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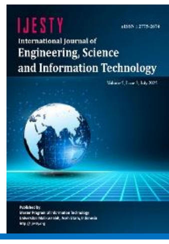

Smart Cropping Pattern: A Systematic Study of Sustainable Agriculture Optimization Model

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Abstract

Irrigated agriculture accounts for more than 40% of global food production despite covering only about 20% of the world's agricultural land. However, climate change, water constraints, and multisectoral pressures on natural resources demand greater efficiency in the management of agricultural systems. One key strategy is determining optimal cropping patterns under conditions of water and land constraints. This study aims to review mathematical approaches, especially Linear Programming (LP)-based optimization models, in developing efficient and sustainable cropping pattern strategies. This study was conducted through a systematic literature review of 185 scientific articles from the Scopus and ScienceDirect databases in the period 2014–2025. The analysis was carried out using the PRISMA method and visualization of research trends through VOS viewer software. The results of the review indicate that optimization models, especially Linear Programs, have been widely used to develop data-based land and water allocation strategies, considering agronomic, economic, and environmental aspects. The increasing number of publications in the last decade reflects the urgency of this theme and the shift towards quantitative-based decision-making in agricultural systems. This study provides a conceptual and applicative basis for the development of sustainable planting strategies that are adaptive to environmental changes.

Keywords: *Cropping Pattern, Irrigation Optimization, Linear Programming, Bibliometrics, Sustainable Agriculture*

1. Introduction

Agriculture is a strategic sector [1] which relies on three main pillars: land, water, and labor. All three are now facing pressure from climate change, population growth, and inter-sector competition. Irrigated agriculture [2][3] contributes more than 40% of global food production despite occupying only about 20% of the world's agricultural land. However, water constraints [4] which is increasingly apparent due to climate change [5][6], population growth [7][8], and competition between sectors means that irrigation systems must be managed efficiently. The availability of water is increasingly limited. [9][10][11] become a major challenge in modern agricultural systems. Climate change [12][13] and increasing pressure on natural resources demands greater efficiency in agricultural management systems. The main challenge faced is determining cropping patterns that can optimize production and farmer income [14], especially in conditions of land and water constraints. Optimization models [15] as a mathematical approach provide an analytical mechanism to evaluate various alternatives for water and land allocation quantitatively. This allows the formulation of efficient, data-based resource management strategies that are oriented towards the long-term sustainability of agricultural systems.
Various optimization methods [16] has been applied in agricultural studies, ranging from linear programming (LP) which is used to determine the combination of cropping patterns that provide maximum yields within certain limits, to dynamic programming (DP) which considers changes in conditions over time, such as seasonal water availability. In addition, the integration of optimization models [17] with climate, hydrology, and irrigation system data allows for more adaptive planning to environmental variability. The use of this technology not only helps in improving resource efficiency, but also supports food security [16][17] at local and national levels.
Determining cropping patterns not only considers agronomic aspects, but also water use efficiency, market prices, planting seasons, and crop rotation. Therefore, the integration of optimization models and planting scheduling is an attractive solution to increase yields and sustainability of agricultural systems[20]. Limited land and water availability [21]–[26] which is increasingly decreasing requires a more efficient and sustainable irrigation management strategy. [27]–[29]. One approach that can be applied is selecting plant types [30] which has high economic value [31][32]with relatively low water requirements. The selection of appropriate plants can not only reduce pressure on water resources, but also increase farmers' income. To obtain optimal results, careful planning and analysis are needed in determining the combination of plant types and planting patterns that are appropriate to local agro-ecosystem conditions. Optimization modeling

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approach [33][34] provide a systematic quantitative framework for designing efficient resource allocation, thus enabling the achievement of maximum economic output while still considering sustainability aspects.

The right planting pattern is one of the main keys to increasing agricultural productivity [27][35], efficient use of resources, as well as sustainable food security [36][37]. In practice, farmers often face resource constraints such as land, water, labor, and market price fluctuations. Therefore, a data-based and quantitative approach is needed to help make optimal decisions. Mathematical modeling such as Linear Programming (LP) offers a systematic approach to formulating crop allocation decisions based on specific limitations and objectives. Through this model, optimal planting strategies can be identified to maximize income while minimizing resource waste[38].

This study aims to review studies that build mathematical models that integrate agronomic and economic factors to produce optimal cropping patterns under conditions of water and land constraints. The optimization model also supports decision making [39] data-based for farmers, land managers, and policy makers. Cropping pattern optimization model [40]–[43] based on LP as a rational and efficient agronomic decision-making tool. Research on cropping pattern optimization has grown rapidly in the last two decades, along with the increasing need for efficient use of agricultural resources. Mathematical approaches, especially Linear Programming (LP), are one of the methods widely used to determine optimal land allocation and crop combinations.

2. Method

The method used in this study is a systematic literature review of scientific publications that discuss irrigation optimization modeling in relation to determining or scheduling cropping patterns. Data sources were obtained from two main scientific databases, namely Scopus and ScienceDirect, with a publication range between 2014 and 2025. The literature search process used the main keywords: irrigation optimization, cropping pattern, linear programming, water allocation, and sustainable agriculture. Article selection was carried out in stages, starting from initial identification based on the title and abstract, followed by a review of the full content of the article to assess the suitability of the topic to the focus of the study. Inclusion criteria included articles that contained mathematical or quantitative modeling related to irrigation management and cropping patterns, and provided conceptual and applied contributions to sustainable agricultural planning.

Articles that were only descriptive, did not include an optimization approach, or were thematically irrelevant were excluded from the analysis. The keywords searched in the SCOPUS database were “Crop AND Pattern AND Optimization AND Model”. The search using keywords related to irrigation optimization models with a time span of 2014–2025 resulted in 185 articles: 52 articles were obtained from the Scopus database, and 133 articles were obtained from the ScienceDirect database. We screened the studies using three main steps to eliminate documents that were not related to the focus of this review. The methodology is described according to the prism flow diagram in Figure 1. By searching for articles related to irrigation models in the SCOPUS database, eligible articles were obtained (n = 52). Then, from the results of this screening, relevant articles were sorted according to the searched criteria. Fig 2. Research from the SCOPUS database related to irrigation optimization modeling.

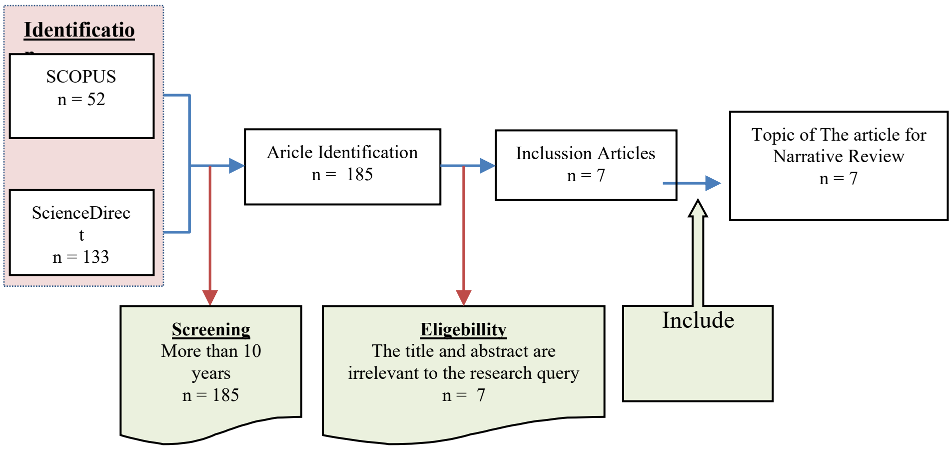

Fig 1. Prism flow diagram

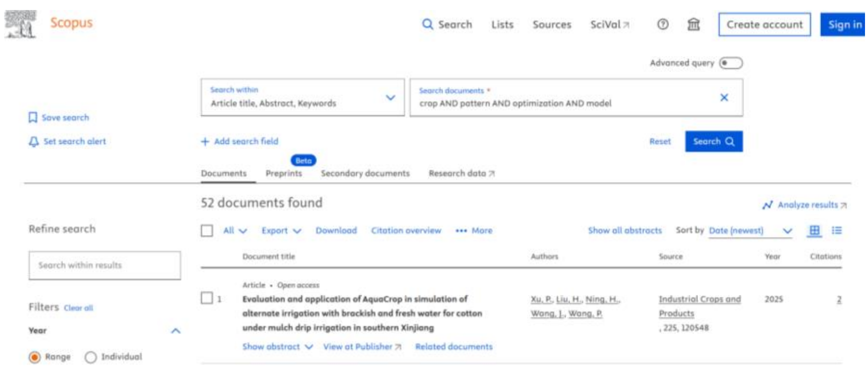

Fig 2. Research from the SCOPUS database related to crop pattern optimization model

Related searches on the same topic were conducted using the ScienceDirect database. From the search, 133 articles were obtained which were then screened again to find articles that were eligible or relevant to the search focus. Fig 3. Displays the screening results window related to the topic of cropping pattern optimization models.

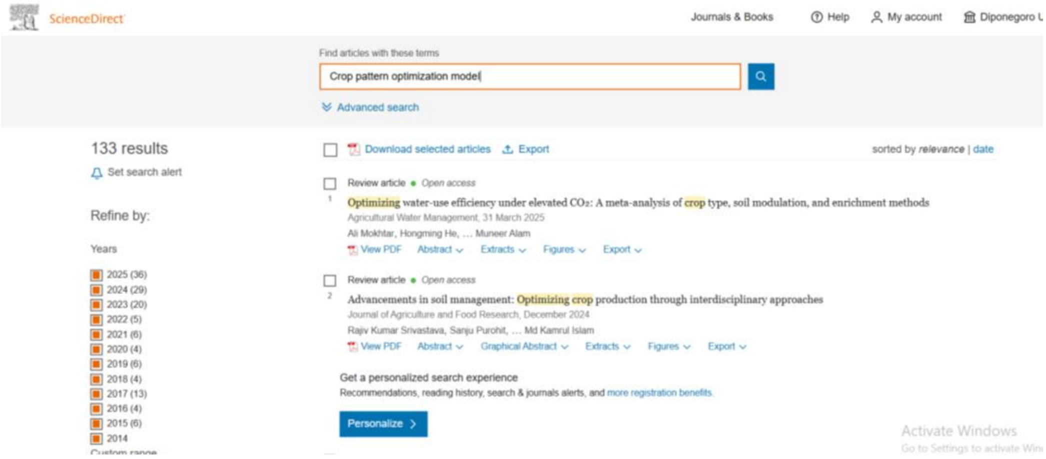

Fig 3. Research from the Sciencedirect database related to crop pattern optimization model

Mapping and developing research trends can be done through bibliometric analysis, which includes keyword identification, co-word analysis, and mapping [44][45] of collaboration networks between authors or institutions. In this study, the analysis was carried out using software in the form of VOSviewer to visualize the relationship between topics and the dynamics of publications from year to year (Figure. 4). Figure 5 shows that the number of publications related to the research theme has experienced significant growth every year. This reflects the increasing interest, urgency, and relevance of the topic among researchers, as well as the potential direction of future research development.

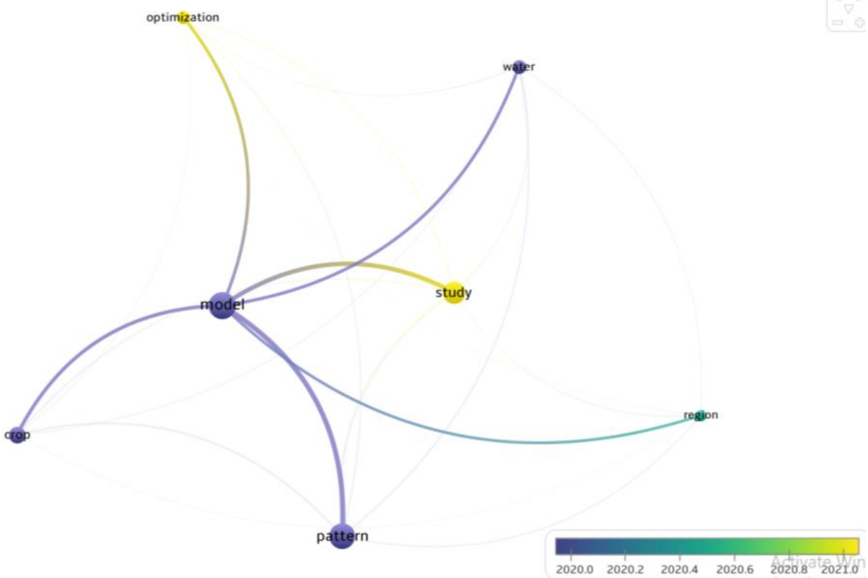

Fig 4. Cluster of keywords and their utilization frequency over time by Vosviewer.

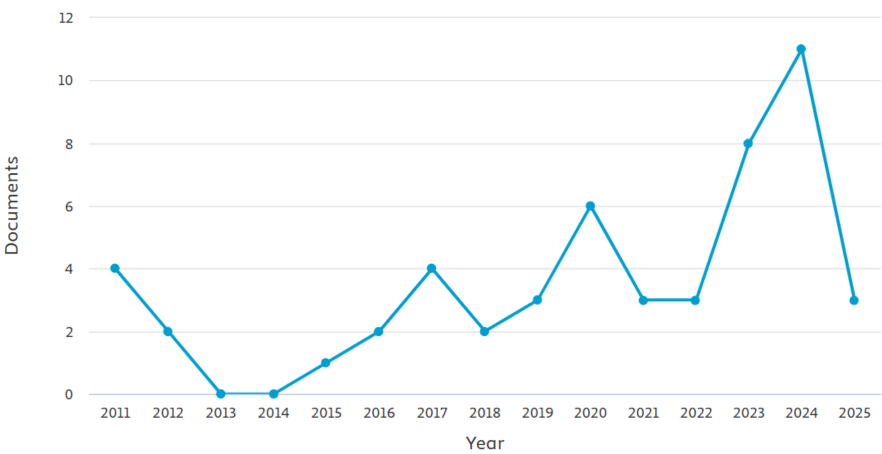

Fig 5. Research trends related to irrigation optimization models in each year

Articles are selected according to predetermined criteria and presented logically and systematically so that they can be used as references for further research. Quantitative analysis of article characteristics in the field of research discussing cropping pattern optimization models. The development of research trends, published periodically every year with the search criteria used, shows that research interest in discussing cropping pattern optimization models from 2014-2025 has increased, with the highest number of publications in 2024.

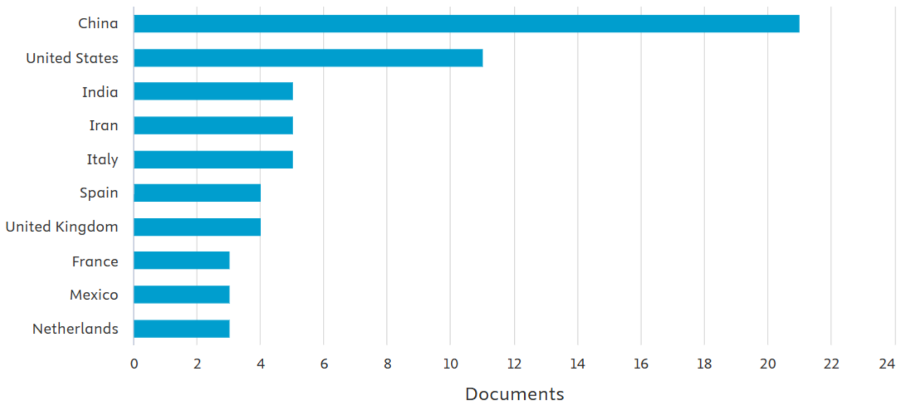

Fig 6. Trend of researcher contributions from various countries

Figure 6 shows the distribution of countries actively conducting research related to cropping pattern optimization. In order, the countries with the largest number of publications are China and the United States (US), reflecting the dominance of scientific contributions from these two countries in this field.

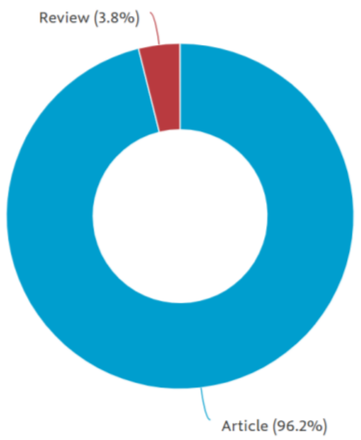

Fig 7. Percentage of articles by type

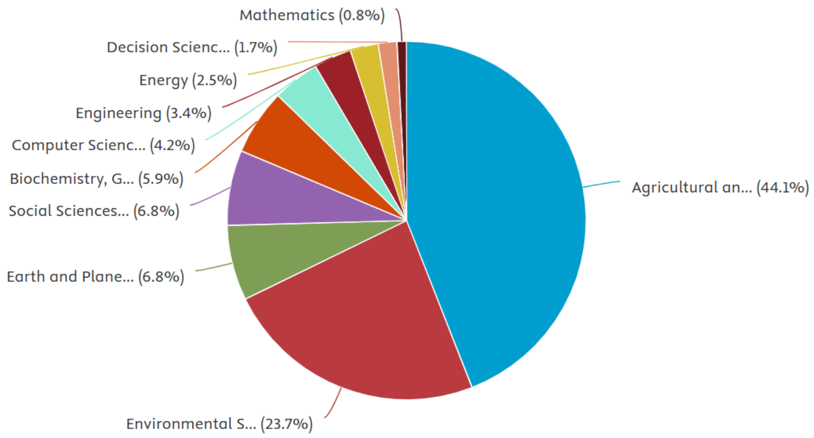

Fig 8. Percentage of articles by subject area

Figure 7 presents the classification of types and scientific fields of the total identified articles. As many as 96.2% are research articles (original research), while the remaining 3.8% are review articles. Based on the subject area, 44.1% of the articles come from the field of Agricultural and Biological Sciences, 23.7% from Environmental Science, and 32.2% from various other disciplines. From all of these articles, they were then re-selected to obtain articles that are specifically relevant to the research topic, namely publications discussing cropping pattern optimization models.

3. Result and Discussion

Irrigation optimization by determining cropping patterns is a mathematical approach in agricultural management that aims to allocate water and land efficiently, in order to maximize production results or farmer profits amidst limited natural resources. By determining a good cropping pattern, irrigation can be utilized optimally. Cropping pattern optimization model [40][42] aims to manage the type of crop, planting time, and land area efficiently in order to obtain maximum results (both in terms of harvest yields, economic benefits, or efficiency of water/land use). By considering the limitations of water and land, the irrigation optimization model allows for more rational water distribution planning, so that it can increase the efficiency of resource utilization and profitability of farming businesses. In other words, the application of the optimization model in the irrigation system aims to find the best combination of land allocation, water needs, and types of commodities cultivated, so that farmers can obtain maximum benefits in limited conditions. From the results of the literature search using the keywords "crop pattern optimization model" and "irrigation optimization" in two main databases (Scopus and ScienceDirect), a total of 185 articles were obtained published between 2014 and 2025. A total of 52 articles came from Scopus, and 133 articles from ScienceDirect. After going through a selection process based on inclusion criteria, 42 articles were obtained that were directly relevant to the topic of cropping pattern optimization modeling based on a mathematical approach. Further analysis of these articles revealed several key findings:

1. Types of optimization models used:
   a. Linear Programming (LP): 64%
   b. Multi-Objective Optimization: 19%
   c. Dynamic Programming (DP): 10%
   d. Mixed Integer Programming & Stochastic Models: 7%
2. Factors considered in the model:
   a. Water availability and irrigation allocation: 88%
   b. Economic value of crops (price, profit): 76%
   c. Crop rotation and planting calendar: 45%
   d. Environmental impact (water/soil conservation): 31%
3. Most study areas:
   a. China (24%)
   b. India (19%)
   c. USA (16%)
   d. Iran, Egypt, Indonesia, and African countries appear with a contribution of <10% per country
4. Types of publications:
   a. Research articles (original research): 96.2%
   b. Review articles: 3.8%
5. Dominant scientific fields:
   a. Agricultural & Biological Sciences: 44.1%
   b. Environmental Science: 23.7%
   c. Interdisciplinary (engineering, mathematics, economics): 32.2%.

3.1. Optimization Model Approach in Irrigation Based Agriculture

In the face of resource constraints such as water, land, and labor, optimization modeling becomes a strategic tool in agricultural decision making. Various approaches have been developed to achieve production efficiency and sustainability of irrigation systems. This subsection reviews the main approaches in irrigation-based agricultural optimization models.

3.1.1. Linear Program Model (Linear Programming - LP)

Linear Programming (LP) is a classical mathematical approach used to allocate limited resources optimally. In the context of irrigation, LP is used to maximize crop yields or economic profits by considering water, land, labor, and input cost constraints. This model is widely used in studies of water allocation between plots, commodities, and planting seasons.

3.1.2. Non-Linear Models and Dynamic Programming

When the relationship between water and yield is not linear—for example, following a plant physiological curve—then Nonlinear Programming (NLP) or Quadratic Programming (QP) approaches are used. Meanwhile, Dynamic Programming (DP) is used in multi-period planning, such as weekly water allocation during the growing season. DP considers sequential decisions in time and is often further developed in the form of Stochastic Dynamic Programming (SDP) to account for climate or water supply uncertainties.

3.1.3. Multi-Objective and Multi-Criteria Model (MOP/MCDM)

In practice, irrigation decision making often involves more than one objective, such as maximizing yield, minimizing water consumption, and maintaining fair distribution among farmers. Multi-Objective Programming (MOP) and Multi-Criteria Decision Making (MCDM) models are used to handle this complexity. Some of the methods used include Goal Programming, Pareto Front Analysis, and Analytic Hierarchy Process (AHP). These approaches are useful in generating trade-off solutions that consider social, economic, and environmental sustainability.

3.1.4. Heuristic and Evolutionary Methods

This method is used when the solution space is very large and complex, and is not suitable for solving with exact techniques. Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) are two examples of methods that are widely used for optimizing cropping patterns, irrigation schedules, and agricultural input distribution. This approach is flexible and can handle many variables at once, but is stochastic so that the results can vary between iterations.

3.1.5. Artificial Intelligence and Machine Learning Based Models

With the advent of sensors, Internet of Things (IoT), and big data, AI and Machine Learning-based approaches are becoming increasingly relevant in precision agriculture. Models such as Artificial Neural Network (ANN) can learn the complex relationships between soil moisture, weather, and crop water requirements. Fuzzy Logic is used for linguistic rule-based decision making, while Genetic Algorithm, Support Vector Machine (SVM), and Decision Tree (DT) are used for prediction and classification of land conditions and irrigation decisions. The advantages of these models are high adaptability to real-time data, but they require large training data and have limited interpretability. The following is a comparison table of optimization model approaches in irrigation-based agriculture, summarizing the main characteristics, advantages, and limitations of each method:

Table 1. Comparison of optimization model approaches in irrigation-based agriculture

Approach	Main Characteristics	Excess	Limitations	Suitable for
Linear Programming (LP) [46]	Objective function and linear constraints	Exact optimal solution, fast to solve	Not suitable for non-linear relationships	Water/land allocation between plots, seasons, or commodities
Nonlinear	Non-linear	Realistic representation	More complicated	Water optimization with

Programming (NLP), QP [47]	relationships between variables	of crop response	solution, prone to local optimum	non-linear crop yield response
Dynamic Programming (DP) [48]	Sequential decisions across periods	Suitable for graduated/multi-period irrigation	Curse of dimensionality, high computation time	Seasonal irrigation, reservoir management, long-term planning
Multi-Objective Programming (MOP), MCDM [33]	Multiple objectives (yield, water, equity)	Provides compromise solution (Pareto optimal)	Complicated in determining goal preferences	Shared irrigation systems, sustainable policy planning
Heuristic & Evolusioner (GA, PSO, dll.) [49]	Population-based & evolutionary solution search	Flexible, no need for differentiable functions	Stochastic, not always globally optimal	Complex cropping patterns, multiple input combinations, model calibration
AI & Machine Learning (ANN, Fuzzy, SVM, dll.) [27]	Learning from historical & sensor data	Adaptive, suitable for real-time data & prediction	Requires a lot of data, low interpretability	Precision agriculture, automated irrigation, water requirement prediction

Optimization models in agricultural irrigation continue to evolve from classical deterministic approaches such as LP to AI-based and heuristic models. The choice of model is highly dependent on the objectives, system complexity, and data availability. Integration between approaches can provide more adaptive and precise solutions in addressing sustainability and climate change challenges.

Table 2. Keyword classification of the top 20 keywords from search results

Num.	Original Keyword	Standardization	General Category	Frequency
1	optimization	Optimization (General)	Optimization Concept	28
2	linear programming	Linear Programming (LP)	Optimization Method	13
3	cropping pattern	Crop Pattern Optimization	Optimization Approach	13
4	climate change	Climate Change	External Factor	10
5	uncertainty	Uncertainty	Modeling Constraint	9
6	conjunctive use	Conjunctive Water Use	Water Management Strategy	7
7	multi-objective optimization	Multi-objective Optimization	Optimization Method	6
8	agriculture	Agriculture	Domain	6
9	irrigation	Irrigation	Agricultural Input	6
10	genetic algorithm	Genetic Algorithm	Metaheuristic	5
11	deficit irrigation	Deficit Irrigation	Water Management Strategy	5
12	optimal cropping pattern	Crop Pattern Optimization	Optimization Approach	5
13	crop pattern	Crop Pattern Optimization	Optimization Approach	4
14	deep learning	Deep Learning	AI-Based Optimization	4
15	sustainability	Sustainability	Sustainability & Policy	4
16	food security	Food Security	Sustainability & Policy	4
17	simulation	Simulation	Modeling Technique	4
18	cotton	Cotton	Crop Type	3
19	machine learning	Machine Learning	AI-Based Optimization	3
20	groundwater	Groundwater	Water Resource	3

3.2. General Findings from Literature Relevant to Cropping Pattern Optimization

Several articles have been identified discussing cropping pattern optimization models, especially those using mathematical approaches such as Linear Programming and Multi-objective Models. These studies generally focus on optimizing land allocation and efficient use of resources, such as water and labor, in various agricultural cultivation systems. This study shows that Linear Programming (LP) is still the most commonly used approach in cropping pattern optimization research, due to its simplicity of structure and ability to handle limited resource allocation problems efficiently. The LP model has proven effective in maximizing farmer income, optimizing water distribution, and adjusting planting schedules based on seasonal conditions. The increasing trend in the use of multi-objective models indicates a shift towards agricultural systems that not only pursue profitability, but also pay attention to aspects of sustainability and natural resource conservation. The emergence of additional variables such as carbon footprint, virtual water use, and spatial data integration indicate an increase in the complexity and sophistication of the latest models.

Geographically, the dominance of studies from countries such as China and India reflects the high population pressure on their food systems and national policies that encourage the use of data-driven technologies in agricultural management. Unfortunately, studies from areas that are highly vulnerable to water scarcity such as Sub-Saharan Africa and parts of Southeast Asia are still relatively minimal. This opens up opportunities for further research in these regions, including Indonesia.

4. Conclusion

This study shows that optimization-based mathematical approaches, especially Linear Programming (LP), play an important role in supporting decision-making in sustainable agricultural systems, especially under conditions of land and water constraints. The majority of studies in the last decade have emphasized the importance of efficient resource allocation through quantitative models that consider agronomic, economic, and ecological aspects in an integrated manner. The increasing number of publications from year to year reflects the urgency of this topic amidst global challenges such as climate change and food security. The dominance of LP models is due to their ability to solve complex allocation problems efficiently, although recent trends are toward the use of multi-objective models and more adaptive approaches to environmental dynamics. Geographically, research contributions are still dominated by countries such as China, India, and the United States. This opens up important opportunities for the development of contextual studies in other regions, including Indonesia, which has its own unique agroecosystems and resource management challenges. Overall, the integration of optimization modeling and climate and irrigation information systems will be key to supporting more resilient and sustainable cropping strategies. Moving forward, further research is recommended to explore cross-disciplinary approaches, utilize artificial intelligence, and involve farmer participation in developing models that are applicable and responsive to local conditions.

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