

Environmental engineering Aplinkos inžinerija

TRENDS IN RESEARCH ON LEACHING OF BIOGENIC SUBSTANCES FROM DRAINAGE SYSTEMS: A SYSTEMATIC LITERATURE REVIEW

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Abstract. Due to the increasing human impact on nature, the significance of environmental research is constantly growing. Inefficient or poorly maintained drainage systems can lead to significant losses of nutrients, promote soil erosion, eutrophication processes, and reduce the biodiversity and resilience of ecosystems. Therefore, the question arises as to what impact drainage systems have on the leaching of biogenic substances. To answer this research question, in this paper we present a systematic literature review of 132 selected papers from the Web of Science and Scopus digital databases. Obtained results of the review reveal that until 2010, the focus was mainly on nitrate studies, but in recent years there has been an increased interest in other nutrients, especially phosphorus. This analysis highlights the importance of nutrients in water quality assessment and the need to optimize fertilization practices in order to reduce environmental pollution. Poorly designed or poorly managed systems can increase pollution, especially during heavy rainfall, and harm water quality and ecosystems. However, the strategic implementation of controlled drainage technologies can reduce nutrient losses, improve water quality, increase crop yields, and reduce fertilizer use.

Keywords: drainage, water quality, free drainage, controlled drainage, biogenic substances.

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1. Introduction

Over the last two centuries, the courses of most European rivers have undergone substantial irreversible changes. Lately, humans have used rivers for a variety of purposes, including irrigation and drainage in agriculture, transportation, power production through hydroelectric dams, and recreational activities (Wolf et al., 2021). However, numerous anthropogenic activities, including channelization, culverting, damming, abstraction, urbanization, pollution, dredging, and intensive agriculture, have exerted a deleterious effect on the river and its environment. In the territory of Lithuania and northern central Europe, excess moisture prevails. Consequently, excess water that is often formed accumulates in soils with a lower surface slope and a heavier granulometric composition on plains and in depressions of hilly terrain. To address this challenge, the implementation of drainage systems has been a long-standing practice. These systems, which consist of a network of functionally interconnected hydraulic structures, are strategically located within the affected regions. Their primary function is to regulate the soil moisture content, creating optimal conditions for plant cultivation (i.e., enhance crop production) (Ritter, 2017). Although moisture

deficiency is often the primary concern, climatic variations cause crops to periodically endure drought stress conditions. The challenges posed by drought in drained soils have led to a change from conventional drainage methodologies to groundwater table management systems. In particular, the United States has witnessed the emergence and widespread adoption of controlled drainage and sub-irrigation over the past two decades, driven by their environmental advantages and the improved productivity of agricultural plants. These systems are equipped with a control structure that enables the adjustment of the drainage system according to the specific needs of the agricultural operation (Wesström et al., 2014).

Drainage systems play a crucial role in regulating soil moisture levels and enhancing plant growth conditions. However, they can also have a negative impact on the environment, particularly by promoting the leaching of nutrients such as nitrogen and phosphorus into surface and groundwater. Intensive drainage accelerates the runoff of water from the soil, while also removing soluble nutrients (Dou et al., 2021). Pham et al. (2023) stated that the leaching pattern is mostly seasonal, with most of the leaching load occurring during periods of high discharge, such as spring snowmelt and milder winters. During spring floods

or after heavy rains, substantial quantities of water comprising high concentrations of nutrients, particularly nitrogen and phosphorus compounds, enter drainage systems. Drainage systems, particularly free drainage ones, are not equipped with supplementary retention mechanisms. Consequently, the collected water, along with its nutrients, is released into natural water bodies, such as rivers, lakes, and even the sea. The presence of nitrogen (N) and phosphorus (P) compounds in open bodies of water from agricultural drainage systems contributes to eutrophication (Grenon et al., 2021; 2023).

Bibliographic or systematic reviews of works on drainage systems and their impact on water quality has already been completed (Bodrud-Doza et al., 2025; Carstensen et al., 2020; Kęsicka et al., 2022, 2023; Wang et al., 2020). Our analysis showed that there is a lack of review articles examining the contribution of drainage systems to leaching biogenic substances. That is, we did not find the research questions and search keywords that were interesting to us in the current list of publications. Some authors analysed irrigation and drainage from a bibliometric perspective (Kannazarova et al., 2024; Kęsicka et al., 2023), while others focused more on mathematical models (Kęsicka et al., 2022). Even when the authors used the same search keywords, they focused mainly on the impact of drainage on crop yield (Wang et al., 2020), rather than on the biogenic substances.

This paper presents a systematic review of the literature on the impact of drainage systems on the loss of biogenic substances. The objective of this article is twofold: first, to collect and summarize the latest information in the field, and second, to develop a systematic approach to drainage and its impact on biogenic material leaching. The primary contributions of this research are as follows: popularity of the topic under consideration depending on

the region and year; identification of the main biogenic substances studied in drainage systems; determining the impact of drainage systems on the leaching of biogenic substances.

The rest of this paper is organized as follows: Section 2 details the research methods to conduct this study. Section 3 presents the results of published research and discussions. Finally, section 4 concludes the paper and presents future research directions.

2. Research methods

The review's methodology was developed and implemented in accordance with the guidelines and indications provided by Kitchenham and Charters (2007) and Kitchenham et al. (2009) and was organised following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines (Page et al., 2021) (Figure 1).

In the preliminary phase, the research design was formulated to delineate the research questions, the scope, and the search strategy for the SLR (Table 1). Based on the (Kitchenham & Charters, 2007; Kitchenham et al., 2009) guidelines, the inclusion (IC) and exclusion (EC) criteria was defined and presented in Table 1.

Studies that were irrelevant (EC1), redundant (EC2, EC5, EC6, EC7) or missing (EC3, EC8), or not in English (EC4) were excluded according to those defined criteria. Consequently, during the Identification step 440 records were extracted from the Web of Science and Scopus databases and 121 (27.5% of initial 440) records were removed before the screening step because not satisfying EC6, EC8, EC4. After the screening step, 144 (32.73% of initial 440) papers were left for the detailed full text reading and considering to satisfy IC1. We used IC3, IC5 and EC5 to identify high-quality, peer-reviewed scientific papers on the drain-

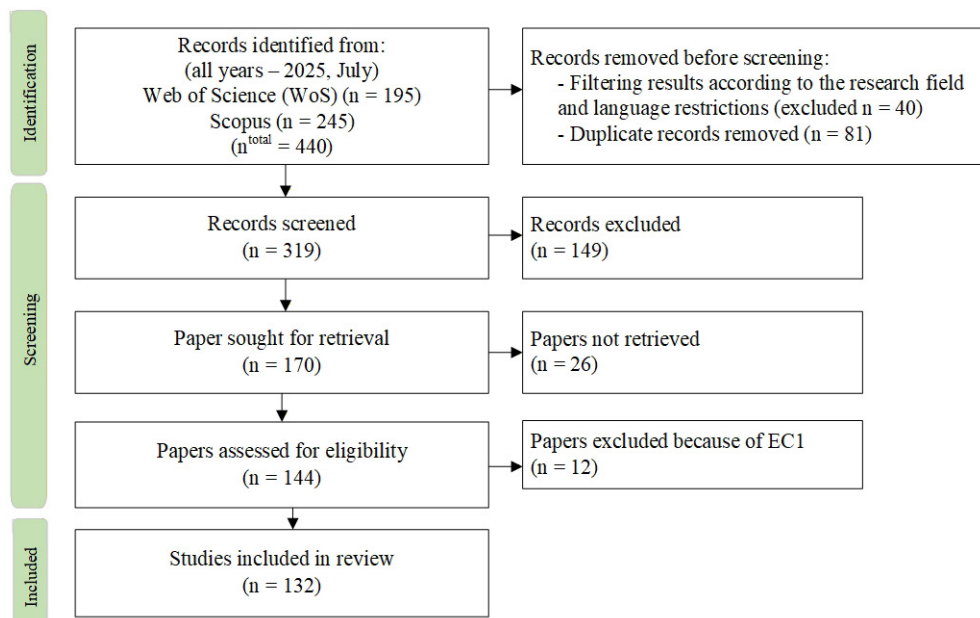


Figure 1. The PRISMA flow diagram (Page et al., 2021) for this systematic literature review

Table 1. Planning SLR

Research questions	RQ1. In which year were articles published examining biogenic substances in drainage water? RQ2. In which country (region) was the research conducted? RQ3. What biogenic substances are assessed? RQ4. What was the influence of drainage systems on the leaching of biogenic substances?
Data sources	We used the Web of Science and Scopus digital databases. Accessed on 1 June 2025.
Search sting	("fre* drainag*" OR "control* drainag*") AND ("water* qual*")
Scope for the search	Web of Science: Water Resources; Environmental Sciences; Agronomy, Agricultural Engineering, Engineering Civil, Ecology, Engineering Environmental, Soil Science, Agriculture Multidisciplinary, Engineering Multidisciplinary, Environmental Studies, Geosciences Multidisciplinary; Scopus: Environmental Sciences; Agricultural and Biological Sciences, Engineering, Earth and Planetary Sciences, Multidisciplinary
Inclusion Criteria	IC1: Universally accepted works related to the water quality of drainage systems. IC2: Original not repeating papers on the water quality of drainage systems. IC3: The full-text paper is available to download. IC4: The paper is written in English. IC5: Peer-reviewed articles, proceeding papers, and reviews. IC6: Not duplicating papers. IC7: The bibliometric data (i.e., title, keywords, and abstract) of the paper is provided.
Exclusion Criteria	EC1. Exclude papers that are not primarily about the water quality in drainage systems, even if they contain relevant keywords: EC1.2: economic analysis as the primary focus; EC1.3: pollutants other than biogenic substances; EC1.4: analysis of specific soils (e.g., saline soils) or urbanized areas; EC1.5: analysis of the drainage influence on crop production; EC1.6: papers that do not mention biogenic substances. EC2. Exclude sources that repeat ideas from earlier works. If there are several papers by the same authors have a similar abstract, i.e., if one paper is an extension of another, the paper with fewer paper is excluded. EC3. The full-text paper is not available. EC4. The paper is written in a language other than English. EC5. Papers shorter than 6 pages are excluded. EC6. Exclude duplicate papers. EC7. Exclude short papers, grey literature, posters, Master's theses, doctoral theses, and books. EC8. The bibliometric data is missing.

age topic, such as journal articles, proceedings papers or reviews. Although secondary studies, including grey literature, can offer valuable insights in fast-evolving areas, they may not provide a comprehensive overview of the subject (Dybå & Dingsøyr, 2008; Garousi et al., 2019).

Finally, after identification, screening and inclusion/exclusion procedures (Figure 1), 132 (30% of initial 440) papers were left for the data extraction. The whole list of those studies is presented as supplementary material of this article.

3. Research results and discussion

3.1. In which year were articles published examining biogenic substances in drainage water (RQ1)?

Publications on the impact of drainage systems on water quality have been found in the Web and Scopus databases since 1986. As we can see from (Figure 2) the popularity of the topic under consideration has grown over the years. Analysing the number of scientific articles by year, we can see that in 1986, 1987, 1988, 1989, 1990, 1991 there were 1 or no articles published. This is the beginning of the study period, which indicates a low number of scientific

papers, possibly due to the beginning of the development of the research field or limited access to data.

The years with the highest number of articles were 2005 and 2009 with 9 articles each, 2023, 2018, 2010, 2011, 2003, 1998 with 6 articles each. This suggests that there has been an increase in publication activity these years. Periodic peaks, possibly related to scientific conferences, project cycles, or research updates. The breakdown of the years by activity shows that as follows:

- 1986–1994: a period of low activity (0–2 articles per year),
- 1995–2005: a steady increase and a peak in 2005,
- 2006–2011: a period of fluctuating activity with a peak in 2009,
- 2012–2025: a period of medium to high activity, especially from 2018.

When examining the popularity of articles over five years, we can see that this area received the most attention in 2016–2020 (28 papers). The last five-year period 2021–2025 (22 papers) has not yet ended, so we can expect that the popularity of the topic may remain at the same level. The largest number of publications, when analysed each year, were published in 2004 and 2010. We can also notice a trend that after a year, those with a lot of

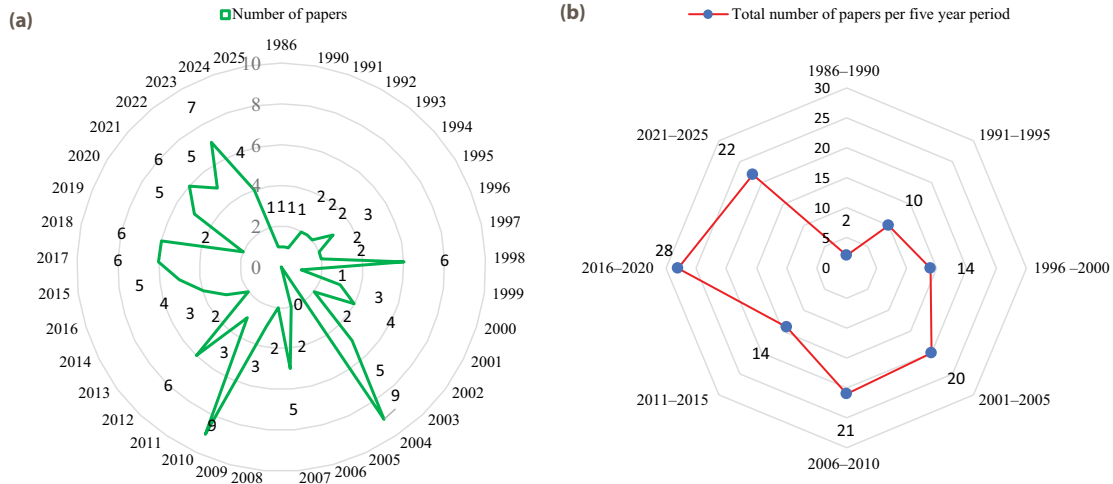


Figure 2. Overview of the frequency of publications: a) Number of papers per years; b) Total number of papers per five-year period

articles are usually followed by others with a small number of articles.

It is worth mentioning that during the period under review, not only did the number of articles increase, but the topics of the articles also expanded. Since the 2001–2005 five-year period, articles have appeared examining climate change and its impact on water flows and quality in drainage systems. The use of computer programs in the field has also increased significantly.

3.2. In which country (region) was the research conducted (RQ2)?

After analysing the distribution of articles by country, it can be clearly seen that most articles on the topic under consideration were written in North America (Figure 3). In this regard, the United States of America (USA) leads (75 papers; 57%), but Canada is also not far behind (25 papers; 19%). Northern and Central Europe are another region affected by this problem. This topic has been discussed in publications written by Dutch, Swedish, Danish, Polish, Lithuanian (16 papers; 12%). A literature review

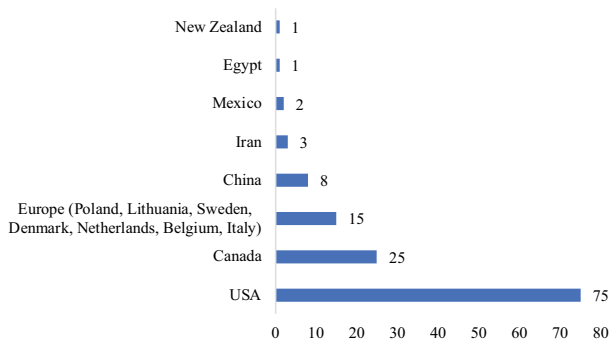


Figure 3. Distribution of papers by country

revealed the existence of an article that was also written about the entire Northern European region. After analysing the distribution of papers by year and region, it was noted that the first publications appeared in USA. The first papers were published by China in 1995 and by Canada in 1996. The European region and other countries began publishing on the topic in question only in 2001. It should also be mentioned that in the last year (2024–2025), all papers found on the topic in question also belong to USA.

3.3. What biogenic substances are assessed (RQ3)?

The results revealed that the papers examined two main biogenic substances, total nitrogen (N) and total phosphorus (P), as well as their compounds, including nitrates, nitrites, ammonium, and phosphates. As demonstrated in Figure 4, at the inception of the period under scrutiny (1986–1990), articles demonstrated limited engagement with the analysis of biogenic materials. Subsequently, beginning in 1990 and extending through the first four or five time periods (ending in 2005), the focus was on nitrates. From 1986 to 2005, 40 articles analysed nitrate, 14 articles analysed total phosphorus, and 11 articles analysed total nitrogen (see Figure 4).

The highest research activity was observed around 2005 and from 2020 to 2025, during which the largest bubbles are visible: 17 articles on nitrates (2005) and 15 articles each on nitrates, phosphorus and their forms, and 11 on total nitrogen. This phenomenon may be associated with the expansion of agriculture and the increased use of fertilizers. After 2005, the situation changed, as other forms of biogenic substances began to be investigated. While nitrates (48) and total phosphorus (44) remain the focus of attention, total nitrogen (35) and ammonium (14) are also widely studied. However, there has been a constant interest in nitrates throughout the period.

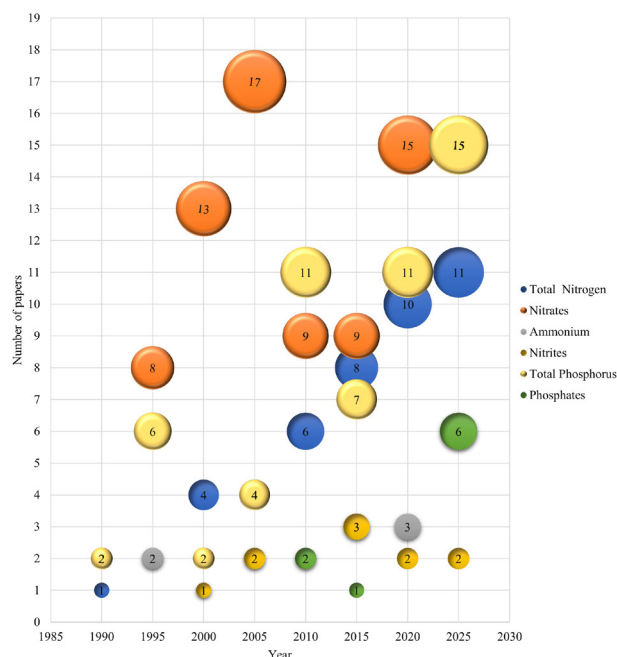


Figure 4. Analysis of biogenic substances in the analysed papers

The activity in scientific articles related to nitrogen and phosphorus and their compounds in recent decades can be attributed to several factors.

The EU Water Framework Directive (2000) and other international initiatives may have stimulated more intensive research on nutrients in waters. Increased fertilizer use has led to growing interest in nutrient runoff into the environment. Increasing pollution of water bodies ("bloating" seas or lakes) has encouraged research on the leaching of nitrogen and phosphorus from soil into open water bodies. Of course, the emergence of innovative, new research methods (sensors, mass spectrometry) has allowed scientists to expand their research areas and delve into more complex compounds, which has led to an increase in publications.

3.4. What was the influence of drainage systems on the leaching of biogenic substances (RQ4)?

Drainage systems discharge large amounts of water into open water bodies. Drainage systems, especially in agriculture, have a significant impact on the leaching of biogenic substances (especially nitrogen and phosphorus compounds) into surface water bodies. Free drainage continuously removes excess water from the soil, along with it leaching nutrients not absorbed by plants, especially nitrates (Subsurface systems directly transport nutrients to streams and rivers). Even in the case of free drainage, the technical characteristics of drainage systems (distances between drains, drain depth, slopes), soil properties and overgrowth of grass, have a significant impact on the leaching of biogenic substances (Pham et al., 2023; Williams et al., 2015). It is stated (Poole et al., 2010), that the

removal of nitrate nitrogen in a shallow drainage system is significantly lower compared to a deep system (it should be noted, that the authors attribute this reduction to reduced drainage volumes in the shallow system, rather than to differences in concentration).

Studies have shown that controlled drainage (CD) reduces the leaching of nutrients into water bodies (Dou et al., 2021; Kalibatienė et al., 2025) (also see Figure 5). The findings indicated that CD enhanced water retention in the soil, leading to a reduction in nutrient concentrations and increased crop yield. Drainage water management is a promising technology to reduce nutrient losses in artificially drained fields. Reusing collected water can contribute to sustainability in agriculture, primarily by reducing the need for fertilizers to ensure sufficient crop yields and minimizing nutrient leaching from drainage systems.

By mapping the impact of drainage on the leaching of nutrients, drainage systems have a twofold impact on the environment (Figure 5). These impacts depend on how the systems are designed, operated, and the environment in which they operate. The positive environmental impacts (Figure 5, green squares) are the retention of biogenic substances in drainage systems, the improvement of groundwater and surface water quality, and the reduction of fertilizer requirements (King et al., 2022; Singh et al., 2024; Wang et al., 2018). Well-designed drainage systems reduce the leaching of nitrogen and phosphorus into the surface and groundwater (Figure 5, blue squares). This helps to protect water bodies from eutrophication – excessive nutrient loads that lead to algal blooms and ecosystem degradation.

Drainage solutions that slow the leaching of biogenic material keep them in the soil for longer (Feset et al., 2010; Kaur et al., 2021; Tan et al., 1998). This allows plants to better absorb them, reducing the need for additional fertilizer (Kaur et al., 2021).

This reduces the flow of water from agricultural activities and allows natural ecosystems to filter pollutants, helping to improve the quality of rivers, lakes, and groundwater (Que et al., 2015; Reinhart et al., 2016).

However, in some cases, a free-draining system can accelerate the leaching of pollutants including nitrates, pesticides, and phosphates, especially in the event of heavy rainfall (Figure 5, red squares) (Pitts et al., 2004). If pollutants are not trapped or decomposed in the soil, they can contaminate the surface and groundwater, which can threaten human health and ecosystems (Ritter, 2010; Stämpfli & Madramootoo, 2003). Repeated, long-term over-drainage can lead to soil degradation, reduced humus content and microbial diversity, which in the long term reduces the soil's ability to clean itself naturally.

The judicious adaptation of drainage systems to the characteristics of a given site is imperative for achieving an optimal balance between agricultural productivity and environmental protection. The systematic analysis showed that the research articles focused on two main biogenic substances – total nitrogen (N) and total phosphorus (P) – and their compounds: nitrate, nitrite, ammonium, and

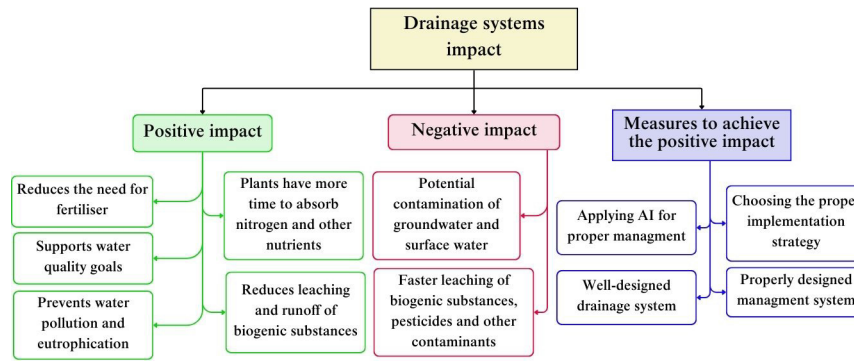


Figure 5. The influence of drainage systems on the leaching of biogenic substances

phosphate forms. In the early period (1986–2005), most of the re-search focused on nitrate, but from 2005 onwards, the analysis of other biogenic substances has been expanded. In recent years (especially 2020–2025), the number of studies covering all these substances has increased.

This trend can be attributed to the intensification of agriculture, the increasing use of fertilizers, international environmental initiatives such as the EU Water Framework Directive, and the development of more advanced analytical methods. Drainage systems have a significant impact on the leaching of biogenic substances (especially nitrogen and phosphorus) into surface and even groundwater. Inadequately designed or free drainage systems can increase the discharge of pollutants into water bodies, especially during heavy rainfall. This threatens water quality and ecosystems. Properly designed, managed and adapted drainage technologies, such as controlled drainage, can significantly reduce nutrient leaching, improve water quality, increase yields, and reduce fertilizer requirements. The environmental impact of drainage systems is therefore twofold and depends largely on their technical solutions and their adaptation to specific natural conditions.

Also, as was found in our previous article (Kalibatiené et al., 2025), authors of various researches found the benefits of controlled drainage over free drainage as follows: enhancing drainage runoff regulation (Satchithanatham et al., 2014), reducing nutrient losses from agricultural fields (Carstensen et al., 2020; Guo et al., 2025), preventing root rot and soil erosion, control of soil moisture (Satchithanatham et al., 2014), and improving surface water quality (Mishra & Agarwal, 2025). However, implementing controlled drainage systems necessitates significant investments. It is reasonable to expect that these investments will yield positive returns over time, contributing to both financial and ecological sustainability.

For the future research such investigations of the drainage systems and their impact on the loss of biogenic substances should be continued and extended, especially for the analysis of artificial intelligence usage for the drainage systems. Also, it is useful to extend the current study by analysing the impact of drainage systems onto whole agricultural activity and productivity.

4. Conclusions

A review of the extant literature on the influence of drainage systems on the leaching of biogenic substances reveals a marked increase in the number of publications on the subject since 1986, with a particularly notable surge in recent decades. This area received the most attention during the 2016–2020 period. It is noteworthy that the most recent five-year period (2021–2025) has not yet concluded, suggesting the probability of the popularity of the topic remaining at the same level. A thorough analysis of the distribution of articles by country reveals that a significant proportion of the extant literature on the subject was authored in North America, specifically the United States and Canada. The topic has also been covered in other regions, at first in Europe, and countries such as Poland, Lithuania, Sweden, Denmark and the Netherlands paying particular attention.

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BIOGENINIŲ MEDŽIAGŲ IŠPLOVIMO IŠ DRENAŽO SISTEMŲ TYRIMŲ KRYPTYS: SISTEMINĖ LITERATŪROS APŽVALGA

Santrauka. Dėl didėjančio žmogaus veiklos poveikio aplinkai aplinkosauginių tyrimų reikšmė nuolat auga. Neefektyviai veikianti arba netinkamai prižiūrima drenažo sistema gali lemti didelius maisto medžiagų nuostolius, skatinti dirvožemio eroziją ir eutrofikacijos procesus, mažinti ekosistemų biologinę įvairovę bei atsparumą. Todėl kyla klausimas, kokią įtaką drenažo sistemos daro išplaunamų biogeninių medžiagų kiekiui. Siekiant atsakyti į šį klausimą, šiame straipsnyje pateikiama sisteminė literatūros apžvalga, apimanti 132 atrinktus mokslinius straipsnius iš „Web of Science“ ir „Scopus“ duomenų bazių. Apžvalgos rezultatai parodė, kad iki 2010 m. daugiausia dėmesio buvo skiriama nitratų tyrimams, tačiau pastaraisiais metais išaugo susidomėjimas kitomis maistinėmis medžiagomis, ypač fosforu. Atlikta analizė atskleidė biogeninių medžiagų svarbą vertinant vandens kokybę ir poreikį optimizuoti tręšimo praktiką, siekiant mažinti aplinkos taršą. Netinkamai suprojektuotos arba netinkamai valdomos drenažo sistemos gali didinti taršą, ypač intensyvių kritulių metu, ir neigiamai paveikti vandens kokybę bei ekosistemas. Tačiau tikslingas reguliuojamo drenažo technologijų taikymas gali sumažinti biogeninių medžiagų nuostolius, pagerinti vandens kokybę, padidinti žemės ūkio augalų derlingumą ir sumažinti trąšų naudojimą.

Reikšminiai žodžiai: drenažas, vandens kokybė, laisvasis drenažas, reguliuojamasis drenažas, biogeninės medžiagos.