

Review

A Systematic Review on the Influence of Drainage Systems on the Environment

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Abstract: Environmental research has become increasingly important due to the human impact on ecosystems, with a particular need to study how different drainage systems affect water quality. Improperly functioning drainage can result in significant losses of biogenic substances, soil erosion, eutrophication, and declining biological capacity. This study addresses the existing knowledge gap by consolidating and critically analyzing the recent scientific literature on controlled and free draining types over forty years (1986–2024) using the Web of Science and Scopus databases. The objective of this systematic review is to collect and summarize information on various drainage systems, their advantages and disadvantages, and their effect on environmental water quality. A review of 144 selected papers from the past four decades indicates that the installation, use, and upgrading of drainage systems remains a subject of extensive debate within the scientific community, particularly regarding their impact on the leaching of biogenic substances into open water bodies. The results obtained from this study indicate that nitrogen (N) (found in 54 papers) and phosphorus (P) (found in 48 papers) are the primary biogenic elements affecting aquatic ecosystems and eutrophication processes. Also, compared to mathematical tools (found in 42 articles), there is a lack of application of AI tools for modeling and predicting the impact of drainage systems on water quality and climate change. Consequently, ongoing research in this area is crucial, offering researchers, practitioners, and wild society with significant insights into the overall effect of drainage on the environment, opportunities for improvement and unexplored research directions for drainage systems.

Keywords: drainage; water quality; free drainage; controlled drainage



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1. Introduction

High-intensive agricultural production in different regions of the world is a significant contributing factor to eutrophication, resulting in a deterioration in water quality and ecosystem degradation on a global scale. One of the factors relating to agricultural practices that contribute to issues concerning water quality is the equipment and use of drainage systems [1].

Drainage systems were installed in various agricultural territories to address the need for effective water management, facilitating the removal of excess water from cultivated land. The Baltic countries, Northern Europe, and North America are notable for their high level of groundwater extraction, which is driven by the implementation of drainage systems.

In North America, approximately 37% of cropland (20.6 million hectares) is located in the eastern and midwestern United States, with an unknown proportion of irrigated areas in the western United States, and about 8 million hectares in Canada are estimated to be artificially drained [2]. The total area of drained agricultural land in Lithuania is approximately 87% [3]. It is important to note that the majority of all drained agricultural areas are drained by *free drainage* [4,5]. This is a conventional drainage system, the primary disadvantage of which is that it functions in a unidirectional manner, continuously removing moisture and excess water from the soil. Such a drainage system washes away various chemical and biogenic substances as water flows out of the soil. Drainage systems tend to intercept nutrient rich (i.e., containing nitrates) soil water and carry it to surface water bodies. As indicated by the finding of multiple monitoring studies, a substantial quantity of total nitrate load is delivered to surface water via pipe drainage systems [6,7].

Controlled drainage has been used more and more often recently. Consequently, there has been an increasing focus on conducting studies to assess the benefits and drawbacks of controlled drainage [8]. While there are some potential disadvantages to consider, such as increased surface runoff, increased P release, reduced trafficability in pastures, NO₃-N losses to deep seepage and damage to crops, etc. [9], these can be mitigated through careful planning and implementation. Studies worldwide suggest that appropriately controlled drainage offers significant benefits for water quality, agricultural productivity, and nutrient and water use efficiency [1,10]. Implemented controlled drainage can lead to a significant reduction in the annual leaching of nitrogen compounds, ranging from 20% to 90%, and total phosphorus, with a reduction of 10% to 30% [4,11].

Z. Jia et al. [12] confirm that controlled drainage led to higher concentrations of nitrogen in drainage water, particularly during events when irrigation was applied to fields that were already too wet. Consequently, there was an increase in drainage events characterized by elevated nitrogen and phosphorus concentrations. The authors' findings indicate that proper irrigation scheduling and management are crucial for maintaining water quality, rather than implementing controlled drainage alone.

Summing up, addressing agricultural water pollution, including the use of drainage systems, is a complex and multifaceted issue that requires a combination of policy, research, and interventions on and off the farm [13]. Water-related policy issues frequently encounter obstacles such as a lack of political will and commitment, inadequate funding, and ineffective monitoring systems, particularly in developing countries [14]. In today's digital age, next-generation technologies are becoming an integral part of human life [15]. Technological advancements are generating new opportunities in agriculture, particularly in the areas of sensors, biologicals, robotics, automation, and digital data. These innovations can be utilized to enhance water resource management and protect water ecosystems. Precision agriculture (PA) enables us to effectively manage spatial and temporal variability by leveraging advanced technologies to precisely match agricultural inputs, enhance economic returns, and reduce environmental impacts [16,17]. The implementation of precision agriculture techniques facilitates the regulation of biogenic substance flow, thus reducing their leakage into open water bodies.

Environmental research has become very popular and relevant due to the impact of human activity on the environment and the need to understand the effect of this impact. The present study constitutes a systematic review of the scientific literature on free and controlled draining types over forty years (1986–2024) and their influence on the environment. Consequently, it aims to collect and summarize information about types of drainage systems, their advantages and disadvantages, and their impact on environmental water quality.

The most relevant reviews on drainage systems and water quality topics are presented and summarized in Table 1. Our analysis revealed a paucity of review articles addressing this topic. The table presents the main related reviews and analyses that were found.

Table 1. Related works similar to the drainage systems.

Reference	Review Type, Years	Research Questions /Aim/Focus	Search Keywords	Database
[18]	Bibliometric analysis 2000–2022	To identify research progress and trends related to CD.	((‘control* drainage’ OR ‘control* tile drainage’ OR ‘drainage water management’ OR ‘groundwater management’) AND (‘agricultural drainage’ OR ‘subsurface drainage’ OR ‘water quality’))	Web of Science
[19]	Bibliometric analysis 2017–2021	To analyze hot topics and important regions of irrigation and drainage research as well as to use historical bibliometric data to gain new insights into trends and the emphasis of international irrigation and drainage research.	“Irrigation and Drainage”.	Scopus
[20]	Meta-analysis 1900–2019	This review compiles the available evidence on nitrate and TP removal efficiencies from both pilot and full-scale field studies on drainage mitigation measures to provide a synthesis of the existing body of peer-reviewed literature.	NA	Web of Science
[21]	Meta-analysis until 31 December 2020	In this study, the authors focused on comparing the results obtained for DRAINMOD model studies under CD vs. FD conditions and its effect on the reduction in outflow and nitrate losses of drained agricultural land. They used meta-analyses to synthetically and also statistically indicate the effectiveness of CD use in quantitative and qualitative aspects of drainage outflow.	“controlled drainage” AND “drainmod”	Web of Science, Scopus
[22]	Meta-analysis 1960–2019	The specific objectives of this study were the following: a) estimate the effects of CD on crop yield and drainage water quantity and quality; and b) identify a cropping system, drainage method, and climate type that benefit crop yield and drainage water quantity and quality under CD systems.	controlled drainage, drainage water management, water table management, yield, nitrogen, phosphorus, and drainage water quality	Web of Science
This review	SLR 1986–2024	When are studies on the drainage topic published? Is controlled drainage always better than free drainage? Is climate change considered in drainage water quality studies? What computer tools are used to model drainage systems? Is artificial intelligence used? What biogenic substances are considered in drainage water quality analyses?	(“fre* drainag*” OR “control* drainag*”) AND (“water* qual*”)	Web of Science, Scopus

As presented in Table 1, we found two bibliometric analyses and three meta-analyses, which are closely related and highly relevant to the current study. However, there are notable differences in the research questions and search keywords, i.e., the authors of [19] analyzed irrigation and drainage from a bibliometric perspective. Only the authors of [21] searched the Web of Science and Scopus, and the other authors reviewed only one database. Nevertheless, the authors of [22] used the same search keywords in their review, but their focus was on the effects of CD on crop yield, not water quality in general. The authors of [21] mostly focused their research of the DRAINMOD model studies under CD vs. FD conditions.

Summing up, the relationship between water quality and free or controlled drainage was not adequately addressed in the reviews, particularly in recent years. They are extremely focused on a specific narrow topic, like crop yield, the DRAINMOD model exploration under CD vs. FD conditions, groundwater, etc.

Therefore, this paper presents a systematic literature review on free and controlled drainage, to collect and summarize the latest information and develop a systematic approach to drainage and its environmental impact. Consequently, the main contributions of this research are as follows:

1. Analysis of the increasing popularity of drainage systems' influence on water quality over the years;
2. Examination of the growing interest in studying climate change and its effects on drainage-related water quality;
3. Identification of key computer tools used for modelling drainage systems;
4. Recognition of the main biogenic substances tested within drainage systems influencing water quality;
5. Detailed justification of the advantages of controlled drainage over free drainage from the water quality perspective;
6. Identification of the main topics analyzed in the papers on drainage systems and water quality.

The rest of this paper is organized as follows: Section 2 details the research methodology to conduct this study. Section 3 presents the results of published research. Section 4 concludes this study with a discussion of potential future research.

2. Review Materials and Methods

The methodology of the review was developed and implemented by the guidelines provided by [23,24] and organized following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines [25]. A summary of this systematic literature review is provided in the PRISMA checklist [25].

2.1. Planning SLR

In the initial step, the planning was performed to define the research questions, scope, and search strategy for the SLR.

2.1.1. Define Research Questions

We defined the research questions (RQs) to investigate the drainage types under different climate conditions. The answers to these RQs helps us to document the SLR results and summarize the current state-of-the-art on drainage types. Consequently, the RQs are as follows:

RQ1. When are studies on the drainage topic published?

RQ2. Is climate change considered in drainage water quality studies?

RQ3. What computer tools are used to model drainage systems? Is artificial intelligence used?

RQ4. What biogenic substances are considered in drainage water quality analyses?

RQ5. Is controlled drainage always better than free drainage?

RQ6. What are the main topics found in the analyzed papers on drainage systems?

2.1.2. Identify Data Sources

For this SLR, we used the Web of Science and Scopus digital databases, as they are particularly relevant to drainage topics. In [26], 28 digital academic databases were compared, and 14 were found to be the most suitable as primary search engines for SLRs. Therefore, we have selected the Web of Science (WoS, <https://apps.webofknowledge.com/>) (accessed on 11 January 2025) and Scopus (<https://www.scopus.com/>) (accessed on 11 January 2025) as the most suitable for drainage topic analysis. The database contains a collection of peer-reviewed papers of high quality on the drainage topic. Also, they allow downloading large sets of the found articles in various formats compatible with reference management tools, such as Mendeley, Zotero, etc., as well as data analysis tools like MS Excel, VOSviewer, Bibliometrix, etc.

2.1.3. Formulate Search String

The first two authors analyzed the RQs to identify the relevant keywords. Furthermore, all of the authors have taken part in the group meeting to finalize the key terms. Finally, the authors have agreed to consider the following search string:

("fre drainag*" OR "control* drainag*") AND ("water* qual*").*

The following scope was used 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.

Also, the keywords “free” and “controlled” were used to specify the drainage type to be analyzed. We aimed to distinguish these two types of drainage, in order to analyze their advantages and disadvantages. If we exclude “free” and “controlled” keywords from the search string, the search returns a high number of articles that are irrelevant to the analyzed topic, such as urban water, saline soil, roads, and dam drainage.

2.1.4. Define Inclusion and Exclusion Criteria

Based on the [23] guidelines, we have defined the inclusion (IC) and exclusion (EC) criteria in Table 2. Studies that were irrelevant, redundant, or not in English were excluded according to those defined criteria.

The first criteria (IC1 and EC1) allow us to select papers that correspond to the drainage topic and do not consider topics on economic analysis of drainage, pollutants other than biogenic substances, specific soils (e.g., saline soils) or urbanized areas, or the influence of drainage on crop production. IC2 and EC2 are used to select only original papers and not papers repeating the same ideas on drainage systems, excluding repetitions of ideas described in earlier works on drainage systems. IC3 and EC3 ensure the accessibility of the full text of the paper, which is necessary for the detailed analysis and preparation of the answers to the research questions. IC4, IC7, and EC4 were used to identify only high-quality

peer-reviewed scientific papers, like journal articles, proceedings papers, or reviews on the drainage topic. Although secondary studies, including gray literature, can offer valuable insights in fast-evolving areas [27], they may not provide a comprehensive description of the overall approach [28]. Secondary studies were used as a supplementary source of information and were not included in the list of primary studies for this review. As the primary search and inclusion/exclusion is based on the title, keywords, and abstracts, only papers with this bibliometric data were selected (IC8 and EC8).

Table 2. Inclusion and exclusion criteria.

Inclusion Criteria	Exclusion Criteria
IC1: Universally accepted works related to water quality of drainage systems.	EC1: Exclude articles not primarily about water quality in drainage systems, even if they contain relevant keywords. EC1.2: Reject articles containing an economic analysis as the primary idea. EC1.3: Reject articles that refer to pollutants other than biogenic substances. EC1.4: Reject articles analyzing specific soils (e.g., saline soils) or urbanized areas. EC1.5: Reject the articles in which the primary idea is to analyze drainage's influence on crop production.
IC2. Include original not repeating papers on water quality of drainage systems.	EC2: Exclude relevant sources that repeat ideas described in earlier works. If there are several papers of the same authors with a similar abstract, i.e., one paper is an extension of another, the less extended (i.e., containing less pages) paper is excluded.
IC3. The full-text paper must be available to download.	EC3. The full-text paper is not available.
IC4. Include fully described scientific papers.	EC4: Exclude papers whose length is less than 6 pages, since such short papers can present only a general idea but not describe overall approach.
IC5. The paper must be written in English.	EC5. The paper is written in other languages, i.e., not English
IC6. Include original not duplicating papers on water quality of drainage systems.	EC6. Exclude duplicating papers.
IC7. Include peer-reviewed journal publications (research papers), proceeding papers, and reviews.	EC7. Exclude shoer papers, grey literature, posters, Master's theses, Doctoral theses, and books.
IC8. The bibliometric data (i.e., title, keywords, and abstract) of the paper is provided.	EC8. The bibliometric data are missing.

2.1.5. Formulate Paper Selection Strategy

For the inclusion/exclusion, we have used the following paper selection strategy (PSS):

- PSS-1. Run the search strings at the selected sources;
- PSS-2. Apply research field (i.e., search scope) and language restrictions (i.e., in Table 1, IC5, EC5);
- PSS-3. Merge two sets of papers (i.e., from WoS and Scopus);
- PSS-4. Exclude duplicating papers (i.e., in Table 1, IC6 and EC6);
- PSS-5. Extract the title, abstract, and keywords for the primary set of papers (i.e., in Table 1, IC8 and EC8);
- PSS-6. Evaluate a primary set of papers (the title, abstract, and keywords) according to IC1 and EC1;

- PSS-7. Read whole text of the secondary set of papers and extract necessary information based on data extraction strategy (see Section 2.1.6).

2.1.6. Formulate Data Extraction Strategy

The data extraction process was conducted according to Table 3, which was developed based on the previously defined research questions. It consists of seven data items (DIs).

Table 3. Data extraction template.

DI No.	Extracted Item	Description or Possible Values	RQ
1.	Reference	Reference to the study	--
2.	Year	Year of publication	RQ1, RQ6
3.	Advantage of CD drainage over FD	Advantage of controlled drainage (CD) over free drainage (FD)	RQ5, RQ6
4.	Climate changes	Does the article discuss the impact of climate change on the research results?	RQ2, RQ6
5.	Type of model	Use of artificial intelligence (AI)	RQ3, RQ6
6.	Used approach (computer model)	DRAINMOD; RZWQM; RZ-SHAW; DNDC; HYDRUS-2D; PHREEQC; AnnAGNPS; GFDL-ESM4; UKESM1-0-LL; MPI-ESM1-2-HR	RQ3, RQ6
7.	Field studied/application domain (biogenic materials and other)	Nitrates; nitrites; ammonium; nitrogen; phosphates; phosphorus	RQ4, RQ6

The first two authors performed the initial data extraction from the selected studies. The three authors then conducted a thorough review and discussion of all results.

2.1.7. Formulating Data Synthesis and Analysis Strategy

To answer RQs, the following data synthesis and analysis strategy was formulated. For the initial analysis, visualization, and quantitative analysis of all the DIs, Microsoft Excel was used. DI1 and DI2 were analyzed using a grouping of DI1 regarding the publication years.

2.2. Conducting the Review

In this second step, the SLR is conducted based on the protocol defined in the first step, i.e., planning the review. The following are the key results of those steps involved in this phase.

2.2.1. Selecting Primary Studies

The primary studies search process began with an exploration of the selected digital databases, i.e., WoS and Scopus. The first search process in the digital databases was conducted on 30 September 2023 and subsequently supplemented on 11 January 2025. Initially, the search string returned a total of 437 studies (see Table 4), which were filtered by the first two authors according to the formulated paper selection strategy (Section 2.1.5). The second phase (PSS2) of filtering results according to the research field and language restrictions yielded 409 studies. Excluding duplicates (PSS4) from the set of studies yielded 318 non-duplicating studies. After final filtering (PSS-7), 144 studies were left for the data extraction. The PSS-1 to PSS-7 steps were executed mainly by the first two authors. The third author was invited to confirm the search findings and list of selected studies.

Table 4. Number of papers (articles (As) or proceedings papers (PPs)) or reviews (Rs) for each PSS.

Years	PSS-1				PSS-2			
	As	PPs	Rs	All	As	PPs	Rs	All
Web of Science (WoS)								
1985–2024	158	37	8	192 *	147	36	8	180
Scopus								
1985–2024	163	74	8	245	149	73	7	229
The merged set of papers (PSS-3)				Exclude duplicating papers (PSS-4)				
1985–2024	296	109	15	409	231	87	0 **	318
Filtered set of papers (PSS-6)				A final set of papers (PSS-7)				
1986–2024	128	42	0	170	106	38	0	144

* some papers belong to articles (As) and proceedings papers (PPs). ** Mendeley divided the articles into journal articles and conference papers.

2.2.2. Performing Data Extraction and Data Synthesis

The data extraction was performed based on the data extraction template presented in Table 3. The summarized results can be found in Table 4. The data synthesis was performed based on the data synthesis strategy described in Section 2.1.7 and presented in the forthcoming results.

2.3. Validity Evaluation

In this SLR, we have identified the following types of validity: internal, external, construct, and conclusion. Although we carefully followed the SLR process to minimize the threats to the validity of the results and conclusions drawn, we faced some threats as discussed below.

The construct validity category includes those major threats identified in this SLR. First, we used brainstorming with all the study's authors to define RQs and analyze similar reviews in the related works section. RQs were explicitly developed to achieve the defined aim and different aspects of drainage systems in the field of Environmental Engineering. The questions were systematically answered and finalized through several iterative improvement processes. Second, the inclusion of all the relevant studies in the field is not guaranteed if they are not included in the WoS or Scopus. Those databases were chosen for this study since they contain the main amount of papers on the analyzed topic.

Also, inclusion and exclusion criteria were used to guide the selection process, with the aim of mitigating this risk. To ensure the reliability of the research, multiple researchers were involved in the selection process for each article.

The internal validity refers to the accuracy and directness of the statements made in the reviewed papers regarding the defined RQs. A review of the related existing literature reviews was performed to mitigate this threat.

In order to answer the final RQ, an inductive thematic analysis was performed to identify different themes within the literature based on the papers' keywords. First, the first and the second author independently selected keywords from the analyzed papers. Second, the frequency of keywords was calculated using the Microsoft Excel tool. Third, those keywords were classified into several topics. This classification task and the result were reviewed by the second and third author. The results were discussed and validated weekly by all authors to resolve conflicts and assess bias, as well as to determine the degree of certainty. Adopting this described procedure enables us to mitigate any potential bias on the part of the authors.

The external validity of this SLR refers to the generalizability of its results and conclusions. These findings are applicable only to drainage systems within the domain of Environmental Engineering. We do not attempt to extrapolate beyond this scope to draw generalizations. Therefore, external validity threats are minimized. All steps in this review are described in detail in Section 3, where the research method is outlined.

3. Results

The results of our systematic literature review are presented in Table 5. The structure is composed of thirteen columns, twelve of which display specific data on the analyzed RQs as follows: year of publication (Year); number of publications (Number); (1)—advantage of controlled drainage (CD) over free drainage (FD); (2)—climate change issues; (3) the use of mathematical model or artificial intelligence (AI); (4) DRAINMOD; (5) RZWQM; the remaining columns describe the analyzed biogenic materials: (6) nitrates, (7) nitrites, (8) ammonium, (9) nitrogen, (10) phosphates, and (11) phosphorus.

Table 5. The results of the systematic literature review (number—how many times the topic is found in the papers; 0—not analyzed).

Year	Number	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
1986	1	1	0	0	0	0	1	0	0	0	0	1
1987	1	1	0	0	0	0	0	0	0	0	0	0
1989	1	1	0	1	1	0	0	0	0	0	0	0
1990	1	1	0	1	1	0	1	0	0	1	0	1
1991	1	1	0	0	0	0	1	0	1	0	0	1
1992	2	2	0	1	1	0	2	0	0	0	0	0
1993	2	2	0	1	1	0	1	0	0	1	0	2
1994	2	2	0	0	0	0	1	0	0	1	0	2
1995	3	3	0	3	3	0	3	0	1	0	0	1
1996	2	1	0	1	1	0	2	0	0	1	0	0
1997	2	1	0	1	1	0	2	0	0	0	0	0
1998	6	5	0	1	1	0	5	1	1	2	0	2
1999	1	0	0	1	1	0	1	0	0	0	0	0
2000	3	3	0	0	0	0	3	0	0	1	0	0
2001	4	3	0	0	0	0	4	1	0	0	0	2
2002	2	1	0	1	1	0	2	0	0	0	0	0
2003	5	4	0	2	2	0	4	1	1	2	0	0
2004	10	8	1	0	0	0	7	0	1	2	0	2
2006	2	0	0	0	0	0	1	0	1	0	0	2
2007	6	3	1	2	1	1	2	0	0	1	0	3
2008	2	2	0	0	0	0	0	0	0	1	0	2
2009	6	3	0	2	2	0	3	0	0	1	0	1
2010	9	6	0	4	3	1	6	0	1	4	2	4

Table 5. Cont.

Year	Number	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
2011	3	3	0	0	0	0	2	0	1	2	0	2
2012	6	4	0	4	2	1	5	2	2	4	0	1
2013	2	1	0	0	0	0	1	1	0	0	0	2
2014	3	1	1	0	0	0	1	0	0	2	1	2
2015	6	1	0	1	0	0	3	1	1	3	1	3
2016	4	4	0	1	0	1	4	0	0	1	0	0
2017	7	3	0	2	1	0	5	0	1	1	0	2
2018	6	5	0	1	0	1	4	2	1	3	0	4
2019	2	0	0	1	0	1	0	0	0	1	0	2
2020	6	3	0	2	0	2	2	0	1	4	0	3
2021	8	5	1	4	4	0	5	0	3	2	1	1
2022	5	4	0	1	0	0	2	0	0	1	0	4
2023	8	6	3	2 (AI)	1	1	6	2	3	5	4	6
2024	4	4	0	0	0	0	2	0	0	3	1	4

The results of this SLR regarding the defined research questions are presented as follows.

3.1. When Are Studies on the Drainage Topic Published? (RQ1)

The period (1986–2024) of the found papers on the drainage topic (RQ1) is presented in Figure 1. The analysis indicates a small increase in the papers related to the analyzed topic, as depicted by the dotted trendline in Figure 2. This could be interpreted as an increase in the relevance and interest of the topic under consideration. The total number of published papers analyzed in this research increased by more than five times over the period. By the year 2000, the number of publications on the subject had reached 28, constituting 19.5% of the total number of papers published during that period. In the subsequent period, the number of publications increased to 116, accounting for 80.5% of the total. To provide a more detailed overview of trends, the number of articles was grouped into five-year periods and analyzed.

During the initial five-year period (1986–1990), four articles were published. The subsequent five-year periods (i.e., 2006–2010, 2016–2020, and 2021–2024) each saw the publication of 25 articles. The relatively small number of articles in the initial period (1986–1990) may indicate that the topic of controlled drainage was not yet as pertinent in research as it has been in recent years. The number of publications began to increase in the fourth decade, with 21 articles being published. Consequently, the number of articles mentioning controlled drainage as a priority drainage system has exhibited a consistent upward trend. Over the past five years, such articles accounted for 76% of the total number of articles examined, suggesting that the topic is becoming increasingly prevalent in discussions.

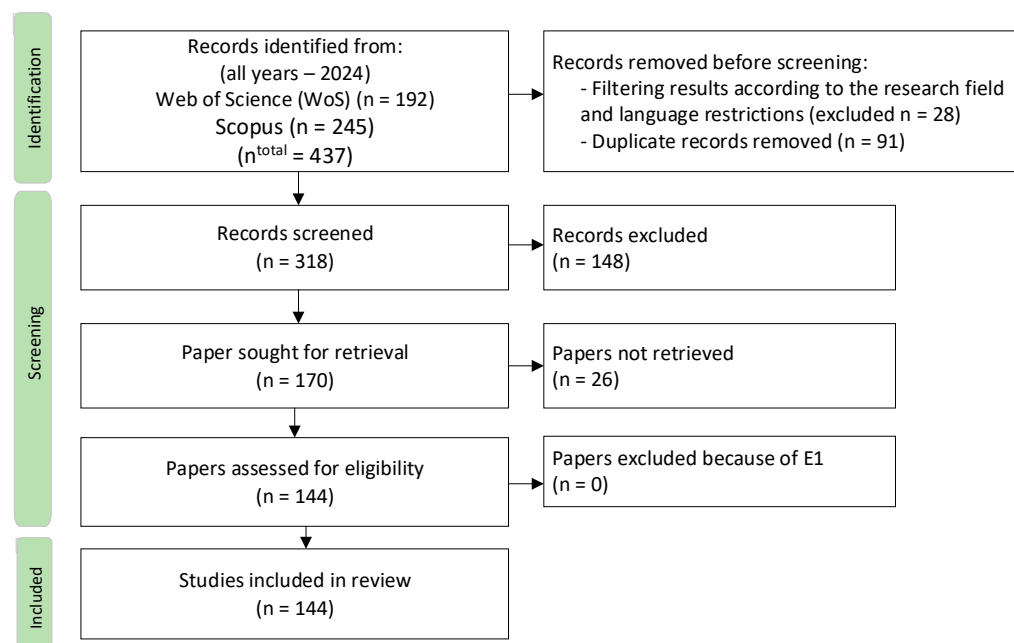


Figure 1. The PRISMA flow diagram (according to [25]) for this systematic literature review.

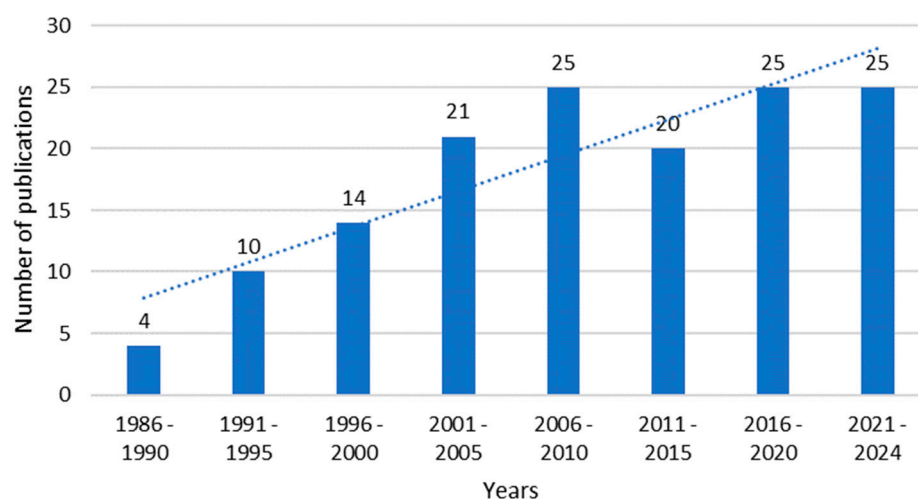


Figure 2. Overview of frequency and types of publications (RQ1).

3.2. Is Climate Change Considered in Drainage Water Quality Studies? (RQ2)

Recent discourse on climate change and its consequences has increased both the frequency and intensity. The Intergovernmental Panel on Climate Change (<https://www.ipcc.ch/>) (accessed on 11 January 2025) has also stated in its report that climate change has recently led to the observation of extreme weather events, including heat waves, heavy rainfall, and droughts. Climate change has led to increased precipitation in many regions. Consequently, Europe and other regions with a similar climate zone have experienced an increase in heavy rains and flash floods.

During the initial period of 1986–2000, there was a lack of publications explicitly linking drainage water quality studies to the pressing issue of climate change (Figure 3). As illustrated in Figure 3, there has been a lack of analysis over an extended period concerning the impact of climate change on drainage systems and the water discharged from them. In the subsequent periods from 2001 to 2015, a single publication was published every five years. This indicates that the subject has not been given high priority in research initiatives, despite the adoption of numerous significant international documents on climate change

since 1997. Among these is the Kyoto Protocol, adopted in 1997 and entered into force in 2005, which aims to combat global warming. The Millennium Ecosystem Assessment (2001) is another relevant document, as it highlights the impact of climate change on water resources. The Johannesburg Sustainable Development Meeting (2002) focused on water resources and the impact of climate change on the surrounding environment. The number of publications in the last five-year period from 2021 to 2024 has increased to four. This suggests that the impact of climate change is increasingly being analyzed in a growing number of scientific fields.

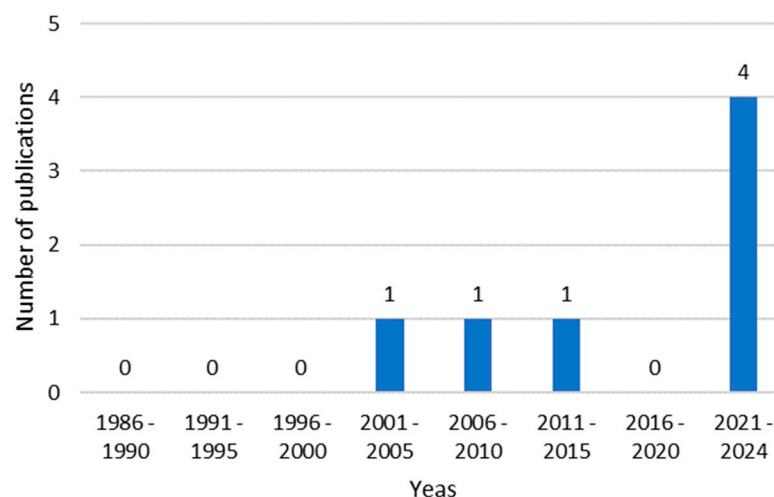


Figure 3. Climate change consideration in drainage water quality studies (RQ2).

The increasing frequency of floods, droughts, and other phenomena that directly or indirectly impact drainage water quality has led to a notable rise in research interest and a concomitant increase in the number of published articles.

The limited number of publications addressing climate change in drainage water quality studies may be attributable to the complexity of the issue, which necessitates specialized research and a substantial data set and resources. Climate change, akin to drainage water quality, is influenced by numerous processes and factors (precipitation, humidity, temperature, fertilizer application, cultivation method, crops grown, etc.). As a result, the issue remains peripheral to scientific priorities, despite its indisputable significance.

3.3. What Computer Tools Are Used to Model and Analyze Drainage Systems? Is Artificial Intelligence Used? (RQ3)

The period of the found works on mathematical models (RQ3) (1986–2024) is presented in Figure 4. As illustrated in Figure 4, there is a clear increase in the need for computer programs and mathematical models to solve environmental problems.

The data indicate that while there has been an increase in the use of mathematical model over time, they are not yet widely adopted. Of the 144 publications reviewed, only 42 (29%) used mathematical modeling programs. A comparison of the ratio of published articles to mathematical models used over the years indicates a decreasing trend. From 1986 to 1995, the proportion of articles employing mathematical models increased to as high as 50% of all published articles on the topic. Subsequently, between 1996 and 2005, the ratio decreased to as low as 20%, and between 2006 and 2024, it was to be around 28–29%. Please note that the SLR revealed that the authors employed different computer tools to model and analyze the drainage systems (see Table 6).

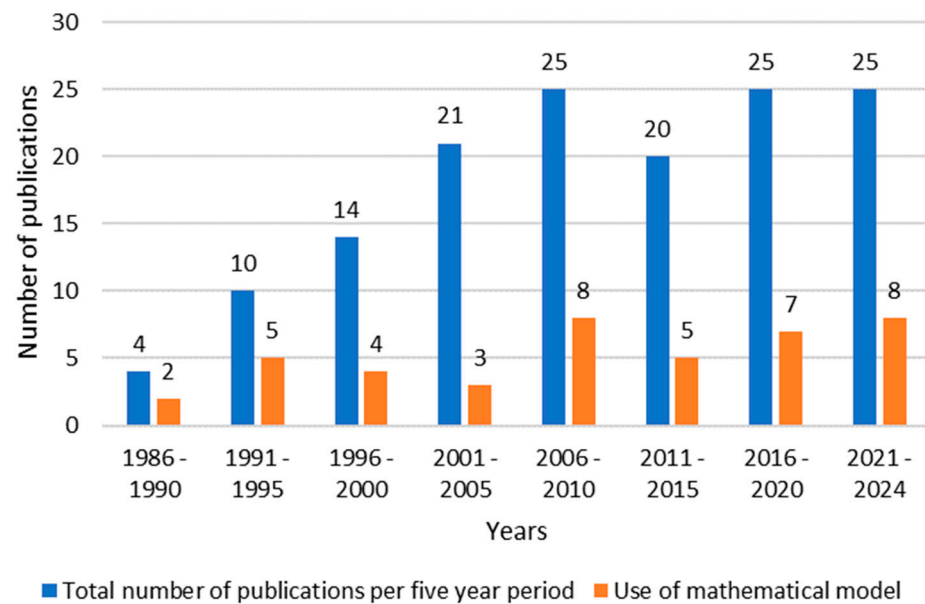


Figure 4. The mathematical models used in drainage water quality studies (RQ3).

Table 6. Computer tools/simulation programs used.

Computer Tools	Description	References
DRAINMOD	DRAINMOD is a hydrological model used to analyze drainage and soil moisture conditions. It is a process-based, distributed, field-scale model developed to describe the hydrology of soils with poor drainage and those that have been artificially drained. The model is based on water balances in the soil profile, on the field surface, and, in some cases, in the drainage system [29].	[30–34]
RZWQM	Root Zone Water Quality Mode (RZWQM) is a root zone water and nutrient model with a focus on water quality and plant interactions. It simulates major physical, chemical, and biological processes in an agricultural crop production system. RZWQM is a process-based model that simulates the growth of the plant and the movement of water, nutrients, and pesticides over, within, and below the crop root zone of a unit area [35]. It is one-dimensional, meaning it is vertical in the soil profile.	[35–37]
DNDC	DeNitrification-DeComposition (DNDC) is a model of the land and nitrogen cycles used to simulate greenhouse gas emissions [38].	[39]
HYDRUS-2D	HYDRUS-2D is a model of soil moisture and solute movement that is based on physical equations.	[40]
PHREEQC	PHREEQC is a chemical reaction model that focuses on geochemical processes in solutions.	[41]
AnnAGNPS	The Annualized Agricultural Nonpoint Source Pollution Model (AnnAGNPS) is a model used to predict erosion and pollution in the agricultural sector.	[42]
GFDL-ESM4, UKESM1-0-LL, MPI-ESM1-2-HR	The Geophysical Fluid Dynamics Laboratory Earth System Model (GFDL-ESM4) is a comprehensive earth system model designed for climate change simulations. The United Kingdom Earth System Model (UKESM1-0-LL) is a sophisticated tool used to make precise climate predictions. The Max Planck Institute Earth System Model (MPI-ESM1-2-HR) employs physical equations to model climate systems. As with GFDL and UKESM, AI components can be used in specific areas.	[43]
NN	In the field of machine learning, a neural network (NN) is a model that draws inspiration from the structure and function of biological neural networks present in the brains of animals. In the analyzed article, seven NN models were found. The seven models consist of the following: NN (FNN), deep feedforward NN (DFNN), long short-term memory (LSTM), bidirectional LSTM (Bi-LSTM), closed recurrent block (GRU), general regression NN (GRNN), and radial basis function NN (RBFNN).	[44]

The original DRAINMOD hydrological model has been modified to incorporate sub-models for nitrogen retention and transport in soil and salinity. The analyzed papers used the DRAINMOD-FOREST; DRAINMOD-N; DRAINMOD-NII; DRAINMOD-KREMAI; and DRAINMOD-DSSAT models. The following sub-models are the most frequently referenced in articles: DRAINMOD-N, DRAINMOD-NII, and DRAINMOD-CREAMS. The DRAINMOD-N and DRAINMOD-NII field-scale models are used to predict nitrogen levels. The DRAINMOD-CREAMS model integrates the DRAINMOD hydrological framework with sub-models within the CREAMS framework. This integration facilitates the prediction of the consequences of drainage treatment and the controlled drainage losses of sediment and agricultural chemicals via surface runoff [45]. DRAINMOD was identified in 28 papers (approximately 20% of the publications analyzed and around 37% of the computer tools identified). The oldest article we examined was from 1989, and the most recent one was from 2023.

Another computer tool that was frequently used was the Root Zone Water Quality Model (RZWQM). RZWQM was identified in nine papers (i.e., approximately 7% of the analyzed papers and around 13% of the identified computer tools). The oldest article we reviewed was from 2007, and the most recent one was from 2023. It should be noted that one paper used RZ-SHAW simulation [46]. The new hybrid model integrates the Root Zone Water Quality Model (RZWQM) with the simultaneous approach. The following computer tools were used once each in the analyzed articles: DNDC; HYDRUS-2; PHREEQC; AnnAGNPS; GFDL-ESM4; UKESM1-0-LL; MPI-ESM1-2-HR; and NN. All of these computer tools were utilized after 2010.

The analysis demonstrated that the use of artificial intelligence (AI) is in its early stages within the selected topic. In the context of computer tools (i.e., GFDL-ESM4, UKESM1-0-LL, and MPI-ESM1-2-HR), the utilization of artificial intelligence components is permissible in designated areas [43].

3.4. What Biogenic Substances Are Considered in Drainage Water Quality Analyses? (RQ4)

Water quality is evaluated based on various physical, chemical, biological, and microbiological parameters. In the context of studying drainage systems, the primary focus is on the impact of agricultural activities on the water quality and water quality indicating parameters, such as the leaching of biogenic substances (especially nitrogen and phosphorus) and possible pollution. In the context of irrigation systems and irrigated fields that receive pollutants from external territories, much attention is paid to the following water quality parameters: turbidity, hardness, water temperature, pH, total dissolved solids (TDS), and electrical conductivity (EC) [47,48]. High TDS values can negatively affect soil structure, the quality of plant growth, and the quality of irrigation systems. Increased TDS values in drinking water may mean that such water is unsuitable for use without additional treatment and contains an excessive amount of harmful substances [49]. In the present article, the focus was on the drainage systems and their impact on water quality. Therefore, only parameters characterizing water quality in drainage systems are analyzed below.

Consequently, in the analyzed papers, we have found two main biogenic materials, nitrogen (N) and phosphorus (P), and their compounds, nitrates, nitrites, ammonium, and phosphates, discussed by authors. Their popularity in scientific papers is presented in Figure 5. Note that the size of the bubbles indicates the number of papers analyzing each biogenic material. A review of the literature reveals that until 2010, the focus was primarily on nitrates. However, since 2010, interest in the other (previously mentioned) biogenic substances has also increased. Since 2010, there has been increased interest in phosphorus (P).

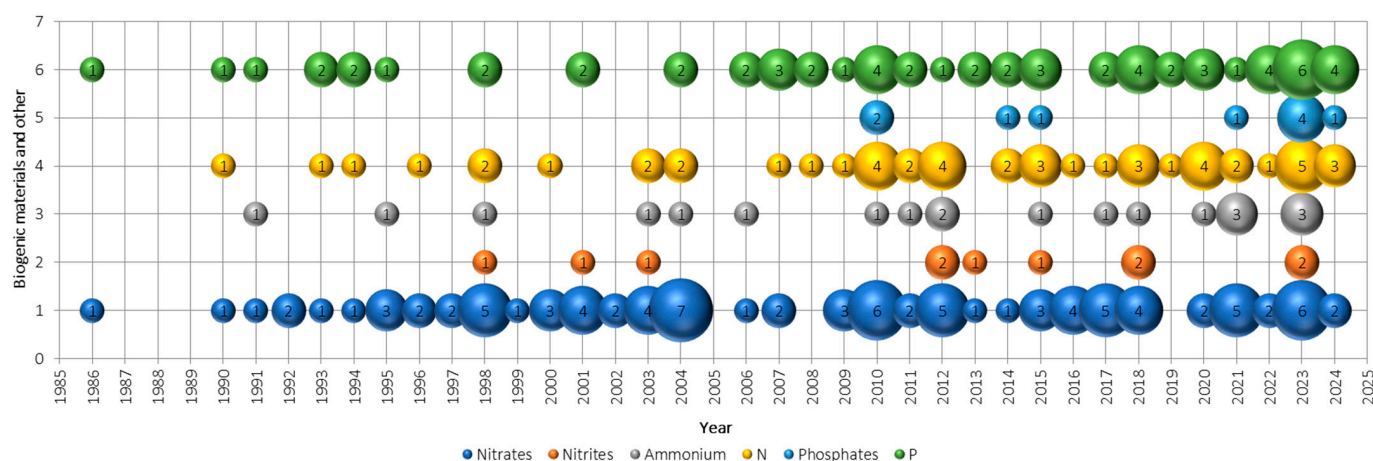


Figure 5. Overview of frequency and types of publications (Note that the numbers in the bubbles present the occurrence of biogenic materials in the analyzed papers).

As illustrated in Figure 5, at the beginning of the period analyzed (1986–1990), articles did not extensively analyze biogenic materials. Subsequently, after 1990, the focus of the first four to five time periods (until 2005) was on nitrates. From 1986 to 2005, 40 articles analyzed nitrate, 14 articles analyzed phosphorus, and 11 articles analyzed nitrogen (see Figure 5). This issue may be related to the expansion of agriculture and the increased use of fertilizers.

The intensive use of fertilizers and pesticides in agriculture may have stimulated research in this area, and meanwhile, phosphate was not mentioned once. This may be due to the fact that their problem was not yet so acute in agriculture.

Since 2005, the study of biogenic substances in drainage water quality samples has become increasingly pertinent. From 2005 to 2024, nitrate analyses were mentioned in 54 articles, i.e., a 26% increase compared to the period 1986–2005. Phosphorus was mentioned in 48 articles (i.e., 29% more frequently than in the previous year), and nitrogen was mentioned in 33 articles (33% more frequently than in the previous year). During this period, phosphate was the subject of ten articles, marking the first investigation into the substance.

Pearson's correlation analysis was used to assess the relationships between different biogenic materials and their concentrations. The correlation analysis is performed using Pearson's correlation coefficient (see Equation (1)) [50].

$$r_{xy} = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2} \sqrt{\sum_{i=1}^n (y_i - \bar{y})^2}} \quad (1)$$

where n is a sample size; i indicates individual sample points; and a and b represent the sample means of two samples, respectively. Table 7 presents Pearson's correlation coefficients for biogenic materials.

As illustrated in Table 7, strong dependencies are identified as follows: (1) N and P (0.659); (2) ammonium and nitrates (0.648); (3) ammonium and N (0.627).

Nitrogen and phosphorus are the principal biogenic substances present in aquatic ecosystems. These biogenic substances are responsible for the growth of plants and algae, as well as for the processes of eutrophication. The concentration of these elements in drainage and surface water bodies can have a significant impact on aquatic ecosystems. The ratio and balance of nitrogen (N) and phosphorus (P) helps scientists to determine which of these elements in water bodies limits or promotes the growth of plants and algae. The concentrations of these nutrients in water can inform the regulation of fertilizer

use in agriculture, the more efficient operation of wastewater treatment plants, and, to a degree, the partial control of ecological balance and the prevention of water bodies being degraded [51–55].

Table 7. Pearson’s correlation coefficients for biogenic materials found in the analyzed papers on the drainage topic.

	Nitrates	Nitrites	Ammonium	N	Phosphates	P	Years
Nitrates	1	0.456	0.648	0.579	0.415	0.306	0.377
Nitrites	0.456	1	0.507	0.526	0.352	0.384	0.301
Ammonium	0.648	0.507	1	0.627	0.567	0.364	0.411
N	0.579	0.526	0.627	1	0.641	0.660	0.628
Phosphates	0.415	0.352	0.567	0.641	1	0.619	0.418
P	0.306	0.384	0.364	0.659	0.619	1	0.634
Years	0.377	0.301	0.411	0.628	0.418	0.634	1

The correlation between ammonium and nitrate concentrations in water can be a valuable indicator of the chemical, biological, and ecological status of the water in relation to soil conditions, nitrogen cycling, and environmental processes [56–58]. The ratio and correlation between these two forms of nitrogen frequently reflect nitrification and denitrification processes. The positive correlation between these two biogenic substances indicates that both forms of nitrogen are present in the drainage water at the same time. This phenomenon can be attributed to two main factors: excess fertilizer application in cultivated fields and/or soil structure disruption. Both of these factors can result in diminished nitrogen retention.

A significant positive correlation between ammonium and nitrogen is often observed in fertilized areas, which are typically farmlands that are equipped with drainage systems. The correlation between these biogenic substances can provide valuable information on ecological processes, pollution sources, and water quality status. This makes them an important component of our analyses.

The year of publication (Year) exhibited a strong correlation with N and P biogenic material concentrations. This indicates that research on the concentrations of these substances remains pertinent throughout the year, a relationship that is particularly evident with the increase in the number of articles on drainage. The study of nitrogen and phosphorus concentrations in drainage water remains a relevant research area, regardless of the time period under consideration. In instances where a drainage system is not functioning efficiently, it can result in significant losses of nitrogen and phosphorus. Consequently, research focused on the concentrations of nitrogen and phosphorus in drainage water assists in identifying the sources of pollution, facilitating the development of effective strategies for its mitigation and enabling the sustainable management and allocation of available resources.

3.5. Is Controlled Drainage Always Better than Free Drainage? (RQ5)

The answer to RQ5 is presented in Figure 6 below. A comprehensive review of 144 articles revealed that 98 of them (i.e., 68%) emphasized the superiority of controlled drainage over free drainage. In essence, controlled drainage is regarded as a more effective and advanced drainage solution, compared to free drainage.

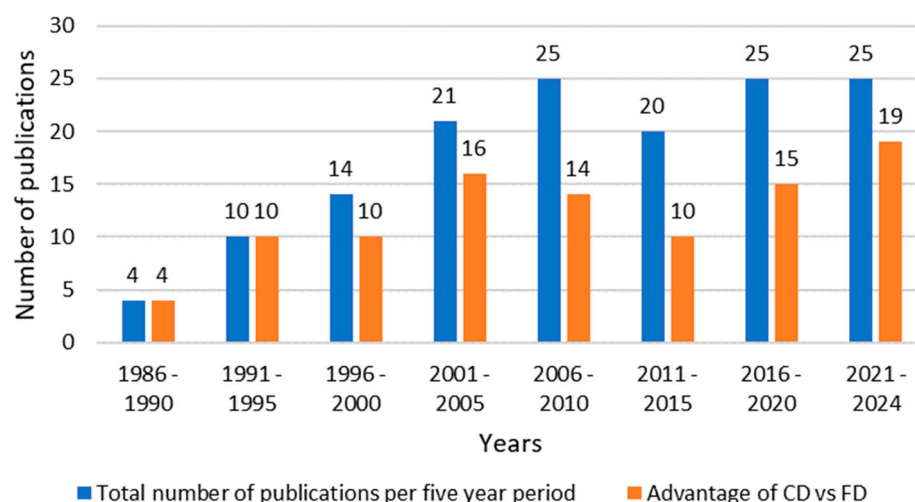


Figure 6. Overview of controlled drainage (CD) vs. free drainage (FD) (RQ5).

A comparison of the advantages and disadvantages of these two drainage systems in scientific papers shows that controlled drainage has more advantages in terms of preserving the quality of the environment during this period. The primary drawback of controlled drainage cited was the substantial initial investment required for its construction [59,60]. The analysis further revealed that implementing controlled drainage systems can substantially reduce total drainage runoff. In certain cases, reported reductions have reached up to 91% [11,56,60].

This reduction in runoff has been shown to decrease the input of biogenic substances into surface waters, while simultaneously protecting aquatic ecosystems and preventing eutrophication processes [61,62]. According to the findings of the research, a reduction in drainage runoff can lead to a substantial decrease in nutrient leaching, ranging from 20% to 80%, across diverse climatic zones and seasons [55,59,63–65]. Researchers have identified another salient aspect in the extant literature that supports controlled drainage over free drainage as the enhancement of crop yields. Controlled drainage facilitates the retention of moisture in the soil, particularly during the dry season, and enables the optimization of fertilizer usage, thereby promoting a more efficient nutrient uptake by the crop [66,67]. Another advantage of controlled drainage documented in the literature is its impact on climate change. The presence of lower levels and concentrations of biogenic substances in the environment has been shown to lead to a reduction in greenhouse gas emissions. This suggests that controlled drainage may have a role in climate change mitigation strategies.

However, controlled drainage may not be feasible in areas with steep slopes or an undulating topography. Proper design, installation, and maintenance are essential for the effective functioning of this drainage system. Inadequate management of the system may result in diminished effectiveness, with potential consequences including field flooding, crop losses, and inadequate nutrient retention, specifically nitrogen and phosphorus. Controlled drainage may not be suitable for crops that are sensitive to excess soil moisture [12,60]. In regions with high precipitation, a poorly managed controlled drainage system may be unable to cope with the volume of water. This approach requires continuous monitoring and management, as well as ongoing farmer involvement. From an economic perspective, it may not be cost-effective for small areas or for the cultivation of low-value crops.

Free drainage is particularly well suited for clay soils and regions with a high moisture level, where the rapid removal of large volumes of water is essential. The installation and maintenance of this type of drainage system is typically less complicated and more cost-effective. However, free drainage systems have the disadvantage of reducing the soil's capacity to retain moisture and increasing the irrigation needs of cultivated fields,

which is particularly problematic in sandy regions. In such areas, water drains rapidly, causing the release of nutrients such as nitrogen and phosphorus from the soil along with drainage water [57,59]. Consequently, soil fertility is depleted, surface runoff is increased, and water quality in neighboring water bodies may be deteriorated, potentially triggering eutrophication processes. The environmental impact of free drainage is therefore inherently negative. Moreover, this system is not capable of adjustment in response to changing climate conditions or adaptation to seasonal variability. Consequently, it offers no contribution to climate change mitigation.

In summary, the drainage system tree of the advantages and disadvantages is presented in Figure 7. A comparison of these two drainages systems reveals that controlled drainage is an effective method of reducing drainage runoff while minimizing the leaching of biogenic substances into surface waters. The long-term benefits of this system include increased crop yields, reduced fertilizer costs, the promotion of sustainable agriculture, and significant ecological benefits for the surrounding environment.

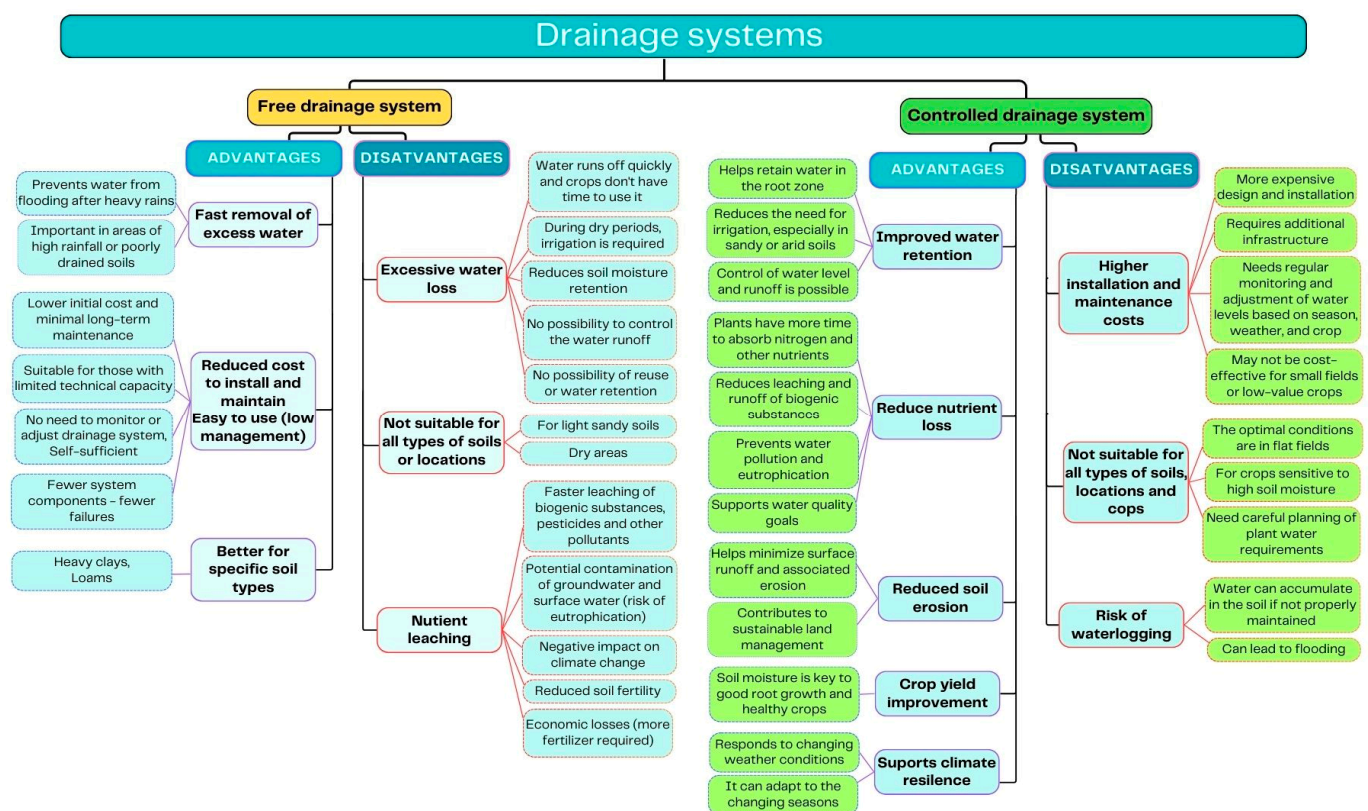


Figure 7. The drainage systems tree of advantages and disadvantages.

The presented drainage systems tree summarizes the advantages and disadvantages of free and controlled drainage systems, presented in the form of descriptive metrics. This enables scientists and practitioners to make informed decisions when selecting an appropriate drainage system. It highlights its key benefits and points out any potential drawbacks.

3.6. What Are the Main Topics Found in the Analyzed Papers on Drainage Systems? (RQ6)

To perform a comprehensive analysis of the trend topics, a selection of keywords from the analyzed papers was performed. The frequency of these keywords in the publications over the five-year period was then calculated, with the data grouped as follows: (1) 1986–1990; (2) 1991–1995; (3) 1996–2000; (4) 2001–2005; (5) 2006–2010; (6) 2011–2015; (7) 2016–2020; (8) 2021–2024. The results of this calculation are displayed on the vertical axes in Figure 8. The selected data, describing the keyword frequency, was analyzed and plotted

using a box plot (see Figure 8). This figure illustrates the most frequently found keywords, namely drainage water management, phosphorus, and water table management.

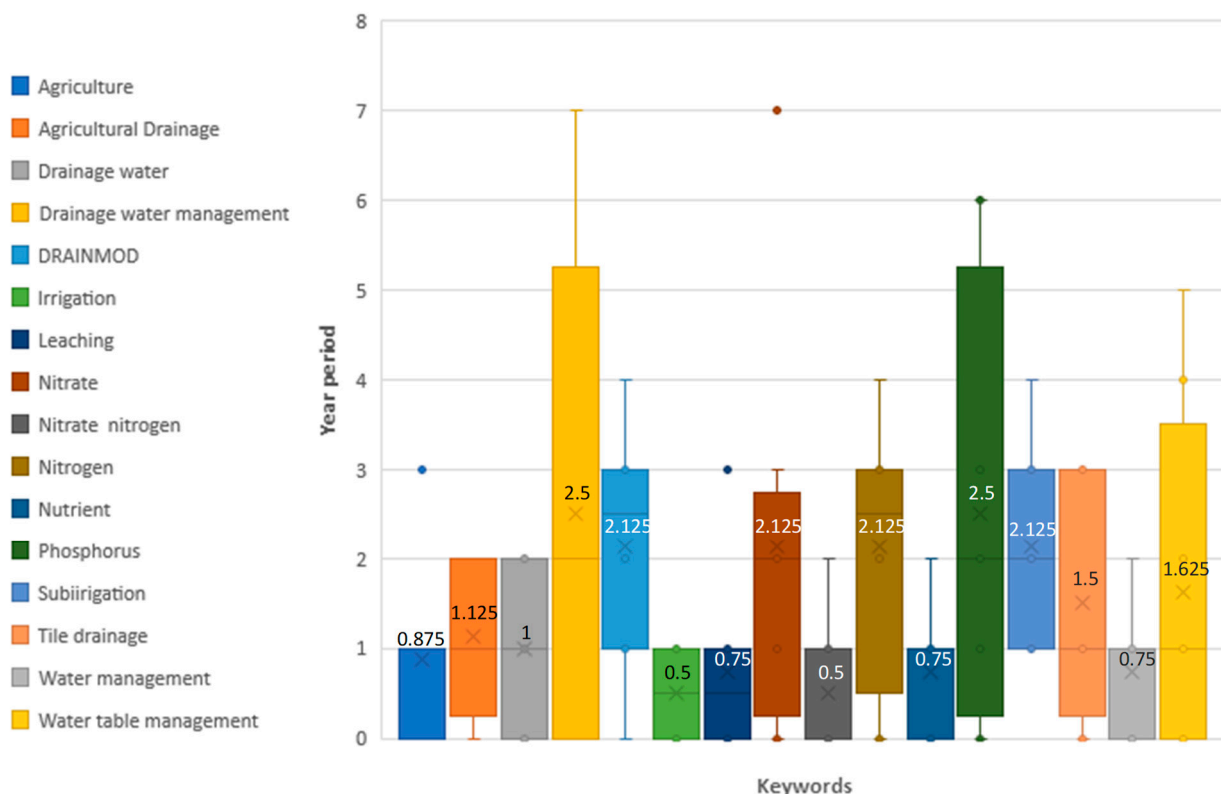


Figure 8. Trends of keywords over the five years (Note that “x” and numbers in the bars present median).

All found keywords were systematically grouped into several topics as follows: Water Management and Quality; Agricultural Practices; Environmental Impact; Modeling and Simulation; Geographical Focus; Climate and Hydrology; and Innovative Practices.

The topic of *Water Management and Quality* analyzes water management and uses keywords related to this topic (drainage water management, water table management, and best management practices). The studies review drainage management systems to assess the impact of controlled drainage, free drainage, or pumped drainage practices on nitrogen and phosphorus concentrations [68]. Issues related to the quality of biogenic substances in wastewater and water are also examined. The following keywords are used: nitrates and leaching, water quality, subirrigation, and controlled drainage.

The topic of *Agricultural Practices* analyzes crop management strategies, different irrigation systems, agricultural chemicals (e.g., herbicides and pesticides), and nutrients. The primary objective of agriculture is to maximize profit through the implementation of drainage, irrigation, fertilizer, and crop protection measures. According to [22], controlled drainage increased crop yield by 0.11%.

The topic of *Environmental Impact* analyzes the impact of agricultural practices and controlled drainage on water quality [69]. A significant focus is placed on the pollution caused by agricultural activities, underscoring the use of keywords such as water pollution and non-point-source pollution. The behavior of sediments and pollutants, as well as their impact on the surrounding environment, are also important factors to consider in the topic (sediment and pollutant behavior).

The topic of *Modeling and Simulation* analyses the use of various computer programs for modeling water flowing through drainage systems. Keywords include hydrologic modelling and computer simulation of water quality and leaching. The model’s applicability to

specific conditions or comparison of models to each other is often examined [30,46]. In this field of research, DRAINMOD [31,33,34,45] is the most widely used computer program. It is a model for drainage and water table management.

The topics of *Geographical Focus and Climate and Hydrology* analyze various agricultural and climatic conditions in different regions. The countries with the most publications are the USA (48%) and Canada (16%). European [51], Asian [70], and New Zealand [9] scientists are also contributing to the field through their articles. The results of the articles cover continents or specific regions.

The topic of *Innovative Practices* analyzes integrated water management systems. In addition to controlled drainage (CD), other measures have been proposed to ensure the quality of the water flowing out of the drain. These include free water surface constructed wetlands (FWS); denitrifying bioreactors (DBR); saturated buffer zones (SBZ); and integrated buffer zones (IBZ). According to the authors of this study, these five measures [20] all contribute to improving the quality of water discharged from drainage.

4. Discussion

After reviewing the relevant literature, we can summarize the results of the systematic literature review on controlled and free drainage types. This summary provides a comprehensive overview of the current state-of-the-art necessary for selecting the most appropriate drainage type. We also examined which biogenic materials were chosen for this study and which computer models were used in the analyzed studies. The systematic review posed five key questions to elucidate the relevance of the topic in the context of the scientific literature. Below we provide answers to those questions.

Regarding RQ1 (“When are studies on the drainage topic published?”), it was found that the overall number of published papers on drainage is relatively small because of the specificity of the topic. Nevertheless, there has been a notable increase in the number of publications in recent years, as the researched topic has gained significant prominence since the beginning of the 21st century. This shift can be attributed to the growing interest in water quality that emerged at the end of the 20th century, which led to the development of new methods to enhance its quality. This interest can be associated with the implementation of sustainable water management systems and an increased focus on the conservation of natural resources. This issue has received significant attention from both the scientific community and those involved in agriculture, with the aim of increasing agricultural productivity [2]. Assessing water quality requires field studies, which require specialized equipment, meticulous preparation, constant observation, and continuous assessment of changing conditions [4,51]. Improvements in laboratory equipment and the development of mathematical models in recent decades have expanded the range of possibilities for research.

When analyzing RQ2 (“Is climate change considered in drainage water quality studies?”), we found a small number of papers regarding this topic. Nevertheless, the number of articles analyzing climate change in drainage water quality studies is increasing. This is due to the absence of direct and very strong mutual influences between drainage systems and climate change, in general. Regardless, there is always a degree of influence between these two components. For example, as precipitation levels decrease, the volume of drainage wastewater also changes, shifting its composition to different seasons. While climate change exerts an influence on drainage water quality through factors such as precipitation, temperature, and agricultural practices, these factors have not been a major focus of research. Therefore, further longitudinal research is necessary in this area.

Regarding RQ3 (“What computer tools are used to model and analyze drainage systems? Is artificial intelligence used?”), we can see that mathematical models are becoming

more popular, but they are not widely used in publications in the field. Various mathematical models are used to simulate hydrological conditions (i.e., DRAINMOD), zone water and nutrients (i.e., RZWQM), land and nitrogen cycles (i.e., DNDC), soil moisture and solute movement (i.e., HYDRUS-2D), chemical reactions (i.e., PHREEQC), erosion and pollution predictions in agriculture (i.e., AnnAGNPS), climate change simulations (i.e., GFDL-ESM4), etc. The most popular of these are DRAINMOD (found in 28 of 144 papers) and RZWQM (found in 9 of 144 papers). Since its invention in 1989 (Evans and Skaggs, 1989), DRAINMOD has been modified by introducing new sub-models. Since 2010, the mathematical modeling of drainage water has been carried out using a growing range of computer tools (DNDC, HYDRUS-2D, PHREEQC, AnnAGNPS, NN, GFDL-ESM4, UKESM1-0-LL, and MPI-ESM1-2-HR). The most recent computer tools were found in 2023 (GFDL-ESM4, UKESM1-0-LL, and MPI-ESM1-2-HR); therefore, their usage in studies is still small. Furthermore, recent findings indicate that certain tools may utilize AI components in specific areas [43]. Nevertheless, it should be noted that the modeling of drainage water quality remains an area where artificial intelligence is not yet employed. This limited usage can be attributed to the absence of extensive, continuous data regarding drainage systems.

The analysis of RQ4 (“What biogenic substances are considered in drainage water quality analyses?”) showed that the analysis of biogenic substances in drainage water is a significant and widely analyzed topic. The relevance of biogenic substances to the agricultural realm, its efficiency, and its influence on global water and climate change can be explained by these substances. Nitrogen (N) and phosphorus (P) are pivotal nutrients in aquatic ecosystems, playing a key role in plant and algal growth and eutrophication processes. The ratio of these elements helps to determine which nutrient limits or promotes biological growth, which helps to regulate the use of agricultural fertilizers [11,51,53,68]. Inefficient drainage systems result in significant losses of N and P, emphasizing the necessity for further research to identify the sources of pollution and develop sustainable mitigation strategies [54,55,71,72]. The presence of elevated levels of ammonium and nitrate in fertilized agricultural areas indicates the simultaneous release of these nutrients into drainage water. This is often due to excessive fertilizer application or soil structure degradation. Summing up, given the significant impact of biogenic substances on water quality, constant monitoring and re-research are essential.

The analysis of RQ5 (“Is controlled drainage always better than free drainage?”) demonstrated the benefits of controlled drainage over free drainage. The drainage tree that has been developed illustrates the merits and drawbacks of free and controlled drainage. The primary benefits identified are as follows: enhanced regulation of drainage runoff, reduction in nutrient losses from agricultural fields, prevention of root rot and soil erosion, control of soil moisture, and improvement in surface water quality. In high rainfall situations, controlled drainage is not sufficient to hold all the water flow, and its effectiveness is reduced. Controlled drainage (CD) does not ensure the quality of the water that flows out, but nearly all articles emphasize its advantage over free drainage (FD). However, implementing controlled drainage systems necessitates significant investments. However, these investments are likely to yield positive returns over time, contributing to both financial and ecological sustainability.

For RQ6 (“What are the main topics found in the analyzed papers on drainage systems?”), after analyzing the articles on drainage systems, we identified several themes related to this topic. These include Water Management and Quality; Agricultural Practices; Environmental Impacts; Modeling and Simulation; Geographic Focus; Climate and Hydrology; and Innovative Practices. When assessing the environmental implications of drainage systems, all these topics are closely related and have a significant impact on water quality and scientific analysis. The most frequently mentioned keywords in the topic are as fol-

lows: drainage water management [73,74], phosphorus [75], nitrate [5], subirrigation [76], DRAINMOD [30,77], water table management, and tile drainage. The analyzed keywords are closely related to the topic under study and reflect the main themes. Despite the wide range of keywords and topics identified, there is a significant gap in research on the use of AI for the study of drainage systems.

5. Conclusions

A systematic literature review on the impact of drainage systems on water quality has shown a notable increase in interest in this subject since 1986, especially in recent decades.

Research on the impact of climate change on drainage water quality is not a priority due to its complexity and the resources required, despite the impact of climate change on the quality of drainage water through changes in precipitation, temperature, and agricultural activities. The application of mathematical models for the analysis of drainage systems has seen a steady rise in recent decades, though it remains limited in its overall use. The most widely used model is DRAINMOD, which encompasses a range of sub-models. The Root Zone Water Quality Model (RZWQM) has also been applied, and while artificial intelligence has potential in this field, it is still in its infancy. A review of the relevant literature indicates that nitrogen (N) and phosphorus (P) are the primary biogenic elements influencing aquatic ecosystems and eutrophication processes. In the current environment, there is a notable absence of leveraging AI tools for modeling and predicting the impact of drainage systems on water quality and climate change.

A recent analysis of published articles reveals that controlled drainage has accounted for 76% of all articles analyzed in the last five years. While controlled drainage is often considered superior to free drainage, its implementation requires a significant initial investment, which makes free drainage a more viable option. The drainage tree proposed in this study provides a more detailed overview of the advantages and disadvantages of both drainage systems. This approach facilitates the evaluation of the prevailing environmental circumstances and the selection of an optimal drainage system for a given context.

Therefore, research in this field remains relevant at all times, as malfunctioning drainage systems can result in substantial losses of biogenic nutrients.

Limitations and Future Research Directions

This SLR provides an analysis of the drainage systems through its systematic review of scientific papers. Despite the relevance and scope of this study, it has some limitations that need to be clarified here. This will provide valuable insights for future research directions.

The keywords for this SLR were oriented towards drainage systems and water quality. In future works, it would be worthwhile to review all papers about drainage systems, not only those related to water quality.

This research is limited to using only two digital databases (i.e., WoS and Scopus). However, those databases are the most relevant for the research topic of drainage systems and provide a significant number of papers for SLRs. In future works, it would be valuable and possible to extend this SLR to other digital databases, especially for the analysis of artificial intelligence usage in the drainage systems topic.

To draw more general conclusions on water quality, it would also be useful to extend this study by complementing it with research on irrigation systems, since both drainage and irrigation systems form a more complete water management system and are increasingly used and needed for sustainable water management. In the course of analyzing irrigation system research, it is planned to expand the scope of research to examine not only biogenic substances but also other water parameters.

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Abbreviations

The following abbreviations are used in this manuscript:

AI	Artificial Intelligence
AnnAGNPS	The Annualized Agricultural Nonpoint Source Pollution Model
CD	Controlled Drainage
DBR	Denitrifying Bioreactors
DIs	Data Items
DNDC	DeNitrification-DeComposition
FD	Free Drainage
FWS	Free Water Surface
GFDL-ESM4	Geophysical Fluid Dynamics Laboratory Earth System Model
IBZs	Integrated Buffer Zones
MPI-ESM1-2-HR	Max Planck Institute Earth System Model
N	Nitrogen
NN	Neural network
P	Phosphorus
PA	Precision Agriculture
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PSS	Paper Selection Strategy
RQ	Research Question
RZWQM	Root Zone Water Quality Mode
SBZs	Saturated Buffer Zones
SRL	Systematic Literature Review
UKESM1-0-LL	United Kingdom Earth System Model

References

1. Almen, K.; Jia, X.; Desutter, T.; Scherer, T.; Lin, M. Impact of Controlled Drainage and Subirrigation on Water Quality in the Red River Valley. *Water* **2021**, *13*, 308. [\[CrossRef\]](#)
2. Ritter, W.F. Agricultural Drainage in the Northeastern U.S.: Past History and Future Challenges. In Proceedings of the World Environmental and Water Resources Congress 2017, Sacramento, CA, USA, 21–25 May 2017; American Society of Civil Engineers: Reston, VA, USA, 2017; pp. 439–452.
3. Rudzianskaitė, A.; Misevičienė, S. Effects of Controlled Drainage on Soil Water Regime and Quality in Lithuania. *Agrofor* **2019**, *4*, 119–127. [\[CrossRef\]](#)
4. Povilaitis, A.; Rudzianskaite, A.; Miseviciene, S.; Gasiunas, V.; Miseckaite, O.; Živatkauskienė, I. Efficiency of Drainage Practices for Improving Water Quality in Lithuania. *Trans. ASABE Am. Soc. Agric. Biol. Eng.* **2018**, *61*, 179–196. [\[CrossRef\]](#)
5. Saadat, S.; Bowling, L.; Frankenberger, J.; Kladviko, E. Nitrate and Phosphorus Transport through Subsurface Drains under Free and Controlled Drainage. *Water Res.* **2018**, *142*, 196–207. [\[CrossRef\]](#) [\[PubMed\]](#)
6. Kalita, P.K.; Cooke, R.A.C.; Anderson, S.M.; Hirschi, M.C.; Mitchell, J.K. Subsurface Drainage and Water Quality: The Illinois Experience. *Trans. ASABE* **2007**, *50*, 1651–1656. [\[CrossRef\]](#)
7. Stankevičienė, R. Comparative Analysis of Nitrogen Compounds Pollution in Controlled and Free Drainage Water. *Environ. Eng.* **2022**, *14*, 1–5. [\[CrossRef\]](#)

8. Rokochynskiy, A.; Volk, P.; Turcheniuk, V.; Tokar, L.; Volk, L.; Mazhayskiy, Y.; Chernikova, O. Drainage Module as Important Factor in Design of Drainage System Reconstruction and Construction Projects in the Polesia Region. In Proceedings of the 19th International Scientific Conference Engineering for Rural Development Proceedings, Jelgava, Latvia, 20–22 May 2020; Faculty of Engineering, Latvia University of Life Sciences and Technologies: Jelgava, Latvia, 2020; Volume 19.
9. Ballantine, D.J.; Tanner, C.C. Controlled Drainage Systems to Reduce Contaminant Losses and Optimize Productivity from New Zealand Pastoral Systems. *N. Z. J. Agric. Res.* **2013**, *56*, 171–185. [\[CrossRef\]](#)
10. Tan, C.S.; Zhang, T.Q.; Drury, C.F.; Welacky, T.W.; Reynolds, W.D. *Impacts of Liquid and Solid Manures under Controlled Drainage with Sub-Irrigation Recycling Systems on Water Quality and Crop Production*; The 2009 Reno, Nevada, 21–24 June 2009; American Society of Agricultural and Biological Engineers: St. Joseph, MI, USA, 2009.
11. Wahba, M.A.S.; El-Ganainy, M.; Abdel-Dayem, M.S.; Gobran, A.; Kandil, H. Controlled Drainage Effects on Water Quality under Semi-Arid Conditions in the Western Delta of Egypt. *Irrig. Drain.* **2001**, *50*, 295–308. [\[CrossRef\]](#)
12. Jia, Z.; Evans, R.O.; Smith, J.T. Effect of Controlled Drainage and Vegetative Buffers on Drainage Water Quality from Wastewater Irrigated Fields. *J. Irrig. Drain. Eng.* **2006**, *132*, 159–170. [\[CrossRef\]](#)
13. Zahoor, I.; Mushtaq, A. Water Pollution from Agricultural Activities: A Critical Global Review. *Int. J. Chem. Biochem. Sci.* **2023**, *23*, 164–176.
14. Kumar, R.; Mishra, A.; Goyal, M.K. Water Neutrality: Concept, Challenges, Policies, and Recommendations. *Groundw. Sustain. Dev.* **2024**, *26*, 101306. [\[CrossRef\]](#)
15. Lowe, M.; Qin, R.; Mao, X. A Review on Machine Learning, Artificial Intelligence, and Smart Technology in Water Treatment and Monitoring. *Water* **2022**, *14*, 1384. [\[CrossRef\]](#)
16. Dayioğlu, M.A.; Türker, U. Digital Transformation for Sustainable Future-Agriculture 4.0: A Review. *Tarim. Bilim. Derg.* **2021**, *27*, 373–399. [\[CrossRef\]](#)
17. Biswas, S.; Halder, S.; Koley, B.; Adak, E.; Sengupta, S. The Role of Precision Farming in Sustainable Agriculture: An Overview. *Int. J. Agric. Ext. Soc. Dev.* **2024**, *7*, 219–228. [\[CrossRef\]](#)
18. Keşicka, B.; Stasik, R.; Kozłowski, M.; Choryński, A. Is Controlled Drainage of Agricultural Land a Common Used Practice?—A Bibliographic Analysis. *Land* **2023**, *12*, 1737. [\[CrossRef\]](#)
19. Kannazarova, Z.; Juliev, M.; Abuduwaili, J.; Muratov, A.; Bekchanov, F. Drainage in Irrigated Agriculture: Bibliometric Analysis for the Period of 2017–2021. *Agric. Water Manag.* **2024**, *305*, 109118. [\[CrossRef\]](#)
20. Carstensen, M.V.; Hashemi, F.; Hoffmann, C.C.; Zak, D.; Audet, J.; Kronvang, B. Efficiency of Mitigation Measures Targeting Nutrient Losses from Agricultural Drainage Systems: A Review. *Ambio* **2020**, *49*, 1820–1837. [\[CrossRef\]](#)
21. Keşicka, B.; Stasik, R.; Kozłowski, M. Effects of Modelling Studies on Controlled Drainage in Agricultural Land on Reduction of Outflow and Nitrate Losses—a Meta-Analysis. *PLoS ONE* **2022**, *17*, e0267736. [\[CrossRef\]](#)
22. Wang, Z.; Shao, G.; Lu, J.; Kun, Z.; Yang, G.; Ding, J. Effects of Controlled Drainage on Crop Yield, Drainage Water Quantity and Quality: A Meta-Analysis. *Agric. Water Manag.* **2020**, *239*, 106253. [\[CrossRef\]](#)
23. Kitchenham, B.; Charters, S.M. *Guidelines for Performing Systematic Literature Reviews in Software Engineering*; Keele University: Staffs, UK; Durham University: Durham, UK, 2007.
24. Kitchenham, B.; Pearl Brereton, O.; Budgen, D.; Turner, M.; Bailey, J.; Linkman, S. Systematic Literature Reviews in Software Engineering—A Systematic Literature Review. *Inf. Softw. Technol.* **2009**, *51*, 7–15. [\[CrossRef\]](#)
25. Page, M.J.; Moher, D.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; Shamseer, L.; Tetzlaff, J.M.; Akl, E.A.; Brennan, S.E.; et al. PRISMA 2020 Explanation and Elaboration: Updated Guidance and Exemplars for Reporting Systematic Reviews. *BMJ* **2021**, *372*, n160. [\[CrossRef\]](#)
26. Gusenbauer, M.; Haddaway, N.R. Which Academic Search Systems Are Suitable for Systematic Reviews or Meta-Analyses? Evaluating Retrieval Qualities of Google Scholar, PubMed, and 26 Other Resources. *Res. Synth. Methods* **2020**, *11*, 181–217. [\[CrossRef\]](#)
27. Garousi, V.; Felderer, M.; Mäntylä, M.V. Guidelines for Including Grey Literature and Conducting Multivocal Literature Reviews in Software Engineering. *Inf. Softw. Technol.* **2019**, *106*, 101–121. [\[CrossRef\]](#)
28. Dybå, T.; Dingsøyr, T. Empirical Studies of Agile Software Development: A Systematic Review. *Inf. Softw. Technol.* **2008**, *50*, 833–859. [\[CrossRef\]](#)
29. Skaggs, R.W.; Youssef, M.A.; Chescheir, G.M. DRAINMOD: Model Use, Calibration, and Validation. *Trans. ASABE* **2012**, *55*, 1509–1522. [\[CrossRef\]](#)
30. Youssef, M.A.; Liu, Y.; Chescheir, G.M.; Skaggs, R.W.; Negm, L.M. DRAINMOD Modeling Framework for Simulating Controlled Drainage Effect on Lateral Seepage from Artificially Drained Fields. *Agric. Water Manag.* **2021**, *254*, 106944. [\[CrossRef\]](#)

31. Negm, L.M.; Youssef, M.A.; Jaynes, D.B. Evaluation of DRAINMOD-DSSAT Simulated Effects of Controlled Drainage on Crop Yield, Water Balance, and Water Quality for a Corn-Soybean Cropping System in Central Iowa. *Agric. Water Manag.* **2017**, *187*, 57–68. [\[CrossRef\]](#)
32. Golmohammadi, G.; Rudra, R.P.; Parkin, G.W.; Kulasekera, P.B.; Macrae, M.; Goel, P.K. Assessment of Impacts of Climate Change on Tile Discharge and Nitrogen Yield Using the Drainmod Model. *Hydrology* **2021**, *8*, 1. [\[CrossRef\]](#)
33. Salazar, O.; Wesström, I.; Youssef, M.A.; Skaggs, R.W.; Joel, A. Evaluation of the DRAINMOD–N II Model for Predicting Nitrogen Losses in a Loamy Sand under Cultivation in South-East Sweden. *Agric. Water Manag.* **2009**, *96*, 267–281. [\[CrossRef\]](#)
34. Brevé, M.A.; Skaggs, R.W.; Parsons, J.E.; Gilliam, J.W. Using the DRAINMOD–N Model to Study Effects of Drainage System Design and Management on Crop Productivity, Profitability and NO₃–N Losses in Drainage Water. *Agric. Water Manag.* **1998**, *35*, 227–243. [\[CrossRef\]](#)
35. Development Team, R.; Hanson, J.D.; Ahuja, L.R.; Shaffer, M.D.; Rojas, K.W.; DeCoursey, D.G.; Farahani, H.; Johnson, K. RZWQM: Simulating the Effects of Management on Water Quality and Crop Production. *Agric. Syst.* **1998**, *57*, 161–195.
36. Grewal, H.S.; Qi, Z.; Shedekar, V.; King, K. Using RZWQM2–P to Capture Tile Drainage Phosphorus Dynamics in Ohio. *J. Environ. Qual.* **2024**, *54*, 217–232. [\[CrossRef\]](#)
37. Ma, L.; Malone, R.W.; Heilman, P.; Jaynes, D.B.; Ahuja, L.R.; Saseendran, S.A.; Kanwar, R.S.; Ascough, J.C. RZWQM Simulated Effects of Crop Rotation, Tillage, and Controlled Drainage on Crop Yield and Nitrate–N Loss in Drain Flow. *Geoderma* **2007**, *140*, 260–271. [\[CrossRef\]](#)
38. Gilhespy, S.L.; Anthony, S.; Cardenas, L.; Chadwick, D.; del Prado, A.; Li, C.; Misselbrook, T.; Rees, R.M.; Salas, W.; Sanz-Cobena, A.; et al. First 20 Years of DNDC (DeNitrification DeComposition): Model Evolution. *Ecol. Model.* **2014**, *292*, 51–62. [\[CrossRef\]](#)
39. Smith, W.; Grant, B.; Qi, Z.; He, W.; VanderZaag, A.; Drury, C.F.; Helmers, M. Development of the DNDC Model to Improve Soil Hydrology and Incorporate Mechanistic Tile Drainage: A Comparative Analysis with RZWQM2. *Environ. Model. Softw.* **2020**, *123*, 104577. [\[CrossRef\]](#)
40. Amin Salehi, A.; Navabian, M.; Varaki, M.E.; Pirmoradian, N. Evaluation of HYDRUS-2D Model to Simulate the Loss of Nitrate in Subsurface Controlled Drainage in a Physical Model Scale of Paddy Fields. *Paddy Water Environ.* **2017**, *15*, 433–442. [\[CrossRef\]](#)
41. Jafari, H.; Raeisi, E.; Hoehn, E.; Zare, M. Hydrochemical Characteristics of Irrigation Return Flow in Semi-Arid Regions of Iran. *Hydrol. Sci. J.* **2012**, *57*, 173–185. [\[CrossRef\]](#)
42. Que, Z.; Seidou, O.; Droste, R.L.; Wilkes, G.; Sunohara, M.; Topp, E.; Lapen, D.R. Using AnnAGNPS to Predict the Effects of Tile Drainage Control on Nutrient and Sediment Loads for a River Basin. *J. Environ. Qual.* **2015**, *44*, 629–641. [\[CrossRef\]](#)
43. Kęsicka, B.; Kozłowski, M.; Stasik, R.; Pińskwar, I. Controlled Drainage Effectiveness in Reducing Nutrient Outflow in Light of Climate Changes. *Appl. Sci.* **2023**, *13*, 9077. [\[CrossRef\]](#)
44. Grenon, G.; Hamrani, A.; Madramootoo, C.A.; Singh, B.; von Sperber, C. Neural Network Model Predictions for Phosphorus Management Strategies on Tile-Drained Organic Soils. *Hydrol. Res.* **2022**, *53*, 825–839. [\[CrossRef\]](#)
45. Skaggs, R.W.; Brevé, M.A.; Mohammad, A.T.; Parsons, J.E.; Gilliam, J.W. Simulation of Drainage Water Quality with DRAINMOD. *Irrig. Drain. Syst.* **1995**, *9*, 259–277. [\[CrossRef\]](#)
46. Jiang, Q.; Qi, Z.; Lu, C.; Tan, C.S.; Zhang, T.; Prasher, S.O. Evaluating RZ-SHAW Model for Simulating Surface Runoff and Subsurface Tile Drainage under Regular and Controlled Drainage with Subirrigation in Southern Ontario. *Agric. Water Manag.* **2020**, *237*, 106179. [\[CrossRef\]](#)
47. Zhang, X.; Li, S.; Zhang, L.; Wang, Q.; Wu, M.; Li, J.; Zhang, H.; Fei, L. Simulation and Evaluation of Water Quality Purification Performance in Irrigation District Drainage Ditch Wetlands under the Influence of Regional External Water Inputs. *Ecol. Eng.* **2025**, *212*, 107538. [\[CrossRef\]](#)
48. Hage, M.; Abdulaziz, A.M.; Elbeih, S.F.; Hewaidy, A.G.A. Monitoring Soil Salinization and Waterlogging in the Northeastern Nile Delta Linked to Shallow Saline Groundwater and Irrigation Water Quality. *Sci. Rep.* **2024**, *14*, 27838. [\[CrossRef\]](#) [\[PubMed\]](#)
49. Hage, M.; Hewaidy, A.G.A.; Abdulaziz, A.M. Groundwater Quality Assessment for Drinking, Irrigation, Aquaculture, and Industrial Uses in the Waterlogged Northeastern Nile Delta, Egypt: A Multivariate Statistical Approach and Water Quality Indices. *Model. Earth Syst. Environ.* **2025**, *11*, 59. [\[CrossRef\]](#)
50. Cleff, T. *Exploratory Data Analysis in Business and Economics*; Springer International Publishing: Cham, Switzerland, 2014; ISBN 978-3-319-01516-3.
51. Pham, T.; Yli-Halla, M.; Marttila, H.; Lötjönen, T.; Liimatainen, M.; Kekkonen, J.; Läpikivi, M.; Klöve, B.; Joki-Tokola, E. Leaching of Nitrogen, Phosphorus and Other Solutes from a Controlled Drainage Cultivated Peatland in Ruukki, Finland. *Sci. Total Environ.* **2023**, *904*, 166769. [\[CrossRef\]](#)
52. Hoffmann, C.C.; Zak, D.; Kronvang, B.; Kjaergaard, C.; Carstensen, M.V.; Audet, J. An Overview of Nutrient Transport Mitigation Measures for Improvement of Water Quality in Denmark. *Ecol. Eng.* **2020**, *155*, 105863. [\[CrossRef\]](#)

53. Madramootoo, C.A.; Abbasi, N.A. One Hundred Years of Drainage Development in the Holland Marsh, Canada, and Implications for Long-term Sustainability. *Irrig. Drain.* **2022**, *73*, 294–303. [\[CrossRef\]](#)
54. Omer, A.R.; Miranda, L.E.; Moore, M.T.; Krutz, L.J.; Czarnecki, J.M.P.; Kröger, R.; Baker, B.H.; Hogue, J.; Allen, P.J. Reduction of Solids and Nutrient Loss from Agricultural Land by Tailwater Recovery Systems. *J. Soil. Water Conserv.* **2018**, *73*, 284–297. [\[CrossRef\]](#)
55. Kröger, R.; Moore, M.T.; Farris, J.L.; Gopalan, M. Evidence for the Use of Low-Grade Weirs in Drainage Ditches to Improve Nutrient Reductions from Agriculture. *Water Air Soil. Pollut.* **2011**, *221*, 223–234. [\[CrossRef\]](#)
56. Amatya, D.M.; Gilliam, J.W.; Skaggs, R.W.; Lebo, M.E.; Campbell, R.G. Effects of Controlled Drainage on Forest Water Quality. *J. Environ. Qual.* **1998**, *27*, 923–935. [\[CrossRef\]](#)
57. Williams, M.R.; King, K.W.; Fausey, N.R. Drainage Water Management Effects on Tile Discharge and Water Quality. *Agric. Water Manag.* **2015**, *148*, 43–51. [\[CrossRef\]](#)
58. Baker, J.L.; Melvin, S.W.; Lemke, D.W.; Lawlor, P.A.; Crumpton, W.G.; Helmers, M.J. Subsurface Drainage in Iowa and the Water Quality Benefits and Problem. In Proceedings of the Drainage VIII, Sacramento, CA, USA, 21–24 March 2004; American Society of Agricultural and Biological Engineers: St. Joseph, MI, USA, 2004; pp. 39–050.
59. Ramoska, E.; Bastiene, N.; Saulys, V. Evaluation of Controlled Drainage Efficiency in Lithuania. *Irrig. Drain.* **2011**, *60*, 196–206. [\[CrossRef\]](#)
60. Sathithanantham, S.; Sri Ranjan, R.; Bullock, P. Protecting Water Quality Using Controlled Drainage as an Agricultural Bmp for Potato Production. *Trans. ASABE* **2014**, *57*, 815–826. [\[CrossRef\]](#)
61. Morari, F.; Lugato, E.; Polese, R.; Berti, A.; Giardini, L. Nitrate Concentrations in Groundwater under Contrasting Agricultural Management Practices in the Low Plains of Italy. *Agric. Ecosyst. Environ.* **2012**, *147*, 47–56. [\[CrossRef\]](#)
62. Wang, M.; Yu, S.; Shao, G.; Gao, S.; Wang, J.; Zhang, Y. Impact of Alternate Drought and Flooding Stress on Water Use, and Nitrogen and Phosphorus Losses in a Paddy Field. *Pol. J. Environ. Stud.* **2018**, *27*, 345–355. [\[CrossRef\]](#)
63. Mejia, M.N.; Madramootoo, C.A. Improved Water Quality through Water Table Management in Eastern Canada. *J. Irrig. Drain. Eng.* **1998**, *124*, 116–122. [\[CrossRef\]](#)
64. Ng, H.Y.F.; Drury, C.F.; Serem, V.K.; Tan, C.S.; Gaynor, J.D. Modeling and Testing of the Effect of Tillage, Cropping and Water Management Practices on Nitrate Leaching in Clay Loam Soil. *Agric. Water Manag.* **2000**, *43*, 111–131. [\[CrossRef\]](#)
65. Tan, C.S.; Drury, C.F.; Sultani, M.; Van Wesenbeeck, I.J.; Ng, H.Y.F.; Gaynor, J.D.; Welacky, T.W. Effect of Controlled Drainage and Tillage on Soil Structure and Tile Drainage Nitrate Loss at the Field Scale. *Water Sci. Technol.* **1998**, *38*, 103–110. [\[CrossRef\]](#)
66. Kaur, H.; Nelson, K.A.; Singh, G. Subsurface Drainage and Subirrigation for Increased Corn Production in Riverbottom Soils. *Agron. J.* **2021**, *113*, 4865–4874. [\[CrossRef\]](#)
67. Tan, C.S.; Drury, C.F.; Sultani, M.; Gaynor, J.D.; Welacky, T.W.; van Wesenbeeck, I.J.; Ng, H.Y.F. Effect of Controlled Drainage/Subirrigation on Tomato Yield and Water Quality. *Acta Hortic.* **1997**, *449*, 327–334. [\[CrossRef\]](#)
68. Grenon, G.; Madramootoo, C.A.; von Sperber, C.; Ebtehaj, I.; Bonakdari, H.; Singh, B. Nutrient Release in Drainage Discharge from Organic Soils under Two Different Agricultural Water Management Systems. *Hydrol. Process* **2023**, *37*, e14953. [\[CrossRef\]](#)
69. Wesström, I.; Messing, I.; Linnér, H.; Lindström, J. Controlled Drainage—Effects on Drain Outflow and Water Quality. *Agric. Water Manag.* **2001**, *47*, 85–100. [\[CrossRef\]](#)
70. Dou, X.; Shi, H.; Li, R.; Miao, Q.; Tian, F.; Yu, D.; Zhou, L.; Wang, B. Effects of Controlled Drainage on the Content Change and Migration of Moisture, Nutrients, and Salts in Soil and the Yield of Oilseed Sunflower in the Hetao Irrigation District. *Sustainability* **2021**, *13*, 9835. [\[CrossRef\]](#)
71. Ritter, W.F. Drainage on the Delmarva Peninsula: Past History and Future Challenges. In Proceedings of the 9th International Drainage Symposium Held Jointly with CIGR and CSBE/SCGAB Proceedings, Quebec City, QC, Canada, 13–16 June 2010; American Society of Agricultural and Biological Engineers: St. Joseph, MI, USA, 2010.
72. Fausey, N.R. Comparison of Free Drainage, Controlled Drainage, and Subirrigation Water Management Practices in an Ohio Lakebed Soil. In Proceedings of the 2004 ASAE Annual Meeting, Ottawa, ON, Canada, 1–4 August 2004; American Society of Agricultural and Biological Engineers: St. Joseph, MI, USA, 2004.
73. Kaur, H.; Nelson, K.A.; Singh, G.; Udawatta, R.P. Long-Term Drainage Water Recycling Affects Soil Health and Soil Properties. *J. Soil. Water Conserv.* **2023**, *78*, 309–321. [\[CrossRef\]](#)
74. Cooke, R.; Verma, S. Performance of Drainage Water Management Systems in Illinois, United States. *J. Soil. Water Conserv.* **2012**, *67*, 453–464. [\[CrossRef\]](#)
75. Zhang, T.Q.; Tan, C.S.; Zheng, Z.M.; Welacky, T.; Wang, Y.T. Drainage Water Management Combined with Cover Crop Enhances Reduction of Soil Phosphorus Loss. *Sci. Total Environ.* **2017**, *586*, 362–371. [\[CrossRef\]](#)

76. Sanchez Valero, C.; Madramootoo, C.A.; Stämpfli, N. Water Table Management Impacts on Phosphorus Loads in Tile Drainage. *Agric. Water Manag.* **2007**, *89*, 71–80. [[CrossRef](#)]
77. Skaggs, R.W.; Youssef, M.A.; Chescheir, G.M. Methods to Estimate Effects of Drainage Water Management on Annual Nitrogen Losses to Surface Waters. In Proceedings of the 9th International Drainage Symposium Held Jointly with CIGR and CSBE/SCGAB Proceedings, Quebec City, QC, Canada, 13–16 June 2010; American Society of Agricultural and Biological Engineers: St. Joseph, MI, USA, 2010.

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