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REVIEW

An overview of limnological studies in Brazilian fish farms

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ABSTRACT. Considering the growth of aquaculture and its potential environmental impacts, this study aimed to evaluate the patterns and trends of research on water quality in fish farms in Brazil, focusing on environmental differences between fishponds and net cages. We conducted a bibliometric survey from the Aquatic Sciences and Fisheries Abstracts (ASFA) and Web of Science databases, using the keywords "fish farm" or "fishpond" and "monitoring" and "water quality". After screening the retrieved documents, a total of 37 original studies were selected. Publication year, locality, pond type, culture characteristics, trophic state index, and values of chemical, physical and biological variables were collected. It was observed an increasing trend in the number of studies over time, with publication peaks in 2014 and 2018. Net cages were evaluated by 60% of the published research, which included between 3 and 750 tanks per study. Fishponds were evaluated by the remaining fraction of the studies, which included from 1 to 50 tanks per study. The five regions of the country were unequally represented: Southeast (54%), Northeast (24%), South (14%), North (5%), and Midwest (3%). Forty-seven distinct variables were recorded, and the most frequent were temperature, dissolved oxygen, and ph. Significant differences were observed in total phosphorus, chlorophyll-a, and orthophosphate concentrations among different pond types, with higher values in fishponds. The findings of our study showed high potential for eutrophication in the aquaculture systems in Brazil and highlighted the urgency for an effective management of this activity in the country. Nevertheless, there is still a lack of information and studies on this topic to support informed decision-making. We also propose some general guidelines.

Keywords: Aquaculture; effluent; environmental impact; eutrophication; monitoring.

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Introduction

Aquaculture is the production of organisms that have their complete or partial life cycle dependent on water, and involves human intervention in the cultivation of these organisms to improve production processes (Cunha, 2008; Lachi & Sipaúba-Tavares, 2008). The main branches of aquaculture are the creation of fish, shrimp, frogs, mollusks, oysters, mussels, and algae (Schulter & Vieira Filho, 2017).

Fish is among the most consumed animal protein in the world, and the increase in its production is associated with population growth, urbanization, and the search for a healthier diet (Lozano, Forest, Wosgrau, Forest, & Binotto, 2014; Rodrigues et al., 2012). World aquaculture fish production grew 39% between 2015 and 2018, increasing from 36.8 to 51.3 million tons per year (Food and Agriculture Organization of the United Nations [FAO], 2020). In Brazil, fish production in 2015 was 574 thousand tons, and according to FAO, the expectation is that in 2030 the production in the country will reach the mark of 1.49 million tons, with 800 thousand tons coming from aquaculture ([FAO], 2020).

The expansion of aquaculture activities has contributed to the generation of negative impacts on natural resources (Miashiro, Lombardi, & Mercante, 2012). One of the most expressive impacts is the large volume of organic waste produced that is discharged into the environment, mostly without any treatment (Américo, Torres, Machado, & Carvalho, 2013). These impacts are intensified due to irregular or illegal practices, improper use of natural resources, and even using areas of permanent preservation for the implementation of culture tanks (Agostinho, Gomes, & Pelicice, 2007).

Studies related to the monitoring of water quality in aquaculture are essential to identify and quantify the impacts caused by these activities. Considering that factors such as the location of the production system and the type of management used can define the intensity of the impact of fish farming, monitoring studies of these systems are essential for identifying and measuring environmental changes, helping to propose management strategies that are more sustainable (Macedo & Sipaúba-Tavares, 2010). In this sense, the present study focused on evaluating some trends and patterns in research on water quality used for fish production in Brazil through a bibliometric survey of papers published in peer-reviewed journals.

Material and methods

Bibliographic research was conducted through the Aquatic Sciences and Fisheries Abstracts (ASFA) and Web of Science databases, using the following keywords: "fish farm" or "fish pond" and "monitoring" and ‘water quality’. The terms were used only in English, and we considered only research papers published in peer-reviewed journals between 2000 and 2020. The search was conducted considering the correspondence of the terms anywhere in the document.

The retrieved documents were selected if they satisfied the following criteria: (i) the main objective was related to water quality; (ii) the study evaluated fishponds or net cages; (ii) the water body were located in Brazil; and (iii) the research analyzed and reported at least one physical, chemical, or biological variable. We extracted the following information from the documents that fulfilled the criteria: title, authors, year of publication, location, number of tanks evaluated, tank characteristics, and the chemical, physical, and biological variables measured. For the latter, the minimum, average, and maximum values of each variable cited in the scientific articles were collected, when available.

The trophic state index (TSI), introduced by Carlson, modified by Toledo and adapted by Cunha, Calijuri, and Lamparelli (2013) was calculated considering the total phosphorus average concentration using the formula $TSI(TP) = 10(6-((0{,}42-0{,}36\ (lnTP))/ln2))-20)$ where TP is the total phosphorus concentration (μg L^{-1}). The trophic level was classified according to Table 1.

Table 1. Trophic State Index (TSI) and equivalence with total phosphorus (TP) concentration in reservoirs. Adapted from Cunha et al., (2013).

Trophic level	Total phosphorus (mg L^{-1})	TSI
Ultraoligotrophic	≤ 0.008	≤ 47
Oligotrophic	0.008 < TP ≤ 0.019	47 < TSI ≤ 52
Mesotrophic	0.019 < TP ≤ 0.052	52 < TSI ≤ 59
Eutrophic	0.052 < TP ≤ 0.120	59 < TSI ≤ 63
Supereutrophic	0.120 < TP ≤ 0.233	63 < TSI ≤ 67
Hypereutrophic	> 0.233	> 67

A descriptive analysis was carried out, and environmental variable differences between fishponds and net cages were assessed through the Mann-Whitney test because the normality assumption was rejected for most variables. Four articles were excluded from these analyses due to elevated numbers of net cages (> 240) which would otherwise have introduced bias. The full information extracted from each selected study can be seen in the supplementary material in Teixeira, Barros, and Pujoni (2024). These nonparametric tests provide preliminary insights into tank type differences but do not account for random effects. Values reported by review papers (i.e., meta-analysis) were not included. To rigorously evaluate the impact of tank type (i.e., fishpond or net cage) and construct confidence intervals, firstly the standard deviation for each variable for each study was estimated using Wan, Wang, Liu, and Tong (2014)'s method, based on sample mean, minimum, and maximum values. Then we performed random effects type test employing inverse variance method to compare overall means between fishponds and net cages (Viechtbauer, 2010). For variables with asymmetric distributions, the tests were carried out using log transformed means, while for variables with well-behaved distributions, the tests were conducted without any transformation. All plots and analyses were performed in R software, and a significance level of 5% was assumed.

Results

The first survey yielded 1310 research articles from the Web of Science and 232 from ASFA. After applying the exclusion criteria, 37 research papers were selected for the next step. From this total, 15 papers were conducted in the fishponds (FP) and 22 in the net cages (NC) (Teixeira, Barros & Pujoni, 2024).

Scientific production on fish farming in Brazil

The highest number of articles was published in 2014 (7) and 2018 (6). No papers were published between 2000 and 2003, and in 2006. From 2007 to 2020, at least one paper was published each year (Figure 1).

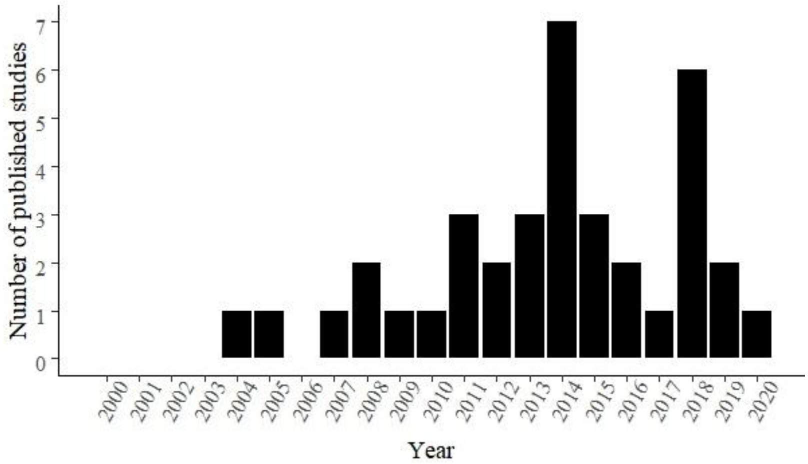

Figure 1. Number of articles published between 2000 and 2020 on water quality in fish farming in Brazil.

During the evaluated period, there were studies from the five geographic regions of Brazil, although the distribution was highly skewed. The southeast region accounted for over half of the studies (54%), with São Paulo state alone being responsible for 41% (15) of the 37 research papers. Espírito Santo and Rio de Janeiro each produced two studies, and only one was from Minas Gerais. The northeastern region contributed 24% of the publications and was represented by the states of Ceará, Pernambuco, and Rio Grande do Norte, with two publications each. Sergipe, Paraíba, and Piauí, each were responsible for one article. The states of Paraná (4) and Santa Catarina (1) were the representatives of the Southern region, accounting for 14% of the studies. Only two articles covered environments in the Northern region, specifically in the states of Rondônia and Tocantins, and just one study was conducted in Mato Grosso state, in the Midwestern region.

Most of the studies (43%) investigated up to 10 tanks. The studies with more than 200 tanks occurred only for net cages. Furthermore, four articles lacked information on the number of tanks in their study description (Figure 2).

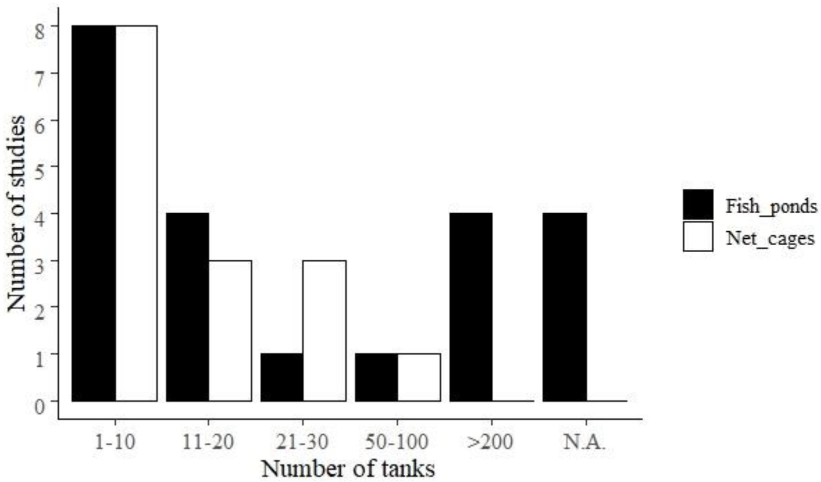

Figure 2. Number of studies in relation to the number of tanks per study. NA = not available.

A total of 47 variables were cataloged in the 37 studies, and the most frequent were water temperature (100%), pH (95%), orthophosphate concentration (95%), nursery size (81%), total phosphorus (78%), electrical conductivity (65%), chlorophyll-a (59%), total ammonia (46%), nitrate-NO_3 (46%), dissolved oxygen (46%), trophic state index (43%), density of fish, total nitrogen, total solids, and Secchi depth (all four with a frequency of 41%) (Table 2).

Table 2. Number of studies surveyed between 2000 and 2020, total number of tanks covered, and minimum and maximum values for the variables considered for the fishpond and net cage types tanks. X – Test not performed due to low sample size.

Variables	Fishpond			Net cages			Mann-Whitney
	Number of studies	Number of tanks	Average	Number of studies	Number of tanks	Average	p-value
Ammonia nitrogen (mg L^{-1})	1	6	0.25	3	32	0.235	X
Ammonium ion (µg L^{-1})	4	76	158.05	3	27	72.3	X
Bicarbonate ion (mg L^{-1})	1	4	38.6				X
Biological oxygen demand (mg L^{-1})	4	77	1.498	2	0	6.25	X
Bloom occurrence	15	204					X
Carbon dioxide (mg L^{-1})	1	9	7.5	2	13	7.4	X
Chemical oxygen demand (mg L^{-1})	1	50	25.6				X
Chlorophyll-a (µg L^{-1})	7	80	90.486	12	67	8.795	0.0052
Color (CU)	1	22	11				X
Density of fish (m^3)	15	204	23.538	18	210	89.315	X
Dissolved oxygen (mg L^{-1})	14	198	5.539	17	206	6.637	0.0707
Dissolved silicate (mg L^{-1})							X
Dominant phytoplanktonic group	15	204					X
Dominant zooplanktonic group	15	204		18	210		X
Electrical conductivity (µS cm^{-1})	8	87	77.188	13	102	64.005	0.4558
Escherichia coli (%)							X
Fecal *Streptococcus* (MPN 100 mL^{-1})							X
Hardness (mg L^{-1})	4	21	23.4	3	87	31.733	X
Inorganic nitrogen (mg L^{-1})	1	6	0.45	1	30	27.1	X
Nitrate (mg L^{-1})	9	147	0.995	3	32	2.695	X
Nitrite (mg L^{-1})	10	139	0.215	6	45	0.407	1
Organic nitrogen (mg L^{-1})	1	2	0.95				X
Orthophosphate concentration (mg L^{-1})	7	95	1.575	9	86	0.025	0.01
Outflow of water (m^3/s)	15	204	411,733	18	210	414,867	X
Oxygen saturation (%)	2	7	147.85	3	4	89.067	X
pH	14	198	6.921	17	206	7.152	0.1287
Phenol (mg L^{-1})	1	50	0.085				X
Pheophytin (mg L^{-1})	1	2	4.7				X
Phycocyanin (mg L^{-1})				1	3	0.001	X
Phytoplankton density (individual mL^{-1})	15	204	36889.5	18	210	71125	X
Presence of cyanobacteria	15	204		18	210		X
Residence time (day)	15	204	8.625	18	210	30.075	X
Salinity (ppt)				2	4	18.22	X
Secchi depth (cm)	5	62	55.2	7	57	285.557	0.0176
Sulfate (mg L^{-1})	1	50	8.7				X
Suspended inorganic matter (mg L^{-1})	1	2	2.4				X
Suspended organic matter (mg L^{-1})	2	3	5.45				X
Temperature (°C)	15	204	25.197	18	210	26.217	0.3952
Thermotolerant coliforms (MPN 100 mL^{-1})	1	30	25705				X
Total alkalinity (mg L^{-1})	6	92	38.18	5	122	49.04	0.583
Total ammonia (µg L^{-1})	7	102	292.37	8	116	111.64	0.1645
Total coliforms (MPN 100 mL^{-1})							X
Total nitrogen (mg L^{-1})	5	55	1.898	8	70	1.588	0.8833
Total phosphorus (µg L^{-1})	10	95	111.501	16	197	60.919	0.0163
Total solids (mg L^{-1})	9	113	76.154	3	32	29.638	X
Trophic State Index	15	204					X
Turbidity (NTU)	6	102	32.2	7	88	12.386	0.1014

Among the variables considered, 34 were common between studies in both tank types. The variables bicarbonate ion, color, phenol, pheophytin, sulfate, dissolved organic carbon, suspended organic, and inorganic matter were exclusive to FP studies. Conversely, the variables salinity, phycocyanin, dissolved silicate and occurrence of total and thermotolerant coliforms, fecal streptococci, and *Escherichia coli* were measured only in studies performed in NC. It was possible to evaluate differences between tank types for 12 variables. Significant differences were observed for total phosphorus, orthophosphate, chlorophyll-a, and Secchi depth, with FP generally showing lower value for the latter and higher values for the other variables.

Differences in overall means between tank types

Considering the random effects test with the inverse variance method, it was possible to evaluate the differences for 15 variables. Here we include only plots with significant differences (Figure 3), while the others are available in the supplementary material (Teixeira, Barros, & Pujoni, 2024). Significant differences were found for total phosphorus, chlorophyll-a, total solids and Secchi depth, with FP typically exhibiting lower Secchi depth and higher values for the other variables. The 95% confidence interval analysis reveals greater variability in FP, possibly due to its smaller sample size compared to NC. No differences were observed for turbidity, dissolved oxygen, nitrite, nitrate, total ammonium, total nitrogen, orthophosphate, total alkalinity, temperature, pH, and electrical conductivity (Teixeira, Barros, & Pujoni, 2024).

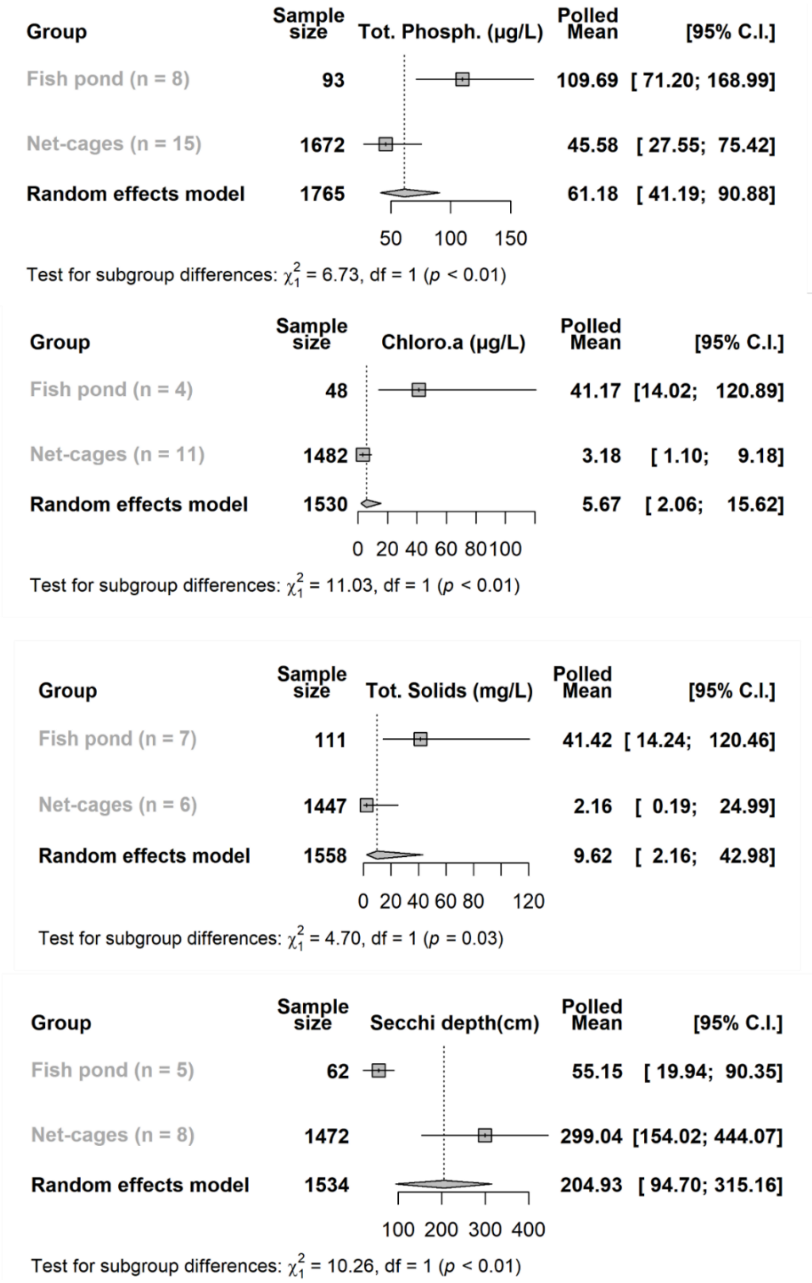

Figure 3. Comparative analysis of average of total phosphorus, chlorophyll-a, total solids and Secchi depth between Fishponds and Net Cages. Each square denotes the mean value of the respective group, and the error bars illustrate the respective 95% confidence interval. Additionally, the diamond symbolizes the overall mean, considering both groups.

In FP, ten studies presented results of parameters indicating the trophic state, and the tanks were qualified as mesotrophic (6 studies) or eutrophic (4 studies). Nineteen studies performed in NC presented the necessary information for calculating the TSI, and the results covered a wider range of trophic conditions: ultraoligotrophic (1 study), oligotrophic (6 studies), mesotrophic (8 studies), and eutrophic (4 studies) (Table 3).

Table 3. Trophic level indicators observed for fishponds and net cages. The study identification number refers to the supplementary material (see Teixeira, Barros, & Pujoni, 2024).

Fishpond				Net Cages			
Study identification	TP (μg L^{-1})	TSI (TP)	Trophic level	Study identification	TP (μg L^{-1})	TSI (TP)	Trophic level
1	112.55	58.47	Mesotrophic	3	30.1	51.62	Oligotrophic
2	49.06	54.16	Mesotrophic	7	15	48.01	Oligotrophic
5	40	53.1	Mesotrophic	9	7	44.05	Ultraoligotrophic
6	163.4	60.41	Eutrophic	10	20	49.5	Oligotrophic
8	174.6	60.75	Eutrophic	13	41.9	53.34	Mesotrophic
12	83.5	56.92	Mesotrophic	15	215.3	61.84	Eutrophic
16	67.3	55.8	Mesotrophic	17	201	61.48	Eutrophic
18	55	54.75	Mesotrophic	19	40	53.1	Mesotrophic
20	213.3	61.79	Eutrophic	21	86.4	57.1	Mesotrophic
33	156.3	60.18	Eutrophic	22	175	60.77	Eutrophic
				23	40	53.1	Mesotrophic
				24	18.8	49.18	Oligotrophic
				25	72	56.15	Mesotrophic
				26	40.3	53.14	Mesotrophic
				27	20.6	49.65	Oligotrophic
				32	29.6	51.54	Oligotrophic
				34	38.9	52.95	Mesotrophic
				36	37	52.69	Mesotrophic
				37	175	60.77	Eutrophic

Discussion

Our findings indicate that fishponds (FP) are more susceptible to eutrophication than net cages (NC), as evidenced by the higher total phosphorus and chlorophyll-a levels, which exceed the thresholds set by Brazilian legislation (Brasil, 2005). This outcome may be primarily attributed to morphological differences since FP are generally shallower and have higher residence time. According to Rosini, Tucci, Carmo, and Barros (2014), residence time and water flow rate are the main factors that determine the impacts of fish farming on net cages water quality. Nevertheless, we are aware that other factors, particularly those related to management, such as stocking density, daily feeding rate, food quality, and carrying capacity also play a big role in determining the final trophic state of the water body (Cruz, Barbosa, Rodrigues, Lima, & Ceballos, 2013; Torres et al., 2017).

It was observed an increase in the number of studies on water quality in aquaculture in Brazil. However, the number of published papers is still incipient concerning the importance of fish farming in the country, reinforcing the need for more studies in this regard. There is a huge lack of representativeness since most of the states were represented by few studies (i.e., two or less). This bias is more associated with the location of the main scientific clusters in the country, rather than the installed capacity, despite the Southern region is the leader in fish farming in Brazil, being a precursor of the activity in the country, followed by the Southeast, Northeast, Midwest, and North regions (Schulter & Vieira Filho, 2017).

Regarding the measured physical and chemical variables, it was noticed that temperature and alkalinity remained within the range indicated as ideal for the growth and development of fish (Faria, Morais, Soranna, & Sallum, 2013). The lowest temperatures occurred in trout ponds, due to the recommended temperature limit of 10 to 20 ºC (Tabata & Portz, 2004, apud Skoronski et al., 2018). The highest alkalinity value (94 mg L^{-1}) occurred in FP located in a karstic region, indicating the influence of local geological characteristics on water quality (Torres et al., 2017). The average pH values were close to neutral and within the limits of 6 to 9 established by the resolution CONAMA 357/2005 for class 2 waters (Brasil, 2005). Some values below 5 mg L^{-1} of DO, in disagreement with the current legislation (Brasil, 2005), were reported in both types of tanks. A great variation in DO concentrations in the studies performed in FP, suggest the influence of flow rate and residence time on this parameter. Regarding nitrogen compounds, some values were found to surpass the legal limits. In general, nitrite concentrations were low, however, there were reports higher than the limit of 1 mg L^{-1}, established by CONAMA resolution 357/2005 (Brasil, 2005). In the studies where these occurrences were verified, the high values were attributed to low water flow (Lachi et al., 2008; Lima, de Oliveira, de Araújo Filho, de Seixas Santos, & Pereira, 2008). High ammonia concentrations (> 60 μg L^{-1}) have also been reported in both types of ponds, especially in the FP. Recommended ammonia concentration for fish production should be below 50 µg L^{-1}, and levels above 60 µg L^{-1} can lead to up to a 5% reduction in the growth of juveniles (Kubitza, 1998; Frances, Nowak, & Allan, 2000). The food supply during the fattening period can interfere with the sudden variation of total nitrogen (Abimorad et al., 2009). This may explain the concentrations of total nitrogen (NT) higher than the limit of 1.27 mg L^{-1} established by CONAMA resolution 357/2005 (Brasil, 2005).

Although it is considered an important variable for determining the water quality, the phytoplankton density was considered in only seven research papers, with four of them indicating high densities (> 50000 ind mL^{-1}) and three pointing out the predominance of cyanobacteria. We also highlight the absence of important sanitary parameters such as the occurrence of total and thermotolerant coliforms, fecal streptococci, and *Escherichia coli* in the NC tanks. The need for greater vigilance in the tilapia production chain was highlighted by (Ferreira et al., 2021), after verifying high rates (> 50%) of contamination by microorganisms in fish and ice samples collected in commercial establishments in the Brazilian Federal District. The growth of these microorganisms occurs during the production process, due to an excess of organic matter resulting from the decomposition of dead animals or food detritus. (Helmi et al., 2020). However, we know that the measurement of these variables is still very time consuming and expensive, so it is essential to develop simpler, faster, and more robust methodologies to evaluate this important parameter.

Our study also reported the most frequently measured variables in both types of tanks and made evident a certain lack of standardization, since only the water temperature had been measured in all 37 studies. We believe that the establishment of a minimum mandatory protocol would be of major help to facilitate comparison between studies. We suggest that this protocol should include variables that are easy to measure and are good metrics to evaluate water quality. Suggested candidates are total phosphorus, pH, dissolved oxygen, Secchi depth, turbidity, and electrical conductivity. Along with defining a minimum set of parameters, we also suggest standardizing sampling methodologies. For nutrient concentrations, we recommend collecting at least three samples (triplicates) in different regions of the water body, ideally covering both horizontal and vertical dimensions or at least the most variable areas. If separate measurements of each triplicate is not feasible, a composite sample from the mixed triplicates should be analyzed. For the case of physical and chemical variables, usually measured with a multiparametric probes, measurement in at least three distinct regions of the tank is recommended, considering both horizontal and vertical dimensions, and reporting either separated measured values or an average. It is crucial to detail this methodology, clarifying that reported values are averages, not single measurements, and including the number of measurements used for these averages. In addition to tank type and size, reporting the geographic coordinates of the sampling site, the date and time of sampling, quantification methods, and brand of devices used is essential. With this simple protocol, we aim to reduce the impact of random noise and discrepant measurements on our understanding of these systems, making it possible to conduct systematic reviews and meta-analysis studies.

We would like to emphasize that the intention of this study was not to perform an exhaustive search on all the studies about water quality conducted in fishponds in Brazil. Although we chose two well-recognized databases, there are still other databases to be explored. In addition, we included only papers published in scientific journals. Nonetheless, this survey enabled us to obtain a clear overview of various methodologies applied, and average values from some important variables, also highlighting the lack of standardization in sampling and analysis methods.

Conclusion

The data collected point to a greater fragility of the fishpond systems to eutrophication. Furthermore, expanding research on fish farming ecosystems is crucial for defining more effective management strategies to maintain water quality, as well as conducting experimental studies to improve management methods and training of fish farmers. Such efforts are essential for implementing more sustainably measures.

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