
PUFA	=	-	=	=	=	↑*
LCPUFA	-	-	-	-	-	-
Omega 3	-	-	=	-	-	↑
Omega 6	-	-	↑	-	-	↓
n3/n6	↑	↑*	↓	-	↓	↑
Reference	[102]	[104]	[107]	[87]	[90]	[124]

Note: SFA: Saturated fatty acids, MUFA: Monounsaturated fatty acids, PUFA: Polyunsaturated fatty acid, LC: Long Chain. Fish species: n: *O. niloticus*, GIFT: *niloticus*—GIFT (genetically modified). Stage: F: Fingerling, J: Juvenile. Statistically significant superior (↑), statistically significant inferior (↓), no statistically significant difference (=) compared to control, no information was found about the corresponding parameter (-). * The difference was only present in some of the diets evaluated.

The most relevant result in the fatty acid profile of the fish when algae were evaluated was with the diet containing *Schizochytrium* sp. meal [102]. Through this diet, a statistically significant increase compared to the control diet was registered in the Omega 3 indicators and the n3/n6 ratio. The other parameters showed no difference compared to the control. The diet with *N. salina* [104] also reported significantly higher values in the parameters mentioned above, which also happened with SFA and MUFA for some of the evaluated diets. The risk of developing diseases such as diabetes in humans directly relates to the intake of SFA-containing foods. Therefore, replacing SFA with PUFA [135] is recommended to reduce the occurrence of arterial diseases.

In the evaluation of food source of animal origin, the diet with *H. illucens* meal [87] stands out, which showed significantly lower values in its Omega 3 concentrations compared to the control, as the only parameter in which there were statistically significant differences. Some diets that used *T. molitor* meal also reported significantly lower values of this compound compared to the control [90]. In this study, all of the diets in which this meal was evaluated had significantly low SFA values and n3/n6. However, the use of the meal significantly increased the Omega 6 levels in all diets compared to the control. The

lower SFA values obtained suggest that this dietary ingredient can potentially improve human health benefits, given the fatty acid profile of fish.

Only one case study of the fungi category showed SSD compared to the control; that is the case of *Aurantiochytrium* sp. meal [124]. In this study, some diets showed an increase in PUFA, which, as already mentioned, are beneficial to human health [135].

2.3.3. Digestibility

Digestibility is usually calculated using the Apparent Digestibility Coefficient (ADC) of mainly dry matter (Equation (4)), protein (Equation (5)), and lipids (Equation (6)). Digestibility was evaluated in 11.1% (16 documents) of the total papers included in this review. Of these, 87.4% (14 documents) evaluated digestibility by ADC. In one article, the Digestive Enzyme Activity (DEA) method was used [16]. In another article, the Digestibility Coefficient method was used by mathematical calculation using the Acid Insoluble Ash method (AIA) [33].

ADC DM: Apparent Dry Matter Digestibility (%)

$$\text{ADC DM} = 100 - 100 \left(\frac{\% \text{marker in diet}}{\% \text{marker in feces}} \right), \quad (4)$$

ADC protein: Apparent Digestibility of protein (%)

$$\text{ADC protein} = 100 - 100 \left(\left(\frac{\% \text{marker in diet}}{\% \text{marker in feces}} \right) \times \left(\frac{\% \text{protein in feces}}{\% \text{protein in diet}} \right) \right), \quad (5)$$

ADC lipid: Apparent Digestibility of lipid (%)

$$\text{ADC lipid} = 100 - 100 \left(\left(\frac{\% \text{marker in diet}}{\% \text{marker in feces}} \right) \times \left(\frac{\% \text{lipid in feces}}{\% \text{lipid in diet}} \right) \right), \quad (6)$$

For the case of terrestrial plants, digestibility was evaluated in seven papers (43.8% of the total reviewed which this parameter was evaluated). In five of the papers, it was evaluated by ADC and in four of them a comparison with a commercial diet was performed. Table 5 shows the results summarized for these four. In the fifth paper, comparisons were made between the two forms of processing (pelleting and extrusion) of supplements from *M. esculenta* scraps and hay of *Manihot glaziovii* Müll. Arg. The pelleting of *M. esculenta* from scraps of the same plant, in comparison with extrusion, was SSS for gross energy digestibility, SSI for dry matter digestibility, and no SSD for crude protein. The extrusion of *M. glaziovii* hay behaved in the same way, but in terms of gross energy and crude protein digestibility, it did not show SSD with respect to the pelleting [136].

In addition to the data reported in Table 5, in the evaluation of okara, which is a pulp formed by the insoluble fraction of the seed remaining after the production of soy milk [49], its digestibility was evaluated by ADC for lipids, and SSS values were obtained for all diets, except for the one in which 30% of dry okara was added, where no SSD were obtained. The ADC for phosphorus reported no SSD in most of the diets evaluated, SSI was recorded when the treatment with 30% dry okara was analyzed, and SSS when the diet contained 30% hydrolyzed okara.

In one of the papers reviewed, the digestibility of *C. nucifera* oil was evaluated with the DEA method, using lipase, amylase, and protease. When supplemented with 4% oil, no SSD were reported in terms of digestibility to the control, while with 2% and 3%, SSS digestibility indices compared to the control were recorded. When a concentration of 1% was used, lipase tests showed no SSD with the control, while SSS values of digestibility were found with the other enzymes [16]. The digestibility values of the diets with *T. cacao*, using the digestibility coefficient, were SSI to the control at all inclusion percentages [33].

Table 5. Summary table on digestibility assessment by Apparent Digestibility Coefficient method. Source: Own elaboration.

Raw Material Origin	Food Source	Fish Species	Stage	Raw Material Processing Method	ADC				Reference
					Dry Matter	Protein	Energy	Lipid	
Plant species	<i>G. max</i>	n	J	By-product: Okara	↓=	↓=↑	↓=	-	[49]
	<i>E. ulmoides</i> , <i>A. membranaceus</i> , <i>L. japonica</i> , <i>C. pilosula</i>	n × a	J	Extract	↑	↑	=	-	[74]
	Unknown	n × m	F	Charcoal powder	↑	↑	-	-	[70]
	<i>M. sculenta</i>	n	J	Root meal, Leaves meal	↑	↓	↑	-	[137]
Animal	<i>H. illucens</i> , <i>C. putoria</i>	n	F	Meal	=	↓=	-	↓=	[76]
	<i>G. bimaculatus</i>	n	F	Meal	-	↑	-	↑	[79]
	<i>H. illucens</i>	n × m	J	Oil	-	=	-	↓=	[80]
	<i>H. illucens</i>	n	J	Meal	-	↑	-	-	[82]
Algae	<i>Porphyra dioica</i> C. Agardh, <i>Ulva</i> spp., <i>Gracilaria vermiculophylla</i> (Ohmi) Papenfuss, <i>Sargassum muticum</i> (Yendo) Fensholt, <i>Chlorella sorokiniana</i> Shihira & R.W. Krauss	n	J	Meal	↓	↓	↓	↓=	[138]
		-	J	Meal	=	=	=	-	[139]
By-product	Poultry, Swine	n	J	Protein hydrolysates; Slaughter residues	=↑	=↑	=↑	-	[140]

Note: Fish species: n: *O. niloticus*, n × m: red hybrid (*O. niloticus* × *O. mosambicus*), n × a: *O. niloticus* × *O. aureus*. Stage: F: Fingerling, J: Juvenile. Statistically significant superior (↑), statistically significant inferior (↓), no statistically significant difference (=) compared to control, no information was found about the corresponding parameter (-).

The digestibility of food sources from animals, algae, and by-products corresponds to 62.5% of the total that evaluate it (10 articles). In one of the papers, raw materials from plants and animals were evaluated simultaneously [136]. They all evaluated digestibility by the ADC method. The comparison and analysis concerning the control are shown in Table 5. Three evaluations were found for the insect *H. illucens*. Its meal reported an ADC protein SSS compared to the control [82] while, in another work, the evaluation of the oil showed an ADC lipid SSI [80] as its inclusion percentage increased. In the third work, *H. illucens* and *C. putoria* meals were evaluated, obtaining ADC protein and ADC lipid SSI to the control. Digestibility results of soldier fly meal inclusion in diets have shown conflicting results. Of course, it is understood that evaluations differ in the level of inclusion in the diet, the rearing and feeding conditions of the fly larvae, and the experimental conditions [76]. Diets using *G. bimaculatus* had SSS in ADC protein and lipid [79]. In addition, a study was found where the ADC of meals of *N. cinerea*, *Z. morio*, *G. portentosa*, *G. assimilis*, and *T. molitor* insects were evaluated, but only compared with each other and not with a commercial control [141].

Two algae digestibility studies were reported, one using a mixture of *P. dioica*, *Ulva* spp., *G. vermiculophylla*, and *S. muticum* meals, reporting lower ADC than the control [138]. The other study used *C. sorokiniana* meal and found no SSD for any ADC [139]. In the by-product category, three studies were reported. Of these, only one made comparisons concerning commercial control. In this study, protein hydrolysates and slaughter residues from poultry and swine were used, and ADC values in dry matter, protein, and energy SSS were reported in some of the diets [140], showing a beneficial effect of the hydrolysis process for the development of fish feed. Another study evaluated slaughter residue meal from goat and sheep and reported no SSD in ADC values in pelleted diets and SSI in ADC protein in diets processed by extrusion [136]. This study and the one conducted with dry protein hydrolysate from tilapia fillet waste [129] did not perform a digestibility analysis

with respect to a control diet. For this reason, they were not considered when constructing Table 5.

In general terms, no consistent relationships were found between digestibility and fish growth rates. However, in the study where *H. illucens* meal recorded low digestibility, it coincided with the lowest growth rates compared to the other studies reviewed where this insect was evaluated.

2.3.4. Survival Rate

Survival data were reported in 55.6% (80 articles) of the total number of papers initially selected. Of these, 67 articles (83.8%) did not show SSD with respect to the control diets, while 13 articles (16.2%) did. Eight articles had SSS and three had SSI. In two of the papers reviewed, treatments with SSS mortalities and others with SSI mortalities were reported simultaneously.

For terrestrial plants, survival data were reported in 44 articles. In 37 articles, the authors found no SSD, while in seven articles differences compared to the control were found. SSS survival rates were found in five of them and SSI in the other two. Survival was also reported in 16 papers that evaluated raw materials of animal origin, 11 from algae; 10 from fungi; and 1 where a combination of terrestrial plant and fungi was used. Statistical differences in some of the diets were reported in six of the eleven papers: five papers using algae and one using animal raw materials. Findings in this regard can be seen in Table 6. Survival rate (SR) is calculated using Equation (7).

$$SR(\%) = \frac{\text{number of final survivors per tank}}{\text{initial number per tank}} \times 100, \quad (7)$$

It is noteworthy that some of the treatments where the alternative diets were evaluated, showed statistically significant increases in survival rates with respect to the control. The authors of these studies attribute this to different reasons, such as: stimulation of the production of total leukocytes, thus improving the immune system, which could have been induced by *C. longa* hydrolyte [18]; increased nutrient availability and use of food and digestive enzyme activity due to the inclusion of polysaccharides derived from *P. vera* peels [53]; improved condition and integrity of livers and lower concentration of total heterotrophic bacteria and *Pseudomonas* sp. in the intestine, possibly caused by the essential oil of *L. origanoides* [24]; presence of phytochemicals in *P. juliflora* with antioxidant activity [142] cited by [56] and antimicrobial activity [143,144] cited by [56]; possible induction of the innate response against disease caused by *Aeromonas veronii* by the presence of antioxidants in *M. nigra* syrup [47]; increase in the quality of the medium by adding *C. lentillifera* at 2% [100]; stimulation of the fish immune system by adding tilapia fillet by-product in the diet at 8% [129].

In contrast, despite the reported antioxidant capacity of *S. persica*, significantly lower survival values were reported for fish fed a diet with this plant in the presence of high zinc concentrations [31]. Also, significantly lower survival rates were obtained in some of the diets evaluated in experiments carried out with *H. brasiliensis* seed derivatives. The authors attributed these results to the presence of toxic substances, such as hydrogen cyanide and cyanogenic glucoside [145]. Significantly lower survival rates are also reported when using the meals of the algae *A. platensis* [108,111], and *C. vulgaris* [101]. No explanation for these results was found in any of the cases by the authors.

In a significant number of experiments, the results were found to be dependent on the concentrations of the ingredients in the evaluated formulations. This was expressed throughout all of the tables above, since in some cases there were two or more symbols expressing that for a certain ingredient allowed obtaining significantly lower, equal, or higher results than the control.

Table 6. Summary table of survival rate assessed by diet. Source: Own elaboration.

Raw Material Origin	Fish Species	Stage	Food Source	Raw Material Processing Method	SSD	Reference
Plant species	n	F	<i>C. longa</i>	Hydrolate	↑	[18]
	n	F	<i>L. origanoides</i>	Essential oil	↑	[24]
	n	F	<i>S. persica</i>	Derived	↓=	[31]
	n	J	<i>M. nigra</i>	Syrup	=↑	[47]
	n	J	<i>P. juliflora</i>	Meal	↑	[56]
	n	J	<i>P. vera</i>	Extract, Seed	=↑	[53]
	n × m	F	<i>Hevea brasiliensis</i> (Willd. ex A. Juss.) Müll. Arg.	Seed	↓=	[145]
Algae	n	F	<i>C. lentillifera</i>	Meal	=↑	[100]
	n	J	<i>C. vulgaris</i>	Meal	↓↑	[101]
	n × m	F	<i>A. platensis</i>	Meal	↓↑	[108]
	n × m	F	<i>A. platensis</i>	Meal	↓=	[111]
	n × m	F	<i>U. fasciata</i>	Meal	=↑	[109]
Animal	n	F	<i>Oreochromis</i> spp.	By-product; Hydrolysate	=↑	[129]

Note: Fish species: n: *O. niloticus*, n × m: red hybrid (*O. niloticus* × *O. mosambicus*). Stage: F: Fingerling, J: Juvenile. Statistically significant superior (↑), statistically significant inferior (↓), No statistically significant difference (=).

Comparing the results recorded in Tables 1 and 2 with those in Table 6, it was observed that the plants and algae that obtained outstanding results in terms of survival also presented weight gain rates equal to or higher than the control, which strengthens the conclusion that better fish health improves yields.

3. Conclusions

This systematic review shows a growing interest in research on different feed sources for tilapia and the evaluation of their effects on growth, digestibility, and product composition parameters. In recent years, the number of publications in this area has increased significantly.

O. niloticus is the most used tilapia species in the studies reported for this review. Weight gain was the most evaluated growth indicator. In more than 50% of the diets evaluated, results were found either without statistically significant differences or superior to the control. This leads to the conclusion that, most of the non-conventional sources analyzed have a positive potential impact as alternatives for producing tilapia. Among the non-conventional ingredients reviewed we found some protein sources that were used to replace fishmeal, soybean, and other protein sources. Other ingredients were used to replace conventional fat sources such as fish oil, soybean oil or corn oil, among others.

Ingredients such as essential oils or plant extracts were mainly used to improve the immune system, and to increase antimicrobial and antioxidant activities. This leads to an improvement in the weight gain and survival indexes of the fish.

As a source of non-conventional proteins, arthropods were predominant, especially black soldier fly (*H. illucens*) and white shrimp (*P. vannamei*) with 9 and 3 evaluations each, with predominant results without significant differences with respect to the control, replacing in the diets conventional ingredients such as fish meal, mainly.

The diets with canola oil (*B. napus*) and chia (*S. hispanica*), with which the fatty acid profile of the fish was evaluated, reported SSS data in all parameters of interest for this review. However, this was not the case for long-chain polyunsaturated fatty acids, where no data compared to the commercial diet were reported. Within these higher values, it was found that the proportion of SFA was also increased, which may represent a risk for the fish. In addition, given the fish's fatty acid profile, including *H. annuus* and *P. frutescens* oils in fish diets may be beneficial for human health.

Digestibility was the least evaluated parameter by the authors reported in this review. For this one, three different ways of calculation were used, and it was possible to observe that the diets with the raw materials evaluated had statistically superior values with respect

to the control. This makes the use of these food sources promising due to their higher digestibility rate compared to traditional foods.

Survival was the parameter most evaluated by the authors, reported in over 50% of the papers. No significant statistical difference was observed in more than 80% of these. Of these, more than 50% of the raw materials came from terrestrial plants. This, combined with the results of the other indices evaluated, leads to the conclusion that most of the terrestrial plants evaluated have potential benefits as alternative feed sources for tilapia, which should be further studied.

Some raw materials may pose a risk to tilapia survival. Therefore, caution in their use and further research is recommended. In this review, the plants *S. persica* and *H. brasiliensis* and the algae *A. platensis*, and *C. vulgaris* were identified in this category.

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