Systematic Review of Best Management Practice Implementation for Agricultural Phosphorus Management in Florida: A 30-Year Overview

Review

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Highlights

- BMPs have been proven to be efficient in managing P loads in Florida.
- BMP efficiencies vary between 20% and 80%, with few higher than 50%.
- Integration of modeling strategies and field demonstrations could improve BMP efficiencies.
- Further implementation of testbeds and pilot studies could improve adoption and enhance our understanding of BMP efficiency.

Abstract. *In Florida, the implementation of best management practices (BMPs) has significantly reduced phosphorous (P) loads from the Everglades Agricultural Area (EAA) into the Lake Okeechobee watershed over the past two decades. While the removal of over 6,165 metric tons of total phosphorus entering the Everglades Protection Area is a notable achievement, some freshwater sources continue to exceed established limits (Naja et al., 2017), demanding a critical examination of BMP efficiency at managing low P concentrations. In this systematic literature review, we analyzed peer-reviewed journal manuscripts published over the past 30 years, focusing on the intersection of phosphorus management, water, Florida, and the environment. The dataset synthesized from our review provides insights into the efficiency of BMPs in terms of P management over time. Our findings show a predominant focus on stormwater treatment areas (STAs) and constructed wetlands as BMPs with demonstrated good efficiency. However, the variability in reported efficiencies underscores the complexity of phosphorus pollution and its impacts. Treatment trains ranged from 20% to 39% for the lower range of efficiency in phosphorus removal and from 60% to 79% for the higher range of efficiency. Focusing on strategies with higher P load reduction efficiencies could enhance future management strategies in Florida. Field-based pilot studies with well-defined control settings can facilitate long-term evaluations of P management programs that allow the implementation of BMPs. Similarly, the evaluation of new technologies, including materials, precision-smart practices, and the integration of modeling strategies with field-scale studies suggest a promising approach to engaging stakeholders in achieving higher BMP efficiencies. This systematic review highlights current BMP strategies that have demonstrated high P load reduction efficiency. There is a need for continued research that simultaneously assesses strategies to reduce P pollution before it forms and employs a multidimensional approach to P management. This approach should integrate multiple successful BMPs through field and modeling strategies.*

Keywords. *Agriculture, Best Management Practices (BMP), Florida, Non-point source pollutants, Phosphorus loads.*

While nutrients such as nitrogen (N) and phosphorus (P) are essential components for maintaining a healthy aquatic environment, in excess they could have adverse effects such as eutrophication. Undesirable changes in ecosystems have been attributed to the long-term disruption of nutrients into natural flows, and it is expected that water quality will continue to be a significant concern in Florida in the foreseeable future (Rice et al., 2002; Silveira et al., 2011). On a global scale, the use of P fertilizer has increased net P storage in terrestrial and freshwater ecosystems by 75% compared to preindustrial levels. A large portion of this increased P is stored in agricultural soils, escalating the risk of P transfer from soil to surface water (Bohlen and Villapando, 2011). This nutrient enrichment from fertilizer use combined with

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land use and other hydrological modifications also have the potential to affect local historic vegetation communities (Miao and Zou, 2012), nutrient cycling, potential primary productivity and species richness, accumulation of organic matter, and overall ecosystem balance (Hartshorn et al., 2016; Nesbit and Mitsch, 2018).

Nutrient loading into receiving water bodies can vary depending on multiple factors, such as rainfall patterns (depth, frequency, intensity, and duration), soil properties, fertilization, irrigation practices, crop type, and watershed management strategies being implemented (Badruzzaman et al., 2012; Carey et al., 2011; Fulton et al., 2015; Song et al., 2022). Previous studies have identified instances of higher nutrient loads following large rainfall events, particularly after prolonged dry conditions preceding the events or a seasonal flush (Nesbit and Mitsch, 2018). This first seasonal flush can significantly contribute to P loads in both stormwater runoff and receiving waters. For example, during storms, increased concentrations of phosphate and dissolved organic matter have been observed in many tributaries. This is attributed to enhanced desorption and remineralization of organic matter and nutrients, as water flows through upper soil horizons rich in organic material (Adyel et al., 2017; Trefry and Fox, 2021; Yang et al., 2021). Furthermore, climate extremes exacerbate eutrophication by increased evaporation and precipitation, solar heating, and more powerful tropical storms, leading to increased runoff and seaward transport of nutrients. In addition, this phenomenon is further enhanced by the pre-existing internal P loading (released from sediments) influencing the overall nutrient ratio of total nitrogen to total phosphorus (TP) (Rolle Longley et al., 2019; Trefry and Fox, 2021). These environmental conditions make P loads in water a significant environmental concern, as these loads can be precursors of harmful algal blooms (HABs).

While denitrification processes can facilitate the removal of N by converting nitrate to nitrous oxide gas, P exhibits a strong affinity for binding to soil organisms and particles such as clay and iron. This affinity restricts its mobility to the atmosphere (Shukla et al., 2021; Yang et al., 2021; Yu et al., 2006). Specifically, phosphate (PO_4-P) is of concern primarily for surface runoff, as it forms complexes with iron, aluminum, or calcium in the soil, depending on the soil pH (Duranceau and Biscardi, 2015; Yang et al., 2021). In the P cycle, soil sorption plays a major role, restricting P movement through the soil matrix. Coupled with the absence of significant gaseous pathways, this can lead to substantial P accumulation with long watershed residence times, as P is released into water only when soils reach their sorption saturation level (Khare et al., 2021).

In Florida, most of the agricultural soils pose a nutrient management challenge due to their low nutrient retention capacity, low organic matter (OM), and hydrological characteristics. Agricultural crop production, low-efficiency fertilizer management practices, and weather extremes can result in runoff and leaching, especially when applied with water-soluble P fertilizers (Bhadha, 2012; Yang et al., 2007; Yang et al., 2008).

According to Brown et al. (2018), in 2018, 157 lakes in Florida (totaling about $1.42*10^5$ hm^2) were nutrient impaired, and about 16 lakes (totaling $1.59*10^5$ hm^2) that were currently not impaired were degrading. Land-based restoration efforts surrounding some of those lakes are challenging as these surrounding lands have urban developments (Nair et al., 2007), resulting in an alteration of the time, distribution, and volume of runoff reaching South Florida wetlands (Julian, 2017). Both agricultural and urban development continue to be a challenge for the sustainability of aquatic ecosystems and population well-being (Hartshorn et al., 2016).

To face these challenges, state agencies have been working on the implementation of management plans that maintain watersheds below the Total Maximum Daily Load (TMDL) thresholds. These TMDLs are defined as the maximum amount of a pollutant a water body can assimilate without exceeding water quality standards (Fulton and Smith, 2008). Various local, state, and federal initiatives have been implemented to reduce P loads from agricultural and other practices (Chen et al., 2006; Ji and Jin, 2016). In 2000, the Florida Legislature passed the Lake Okeechobee Protection Act (LOPA), directing state agencies to implement a comprehensive long-term program to restore and protect Lake Okeechobee and its downstream receiving waters. This LOPA mandated that the lake's TMDL be met by 1 January 2015, with a new framework for Florida's TMDL prioritization that focuses on the watershed scale (Bubel et al., 2022). In the case of P, the criterion in paragraph 62-302.530(47)(b), F.A.C., mandates that concentrations of more than 0.1 mg/L are considered high for freshwater bodies and detrimental to aquatic ecosystems in South Florida (Lang et al., 2010).

The economic impact of eutrophication is significant, costing the United States up to \$4.3 billion a year in N and P management (Khare et al., 2019; Shukla et al., 2017a). For instance, in Florida, a study by Song and Pang (2021) showed that water pollution in the Lake Okeechobee basin incurred total economic losses near US \$1 million in 2018. Hoagland et al. (2009) assessed the economic impact of illness, particularly respiratory conditions, linked to HABs resulting from eutrophication along the Florida Gulf Coast, with estimates ranging from US \$0.5 to \$4 million. Dunne et al. (2015) reported a median cost of US \$277 per kilogram for P removal in several large-scale treatment wetland systems in Florida. Similarly, in a phased assessment conducted by Khare et al. (2019), it was concluded that to achieve the Lake Okeechobee TP TMDL, basin-wide restoration strategies—an investment of approximately US \$4.26 billion-would be required.

As part of watershed management efforts aimed at P management, various strategies have been implemented. One key intervention was the construction of stormwater treatment areas (STAs), specifically designed to remove P from runoff water around the Everglades Agricultural Area (Zapata-Rios et al., 2012). These STAs, along with other BMPs, are activities of structural and non-structural nature that are considered practical and effective in enhancing the water quality of agricultural and urban discharge. BMPs are tailored to specific locations, considering multiple economic and technological factors (Khare et al., 2019; Schade-Poole and Möller, 2016). Agricultural BMPs have the potential to optimize crop nutrient management and minimize environmental impacts if there is proper design, installation, maintenance, and management. They have the potential to reduce agricultural runoff and leachate from 80 to up to 150 µg/L (as TP) in runoff water. Quantifying the nutrient reduction efficiency of these BMPs is necessary to assess their effectiveness, and this efficiency varies depending on location, input concentrations, hydraulic retention time, and the interplay of ion exchange and biological activity. While the impacts of these BMPs can generally be monitored and predicted at the source or field level, it is hard to extrapolate their effectiveness at the basin level (Entry and Gottlieb, 2014; Khare et al., 2020; O'Reilly et al., 2012; Shukla et al., 2011). Understanding the efficiency of BMPs and other water quality improvement measures in reducing P removal is essential for the development of strategies that optimize nutrient removal around the Lake Okeechobee watershed and other freshwater sources in the US (Khare et al., 2021; Schade-Poole and Möller, 2016).

Despite these watershed management efforts, they have proven to be insufficient. In the year 2000, Florida ranked among the top quartile of regions worldwide in terms of P surplus resulting from fertilizer applications, with a surplus ranging from 13 to 840 kg of P/ha/yr. (Hendricks et al., 2014). With a projected 2.4-fold increase in global P fertilization by 2050 (Hendricks et al., 2014), it is anticipated that this surplus will continue to rise. Consequently, there is a pressing need to establish metrics to assess the efficiency and techno-economic feasibility of these management plans aimed at reducing the continuous surplus of P. Sustainable solutions are imperative to uphold and enhance P retention efficiencies, enabling the reduction of loads in water bodies such as the Lake Okeechobee watershed.

BMPs in Florida

In Florida, BMPs are defined as "practices based on research, field testing, and expert review determined to be the most effective and practicable on-location means, including economic and technological considerations, for improving water quality in agricultural and urban discharges" (Duersch et al., 2020; Obreza and Sartain, 2010). Over the past two decades, the implementation of these BMPs has resulted in a reduction of 6,165 metric tons of P load from the Everglades Agricultural Area (EAA) to downstream ecosystems (FDEP, 2021). According to FDACS (2023), around 62% of agricultural lands are enrolled in the BMP program statewide. BMPs implemented in the Lake Okeechobee watershed include onsite retention of stormwater, fencing for filter strips, wastewater diversion away from wetlands to pastures and field crops, improved grazing practices, and improved fertilization management (Nair et al., 2007). Growers in the EAA are required to implement BMPs and conduct monitoring of daily rainfall, drainage water volume, and drainage water P concentrations (Daroub et al., 2009). These BMPs cover (1) soil testing and application of P fertilizer according to a calibrated soil test, (2) controlled P fertilizer application methods, (3) water management practices, and (4) sediment source and transport controls (Grunwald et al., 2009). Despite extensive BMP implementation, regulatory, and incentive-based programs, P loads into Lake Okeechobee continue to exceed target loads. In 2009, according to the South Florida Water Management District, the total P load to the lake was 656 metric tons, which exceeded the TMDL of 140 metric tons (Silveira et al., 2011). From the grower perspective, concerns regarding mandatory implementation of largely untested BMP strategies, uncertainty in quantifying the success or failure of farm BMP plans, and the lack of historic farm-level P load from farm drainage sources are factors that influence the stalled implementation of BMPs. In addition, P loads can be influenced by unpredictable environmental conditions and other factors beyond the BMPs themselves (Rice et al., 2002; Shukla et al., 2011). There is a pressing need for innovative metrics, methods, systems, and tools for nutrient control and management, particularly from P sources (Ryan et al., 2010). Despite growing support for the implementation of BMPs in agriculture, the effectiveness of BMPs remains uncertain. This review aims to assess peer-reviewed publications published over the last 30 years on the efficiency of BMPs in the reduction of P loads from non-point sources in Florida. The findings from this review can inform the selection of BMPs based on their efficiency and contribute to future efforts aimed at prioritizing the placement of BMPs within watershed-scale nutrient management plans. Our review contributes to identifying the geospatial distribution of the reviewed studies and uses them as a baseline to identify areas with similar environmental conditions for implementation.

Systematic Review Design

We conducted a systematic literature review (SLR) following the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA)-guided literature search method. The PRISMA 2020 is a guideline that focuses on ways in which authors can ensure the transparent and complete reporting of systematic reviews and meta-analyses (Liberati et al., 2009; Page et al., 2021). This method of study is carried out in a steady and particularized manner for article selection and screening of appropriate review articles (Jagaba et al., 2021). Figure 1 shows the research method utilized in this study for the SLR.

The search process adopted in this review focused on two (2) electronic databases, Scopus and ScienceDirect (fig. 1), which are part of Elsevier's platform. Scopus differs from ScienceDirect as it hosts Elsevier and non-Elsevier content while delivering an overview of the world's research. ScienceDirect, however, hosts the full texts of Elsevier content to obtain publications related to the review scope. The databases were selected as they included a more expanded spectrum of journals covering many documents not covered by other databases, documents with a higher impact factor, more reliable and scalable methods to extract data, and more widely used in academic research (Falagas et al., 2008; Martín-Martín et al., 2018; Visser et al., 2021; Zhu and Liu, 2020). The search criteria for this review covered the years 1995 through July 2022 and focused on identifying previously published peer-reviewed journal manuscripts. The aim of our search string is to capture all results that relate P to water and the environment in Florida. This approach allows for the gathering of a comprehensive database of references and documents linking these terms, which were subsequently filtered to specifically focus on documents where BMPs were the primary research focus. The initial search

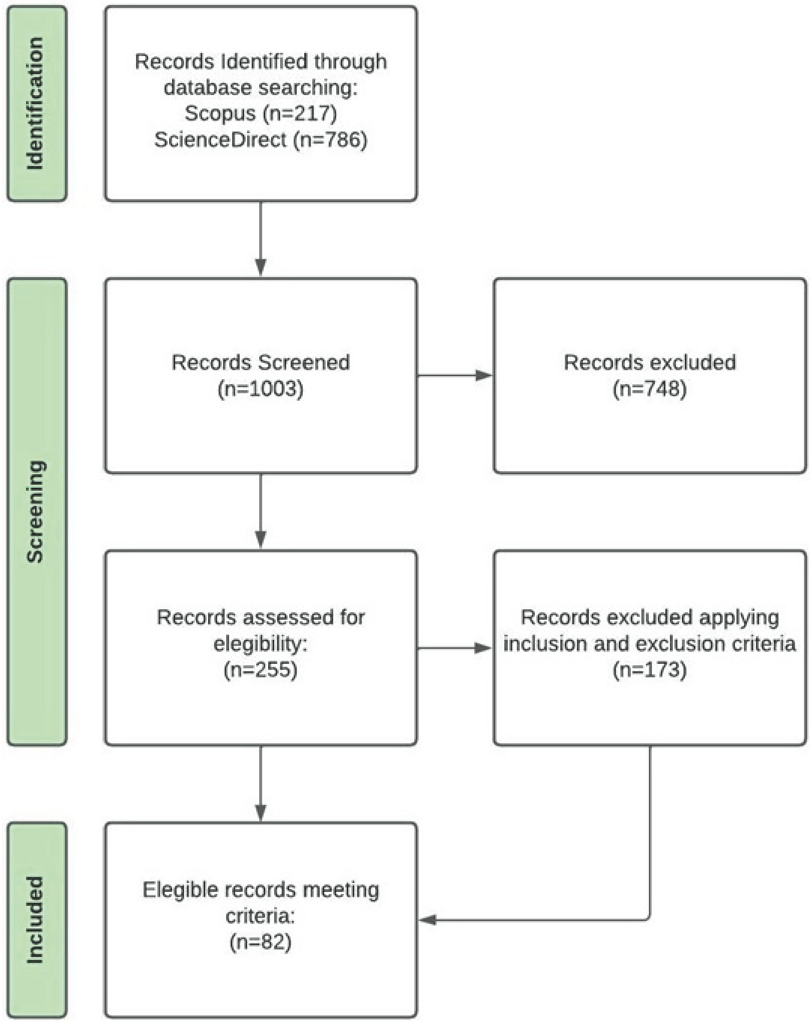


Figure 1. PRISMA 2020 flow diagram for the systematic literature review on BMPs for phosphorus management in Florida.

string used in all databases was: Florida AND Phosphorus AND Water AND Environment. The keyword BMP was not incorporated in the initial search in order to capture all P-related studies in Florida.

Screening

The initial results were screened to remove duplicates. Since two electronic databases were considered, after excluding duplicates, the remaining records were screened for relevance. Book chapters, documents without full access, dissertations, conference proceedings, and abstract-only papers were excluded. The initial screening resulted in over a thousand documents, and the resulting papers were screened following the methodology used by Page et al. (2021). The exclusion and inclusion criteria consisted of identifying the most relevant publications that assessed or implemented BMPs in Florida, with a special emphasis on articles with research methods that included a description of their contributions to BMP efficiency. Publications that included the following criteria were incorporated into this review:

- Study reports BMP efficiency values.
- Study published between January 1995 and July 2022.
- Study is conducted in the state of Florida.
- Study mentions phosphorus (total, ortho, etc.) and BMPs for phosphorus management in agricultural (non-point source) areas.

Publications with the following criteria were excluded from this review:

- Books and presentations.
- Reports from state agencies.
- Nitrogen, potassium, and other nutrients are the main study objectives.
- Study not available as open access.

A total of 255 papers were identified from the databases. After applying the inclusion and exclusion criteria, 81 papers were selected for this systematic review from the PRISMA-guided literature search. The identified papers were reviewed in detail, and their findings were synthesized, organized, and presented. For this, a dataset in Microsoft Excel was created, and results were classified within a set of common variables extracted from the selected papers. These variables included: (1) type of P studied, (2) type of BMP, (3) percentage of P management/reduction efficiency, (4) type of study: field, laboratory, or simulation/model and their respective methods, (5) years of data available for BMP assessment, (6) year of publication, (7) location of the study, (8) duration of the study, and (9) main findings.

We assessed the dataset developed in Microsoft Excel using the R programming language's descriptive statistics functions. Our analysis focused on examining various aspects, including the variables selected, the proportion of papers reporting within each variable, as well as the range and mean values associated with the variables. In addition to the analysis previously mentioned, an in-depth analysis was carried out evaluating the effects of five main variables, including percentage of P management/reduction efficiency, research methods, year of publication, study duration, and research gaps. The study location was used to develop data visualization maps using ArcGIS Pro 3.1.0.

PRISMA Analysis Results

Geospatial Distribution and Temporal Trends of BMP Research for Phosphorus Management in Florida

Figure 2 shows the geographical distribution of peer-reviewed studies related to BMP for P management in Florida. Hotspot areas, especially around Lake Okeechobee, a key region of the greater Everglades ecosystem restoration and sustainability efforts in South Florida (Khare et al., 2019), the Southeast of the EAA, and the Everglades National Park, underscore the primary regions of research focus across the state. Additionally, locations in East and Central Florida are discernible but not as pronounced as the EAA. Six studies were excluded from this map because they were either review studies or lacked descriptions of the study area. This geographical categorization could facilitate the identification of spatial patterns in water quality and soils, assisting BMP implementation in areas with comparable conditions (Caccia and Boyer, 2005). Documenting these regional spatial distributions provides baseline data that can be streamlined for optimizing BMP management (Rivero et al., 2007b). Furthermore, watershed-scale quantification of nutrient dynamics, including legacy nutrients, is crucial for developing effective nutrient management strategies to improve water quality (Khare et al., 2021).

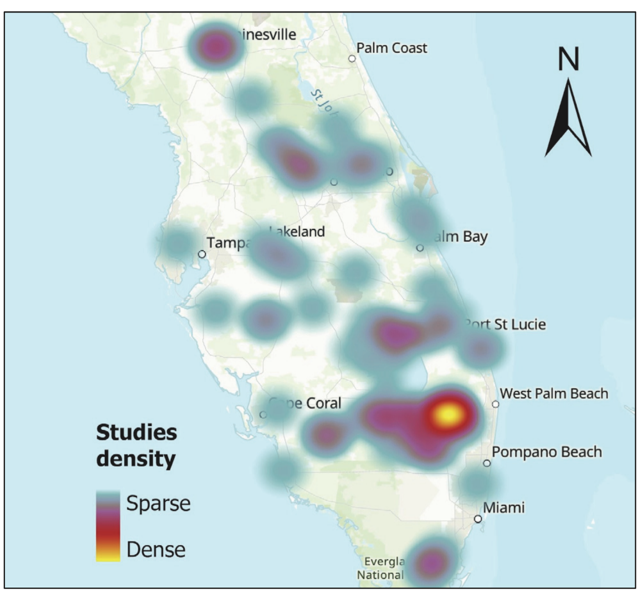


Figure 2. Heatmap of phosphorous BMP studies in Florida based on a selection of 75 documents across the last 30 years.

Figure 3 provides a summary of BMP-related studies over the past 30 years, with the color distribution indicating the volume of data used per study, ranging from months to over 30 years. Results show a peak in publications in 2012, with a notable increasing trend between 1995 and 2012. From 2014 to 2022, publications remained frequent, with 2013 being an exception, possibly due to decreased university funding (Mitchell, 2013) and extreme weather patterns. Most papers (93.8%) were published after 2006, indicating a significant increase in P-related BMP research during the last two decades. These findings coincide with the possible effects of the hurricane season after 2005, with three major hurricanes landing in Florida (Katrina, Deniss, and Wilma) and the increase in historic temperatures after 2006. Data availability analysis revealed that 60.7% of papers had less than four years of data, indicating a reliance on short-term studies. In contrast, 13.2% had over 20 years of data, with larger datasets emerging after 2010, particularly in 2017 and 2021. Post-2016, studies with more than five years of data became more frequent, suggesting a shift towards longer-term datasets. In the context of P management, this could allow for a more comprehensive understanding of P dynamics in agricultural watersheds.

BMP Efficiency in Managing Phosphorus: Categorization, Trends, and Implications for Hydrological Studies in Florida

To describe the relevance of best management practices (BMPs) in managing P, we categorized studies based on the type and frequency of BMPs and reported efficiency values (fig. 4). Most studies focused on evaluating constructed wetlands, a combination of multiple BMPs or treatment trains, stormwater treatment areas (STAs) (Pietro and Ivanoff, 2015; Shukla et al., 2017a; Zhao and Piccone, 2020), and water management practices, including irrigation management and data-based approaches (Song et al., 2022), among others. Vegetation buffers and other vegetation-related treatments (Pietro and Ivanoff, 2015; Zhao and Piccone, 2020), amendments (Dierberg et al., 2017; Duranceau and Biscardi, 2015), and approaches for nutrient tracking (Hendricks et al., 2014; Obreza and Sartain, 2010; Rice et al., 2002) were also frequently studied. On the other hand, BMPs such as the use of ditch fencing or culvert cattle crossing, vertical biofilters or buffers, and polymers were less explored. Surprisingly, BMPs such as fertilizer management and confinement facilities had lower frequencies. However, the category of treatment train included fertilizer management, although not as an individual solution for non-point source pollutants (Daroub et al., 2009; Lang et al., 2010; Oladeji et al., 2007). Other frequent combined BMPs included vegetative BMPs added alongside adsorptive material treatments (Kuo and Muñoz-Carpena, 2009; Pietro et al., 2006; Schaus et al., 2010), calibrated soil tests combined with irrigation management (Daroub et al., 2009; Rice et al., 2002), and nutrient application control alongside improved water management infrastructure (Lang et al., 2010). It is important to note that this study did not include local agency reports, such as those from the Natural Resources and Conservation Service or the

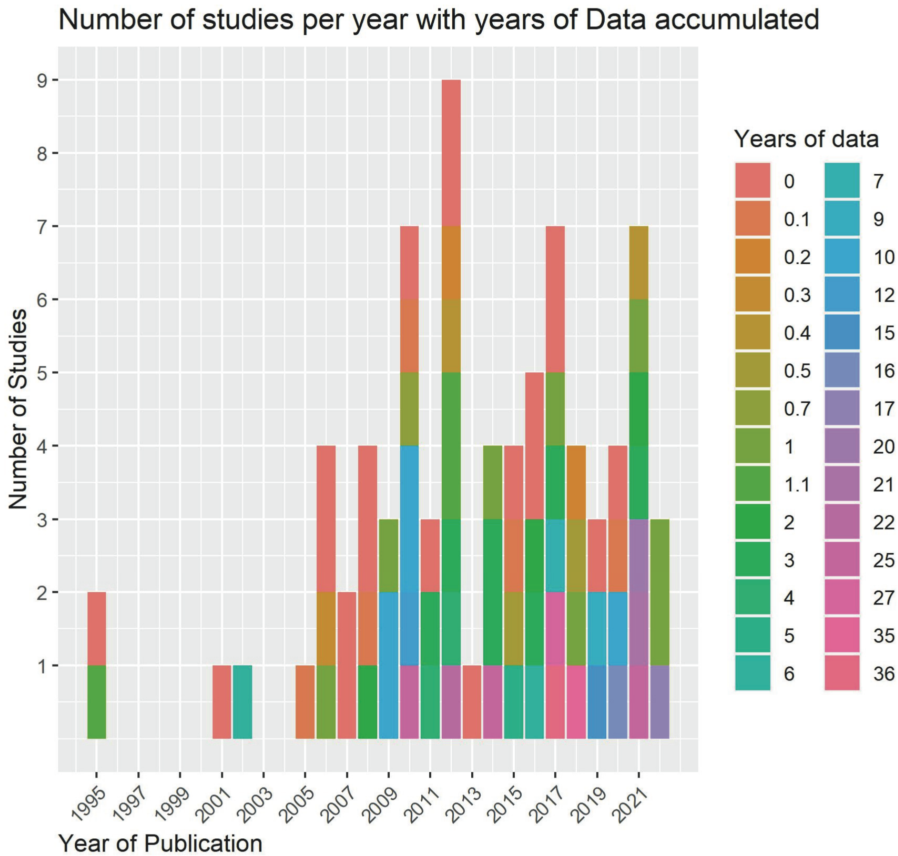


Figure 3. Relation between year of publication, duration of the study, and number of studies.

Florida Department of Agriculture and Consumer Services (FDACS, 2023). Rather, it focused on peer-reviewed documentation, which could be related to the low frequency of fertilizer management studies reported as individual BMPs in this review.

In terms of BMP efficiency (fig. 4), 57% of the studies (46) reported numerical efficiency values. Among these studies, 2% (1) reported P reduction efficiencies higher than 80%, and 19% (9) reported P reduction efficiencies between 60% and 79%, with the majority falling between 20% and 60%. 40% of studies (18) reported an efficiency range with a variation higher than 20%, such as those studies with reported efficiencies between 5% and 60%. Thus, these studies with high variation were not incorporated in figure 4, but they were used for statistical analysis in our study. Modeling studies, although not directly recognized as BMPs, were included if the scenario results provided efficiency ranges higher than 20%.

Figure 5 shows the efficiency variability of frequently implemented BMPs over the past thirty years from the 46 studies reporting efficiency values. Constructed wetlands, despite being the most studied BMP, showed a mean efficiency lower than 40%. We hypothesize that this efficiency response was influenced by extreme weather events (Nesbit and Mitsch, 2018). Table 1 provides a summary of the results from the number of studies that considered extreme conditions (including drought, wetness, El Niño-Southern Oscillation (ENSO), and hurricane periods) and land uses. As shown, only 25% of the studies included these factors when implementing or evaluating the BMPs, which could lead to differences in resulting efficiency for the BMPs. Treatment trains with BMPs Type I, II, and III as nutrient management + stormwater ponds + field chemical treatment or removal of accumulated sedimentary material + reduction in drainage pumping + water control structures (Corrales et al., 2017; Khare et al., 2019; Khare et al., 2020; Lang et al., 2010) were the second most studied and presented more variable efficiency ranges with a mean of 40%. This result is expected, as the combination of BMPs might provide multiple performance outcomes. STAs reported efficiencies ranging from 60% to 85%. Despite this effectiveness, they can have negative efficiencies due to extreme weather that could potentially turn them into P contributors (Zapata-Rios et al., 2012). Previous studies have reported that wetlands and STAs can effectively reduce P loads in surface waters, with average values of mass removal of 6.5 and 3.7 kg ac^{-1} y^{-1}, respectively (Dierberg et al., 2012; Gu and Dreschel, 2008; Nesbit and Mitsch, 2018; Pietro and Ivanoff, 2015). However, these reduction strategies are costly to implement, as mentioned by Khare et al. (2019), who estimated a cost of US$4.26 billion to achieve the TP target. The implementation of treatment train scenarios shows promise, with efficiency ranges between 5% and 75% (Brown et al., 2018; Corrales et al., 2017; Khare et al., 2019). Future evaluations should focus on the economic and technical feasibility of these treatment trains, prioritizing those with higher efficiencies and more rapid reduction outcomes. Vegetative management treatments and absorptive media (Schaus et al.,

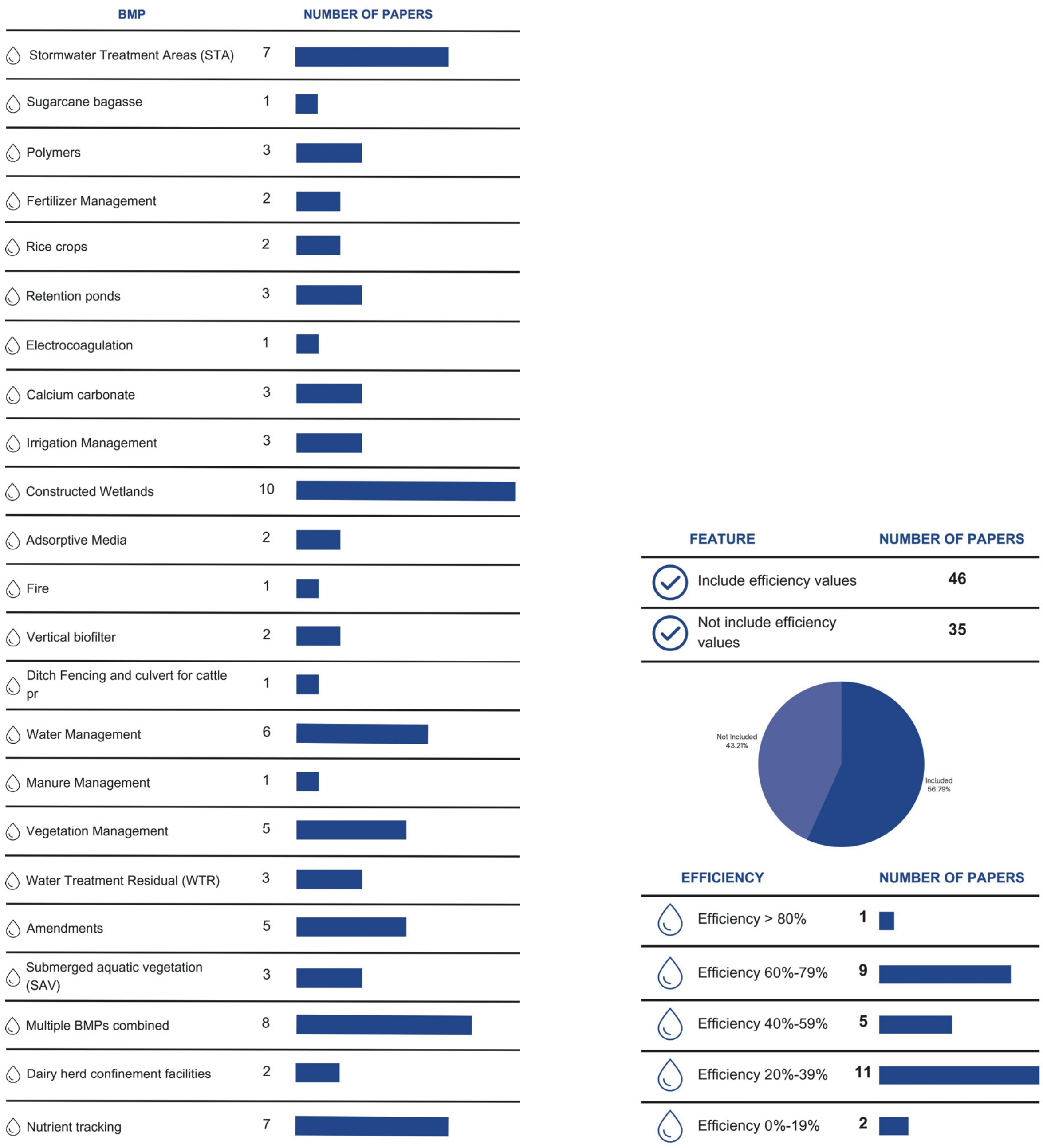


Figure 4. Frequency of BMPs reported and their efficiency ranges. Left: distribution of studies per BMP assessed. Upper right: percentage of studies reporting P load reduction efficiency. Lower right: distribution of BMP efficiency ranges from studies reported (studies reporting an efficiency range with a variation higher than 20% were not included in this figure).

2010) reported efficiencies ranging from 20% to 60% (Dierberg et al., 2017; Duranceau and Biscardi, 2015), while electrocoagulation processes (Franco et al., 2017) achieved efficiencies above 80% in controlled laboratory settings. Besides the BMPs assessed, emerging tools such as precision water and nutrient management, as well as sensor-based in-field management, are gaining relevance. These nutrient-tracking tools contribute to a better understanding of P movement across soil-water and plants, while enhancing informed nutrient management programs (Kadyampakeni et al., 2014; Obreza and Sartain, 2010; Song et al., 2022).

Figure 6 shows the relationship between study type (field, lab, or model) and BMP efficiency. Model-based studies showed the highest mean efficiency, followed by field studies and laboratory studies. However, based on the ANOVA results, the difference between studies is minimal. The Tukey HSD test corroborated that, for this review, the study type does not have a significant influence on the BMP efficiency obtained with a p-value of 0.86 and 0.98, respectively. Standard deviation results indicate the highest variability was related to field studies, followed by model-based and laboratory studies. We further assessed the relationship between study type and duration of the study (fig. 6b) and found that field and laboratory categories showed statistically similar durations, typically ranging between 0 and 5 years. Field studies tended to have outliers, with some

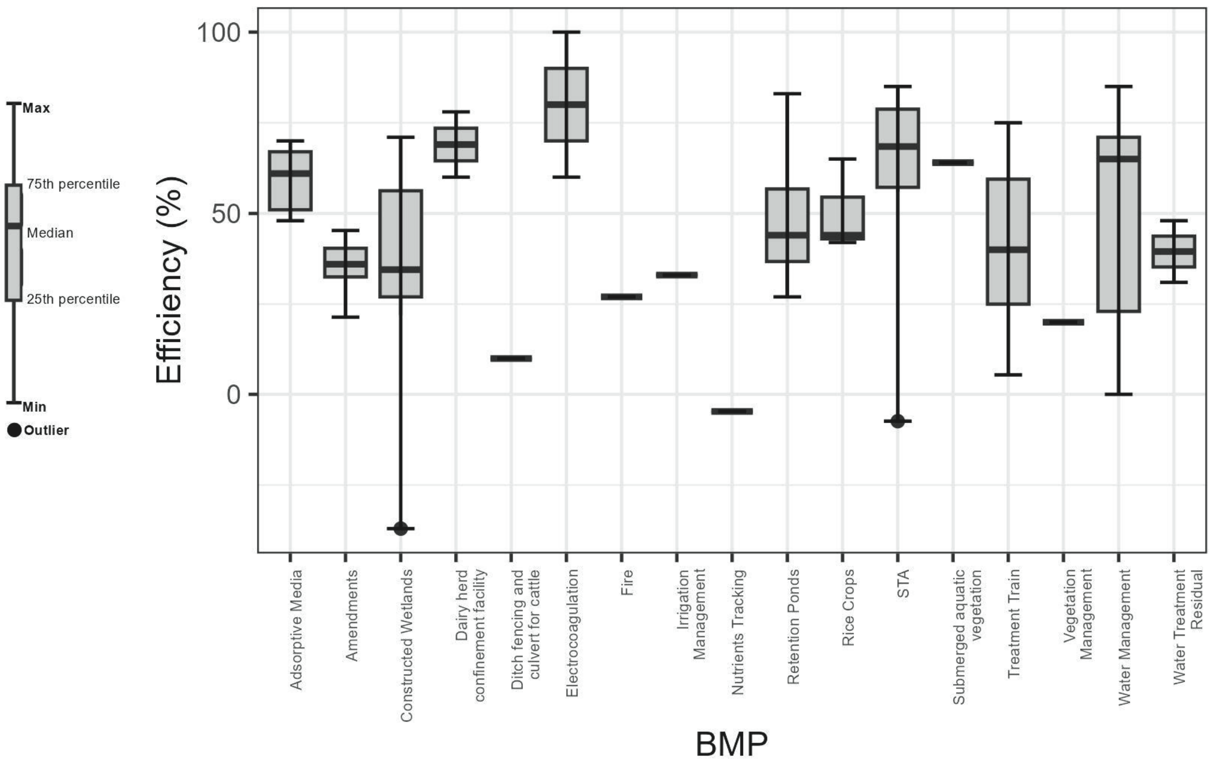
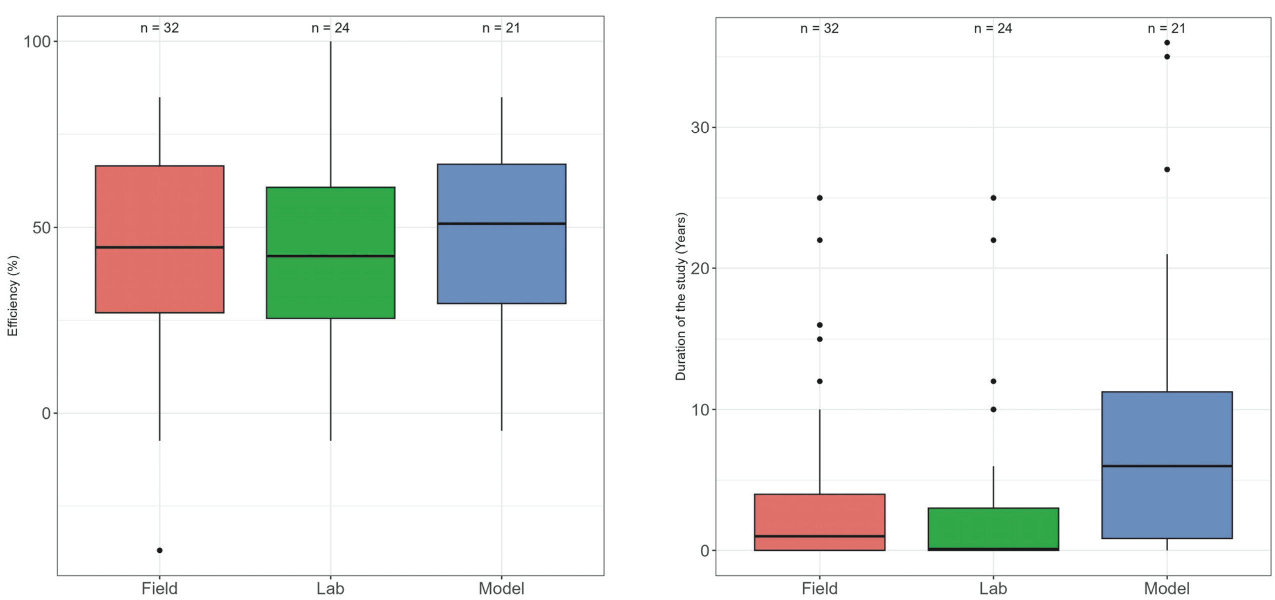


Figure 5. Distribution of efficiencies per BMPs assessed in this study.

Table 1. Frequency of land use and extreme conditions considered in the studies.

Total Number of Studies	Studies Considering Extreme Conditions	Studies Considering Land Use
81	18	20

studies extending beyond fifteen years. Model-based studies had mean study durations around five years, with higher variance, and outliers over thirty years. ANOVA and Tukey test results indicate no significant differences in BMP efficiency between laboratory and field studies or between model and field studies. However, there were statistical differences between the model and laboratory studies, with a p-value of 0.0471. The results suggest an increase in the study duration for modeling applications on average, but this does not translate to an increase in the efficiencies obtained. This could be related to the type of historical data available and the relationships between field data collection and scenario analysis from this data.



(a) (b)

Figure 6. (a) Relation between the study type and the BMP efficiency reported, and (b) Relation between the study type and study duration.

DISCUSSION

IDENTIFICATION OF RESEARCH NEEDS

Lack of Testbeds or Pilot Studies

One of the most important gaps identified in this review is the limited implementation of testbeds or pilot studies with well-defined control settings. The inclusion of such testbeds would provide valuable insights into the practical effectiveness of BMPs across different hydrological settings. As described by several authors (Xu et al., 2022; Duranceau and Biscardi, 2015; Franco et al., 2017; O'Reilly et al., 2012), future research should explore the application of materials and technologies that have demonstrated improvements in P removal in controlled environments. Scaling up these technologies to larger settings, such as pilot studies or testbeds, would offer a more comprehensive understanding of the efficiency of these BMPs in real-world conditions. For instance, Smith et al. (2014) presented a pilot-scale membrane bioreactor that showed notable improvements in P removal. This pilot had a dual purpose: first, assessing the individual physical, chemical, and biological processes that govern the effectiveness of the bioreactor within the unique environmental conditions of Florida (Xu et al., 2022; Silveira et al., 2019); and second, aiding in the anticipation of operational and design challenges, as well as assessing the adsorbent materials' lifespan (Duranceau and Biscardi, 2015; Franco et al., 2017; O'Reilly et al., 2012). Similarly, Shukla et al. (2020) evaluated P management strategies for edge-of-the-farm stormwater detention systems, showing that biomass harvesting-composting emerged as a practice with 90% greater cost-effectiveness than state-funded treatment implementation. This approach not only demonstrated significant P removal but also good feasibility given that these detention systems are located on-site. The addition of these management practices as part of the payment-for-services programs could incentivize P recycling.

Integrating Modeling and Data-Analysis Strategies

Integrating modeling strategies with field implementation, as suggested by Khare et al., 2019, offers a promising approach for increasing stakeholder adoption. This integrated approach aims to cultivate trust among stakeholders by facilitating evidence-based decision-making rooted in scientific principles, thereby enhancing our understanding of the effectiveness of BMPs. With the rise of real-time data collection and monitoring, more data is available, along with the growing popularity of machine learning and deep learning applications for more rapid decision-making. However, this increasing trend in P-BMP research using remote sensing, in-field sensors, automated sampling devices with GIS tools, and data-analysis strategies alongside physical and data-based modeling presents challenges related to model parametrization quality and the variability of monitored data frequency (Campbell et al., 1995; Chebud et al., 2012; Dierberg et al., 2012; Flaig and Reddy, 1995; Kuo and Muñoz-Carpena, 2009). To address these challenges, multiple models and simulations have been employed to gain a better understanding of the relative importance of the various processes involved in the retention of all P forms. Predictive models can also be used to improve monitoring efforts by taking advantage of existing data collected (Kuo and Muñoz-Carpena, 2009; Marois and Mitsch, 2016; Rivero et al., 2007a). Additionally, the broader application of multivariate data analysis tools such as Principal Component Analysis (PCA), nonparametric tests, and advanced statistical techniques is recommended to provide water managers with more information for guiding management plans (Daroub et al., 2009; Moncada et al., 2021). Nevertheless, these methods are not without limitations. For instance, in some cases, the estimates generated by loading and water quality models may not be applicable for time periods shorter than a year, adding challenges for analysis as these can mislead the decision-making process. Addressing these uncertainties requires the implementation of data quality assurance, control protocols, and the integration of data-based algorithms (such as machine learning) into physical models to enable more efficient BMP scenario assessment through hybrid modeling approaches (Murcia and Guzman, 2024). Understanding the data distributions, data uncertainties, and the correct interpretations of nonparametric tests is imperative to providing effective tools for BMPs that facilitate improved P removal (Fulton and Smith, 2008; Moncada et al., 2021).

Future Research in Treatment Train Assessments and Long-Term Studies

Long-term test beds, hydrologic, and water quality studies serve to strengthen the availability of field data for the implementation of modeling studies (O'Reilly et al., 2012). The complexity of P behavior in soils and freshwater environments, influenced by various factors including soil properties, P availability, and other environmental features, underscores the necessity for a comprehensive investigation. While certain methodologies demonstrate short-term efficacy in P treatment (Shukla et al., 2017b), there remains a need for further research to accurately quantify and monitor net P removal rates, comprehend floc stability, discern P sequestration dynamics, evaluate treatment performance, and assess potential ecosystem impacts over extended timeframes. Such endeavors are essential for determining the long-term sustainability of nutrient removal capabilities (Bachand et al., 2020; Pietro et al., 2006; Yang et al., 2008).

Because the implementation of one BMP by itself has been shown in this study to not be as efficient as expected, the implementation of treatment trains has been shown as a promising opportunity to obtain higher efficiencies by combining the effects of multiple BMPs of Types I, II, and III in an articulated system, which could improve the efficiencies in the retention of TP as presented by Corrales et al. (2017) and Rice et al. (2002), obtaining ranges of efficiencies mostly between 30% and 70%.

Similarly, combining modeling and field studies can bridge the gap between numerical solutions and real-life implementation, facilitating the prioritization of BMP-related solutions as presented by Khare et al., 2020, where a novel top-down evaluation successfully assessed the potential impacts of BMPs and STAs on water quality remediation by combining modeling and field observations, leveraging robust datasets from continuous monitoring at actual locations (Moncada et al., 2021).

Despite our current focus on BMP assessment trends, it remains crucial to continue implementing field-scale BMP studies that demonstrate long-term efficiency and both technical and economic feasibility. Future research efforts should focus on investigating the synergistic effects and trade-offs when combining different BMPs and water management strategies as part of treatment trains (Song et al., 2022), addressing P management from both the source and the field level. Establishing long-term research and management plans is essential to capture the temporal dynamics of BMP performance, including long-term effectiveness and potential legacy effects (Corrales et al., 2017).

The use of electrocoagulation treatments for the removal of a variety of pollutants, including dissolved P, has been of interest to researchers (Mollah et al., 2004). Electrocoagulation treatments neutralize the pollutants as phosphate and aggregate them together, forming a floc, settling them of the solution (Franco et al., 2017). This treatment was the only BMP that showed an efficiency near 100% in laboratory conditions. Franco et al. (2017) implemented an electrocoagulation treatment on surface water extracted from Billy Creek, located within the city of Fort Myers, which resulted in a 99% reduction in P concentration. The study also mentions the potential feasibility of electrocoagulation treatments for the removal of P, particularly at the outflow of wetlands and retention ponds. High-efficiency systems, such as electrocoagulation, when combined with other engineered devices, such as the floating island system tested by Brown et al. (2018) and other adsorptive materials, show promise in enhancing the efficiency of existing BMPs. However, questions persist regarding the environmental and economic feasibility of scaling up these BMPs for water management on a larger scale.

Evaluating the efficiency of P-BMPs in an agriculture context presents several challenges and limitations, primarily due to the complex nature of agricultural systems and the diverse environmental conditions across various landscapes throughout the state. For example, in the Lake Okeechobee watershed, the physicochemical characteristics of the soil are highly diverse, encompassing a complex array of soils consisting of Spodosols, Entisol, and Histosols, characterized for having contents of sand greater than 90% and exhibiting limited capacity to chemically retain P in surface horizons. Each soil type in this case requires different management practices and contributes differently to P loads into Lake Okeechobee (Corrales et al., 2017; Flaig and Reddy, 1995). The effectiveness of BMPs is heavily influenced by factors such as soil type, weather and climate patterns, hydrological characteristics, and land use, which often dictate the seasonal pattern of nutrient fluxes (Zhang et al., 2009). Notably, extreme conditions, such as those following hurricanes, can significantly alter P concentrations, as observed in studies by Zhang et al. (2009) and Nesbit and Mitsch (2018), where peaks in soluble reactive P concentrations occurred shortly after peak rainfall events. Similarly, Williams et al. (2008) found that nutrient concentrations during hurricane seasons were two to five times higher than long-term averages. On the other hand, P fluxes have changed as a consequence of the intensive management of water levels in support of human land use changes (Lapointe et al., 2012). Furthermore, the relationship between land use disturbances and water quality issues, particularly regarding TP loads, has been investigated by Carey et al. (2011), who identified human disturbances and urban development patterns as significant contributors to these loads. Xiong and Hoyer (2019) also highlighted the direct effects of agriculture and wetlands on TP. These variations underscore the challenge of generalizing individual or combined BMP solutions as a strategy that "fits all". Moreover, the slow movement of P in the soil necessitates long-term studies to observe and quantify BMP impacts, particularly concerning legacy P (Shukla et al., 2021). This aspect further complicates the evaluation and implementation of BMPs in agricultural settings.

Water quality changes and ecosystem responses often unfold gradually over years or even decades. Short-term studies may not fully capture the extent of BMP effectiveness (Shukla et al., 2017a), emphasizing the need for longer-term monitoring with periods ranging from 5 to 30 years to assess both their long-term benefits and potential legacy effects. Measuring the impacts of BMPs on water quality and ecosystem health requires robust monitoring and data collection efforts. This involves establishing appropriate monitoring networks, implementing standardized sampling protocols, and ensuring data accuracy and reliability. Additionally, there is a pressing need for consistent and standardized metrics to assess BMP effectiveness. The current lack of uniformity in the methods and indicators used to measure BMP performance makes it challenging to compare and synthesize findings across studies. Developing standardized protocols and metrics for evaluating BMP efficiency would significantly improve the consistency and comparability of research outcomes. However, it is crucial to recognize the substantial cost and resource implications associated with implementing BMPs and conducting comprehensive evaluations. Short-term plans should prioritize water and nutrient management practices grounded in data, particularly precision and smart management. Long-term strategies should include assessments of combined practices, such as adsorptive media, considering the cumulative impacts of climate change, land distribution, and hydrological processes in the state.

Besides the BMP efficiency results provided in this study, it is important to highlight that P detection limits have changed over the last three decades. Lower detection limits and advancements in detection methods have influenced the reported BMP efficiency values over time. The average BMP efficiency of the studies reviewed ranged from 54% in the period from 1995 to 2005, 51% from 2015 to 2022, and 40% from 2005 to 2015. Although average efficiencies decreased from 2005 to 2015, possibly due to the reduction in detection limits, the development of improved detection methods may have contributed to the upward trend in efficiency observed from 2015 to 2022. For instance, Chimney and Goforth (2006) reported that in 1993, the Florida Department of Environmental Protection (FDEP) set a target outflow limit of 50 μg/L of TP for STAs, which was reduced to 10 μg/L by 2003 (Zacharias and Kaplan, 2023). This change in target values shows how the same BMP may yield different efficiency values depending on the year of evaluation. On the other hand, multiple methods for determining TP were used in the studies considered in this review including the Jackson method (Jackson, 1967) (Reed et al., 2006), the ash method (Silveira et al., 2006), US EPA method 365.4 (Fulton et al., 2015; Fulton and Smith, 2008), EPA method 365.1 (Brown et al., 2018; Shukla et al., 2017a), method SM 4500-P-F (Dierberg et al., 2017; Entry and Gottlieb, 2014; Pietro and Ivanoff, 2015), and EPA method 365.2 (Dierberg et al., 2017). According to the Water Research Foundation (WRF) (2015), the primary difference between these methods lies in their measurement times. It is important to investigate how a detection method or modification of the detection limit influences P-BMP management efficiencies to ensure a more balanced comparison across studies.

Conclusions

A systematic review was conducted to identify and analyze relevant literature on the efficiency of BMPs implemented or evaluated in the state of Florida over the last 30 years. Our review focused on the evaluation of the type, duration, efficiency, and impact of P management from nonpoint sources. Our findings indicate that multiple strategies have been implemented throughout time, but few show efficiencies higher than 50%. The evaluation of BMP efficiency trends continues to be refined as more data becomes available. Different approaches have been considered over the last thirty years, driven by increased support from state and federal laws regulating the protection of freshwater systems in the past two decades. However, it is imperative to establish clear demonstration programs with field-scale applications that show how highly efficient BMPs at the source level impact the reduction of P loads in freshwater systems.

Based on our assessment, most of the studies reported an average of 4 years of available data, with several studies reporting datasets no longer than a year. These results highlight the importance of providing efficiency values based on long-term datasets that capture the full efficiency of a BMP adopted in real-life conditions. However, there were no significant differences between the duration of the study and the reduction efficiency reported. Over the last decade, there has been an increase in studies with longer-term datasets, which could contribute to a better understanding of BMP efficiency. Additionally, weather extremes and rainfall patterns in Florida have a strong influence on those BMPs, with studies showing negative efficiency, during such extremes. Further investigation into solutions to manage P during extreme events will contribute to the improvement of BMP efficiency covering extensive areas such as the constructed wetlands or STAs.

Most of the studies assessed in this review were concentrated in areas surrounding Lake Okeechobee, particularly in the Southeast Everglades Agricultural Area (EAA), due to the region's significance in water management, characteristic soil types, and challenges posed by nutrient pollution. STAs and constructed wetlands demonstrated effectiveness in reducing P loads in this area, with ongoing efforts to achieve loads below TMDLs. The results of our review also showed that modeling-based assessments, utilizing longer-term datasets, and simulating various scenarios play a crucial role in defining BMP efficiency. Integrating these modeling results with field implementation through testbeds can enhance stakeholder engagement, promoting the sustainable implementation of BMPs.

In Florida, BMPs have proven to be successful, with higher efficiencies across the years. Long-term studies could hold more insights into BMP efficiency with the inclusion of more refined datasets. P management should consider combining successful strategies to maximize BMP efficiency. For example, constructed wetlands and STAs could be combined with vegetative buffers, irrigation management, precision nutrient management, and the incorporation of stakeholder-based decision support systems. This integrated approach could provide an enhanced benefit to P management in the long-term. Additionally, future work could inquire into the revision of stakeholder engagement studies and how these engagement processes can influence the implementation of BMPs.

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