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Sustainability and Productivity of Village Tank Cascade Systems: A Bibliometric Analysis and Knowledge Mapping

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Abstract: Research on social–ecological systems is rapidly expanding globally in response to human-induced climate change, biodiversity loss, and ecosystem degradation. Safeguarding these traditional agroecosystems is vital according to the 2030 Agenda for Sustainable Development. In the last decade, there has been a growing research interest in the Village Tank Cascade Systems (VTCSs) of Sri Lanka, recognised as social–ecological systems. However, few studies have systematically analysed VTCS research in Sri Lanka. To examine this apparent knowledge gap in more detail, a bibliometric analysis and knowledge mapping were conducted to systematically analyse and interpret the state, trends, clusters, and emerging fields of VTCS research. In total, 159 peer-reviewed research publications between 1985 and 2023 were obtained from the Web of Science Core Collection, Scopus databases, Google Scholar, and ResearchGate to perform this analysis. Furthermore, this study employed the Sustainability Assessment of Food and Agriculture systems (SAFA) tool, developed by the Food and Agriculture Organization of the United Nations, to map the inclusion of sustainability and productivity dimensions in VTCS research, in alignment with the objectives set forth by the 2030 Agenda for Sustainable Development. The study provides insight into dominant and neglected areas of future VTCS research.

Keywords: village tank cascade systems; social–ecological systems; bibliometric analysis; bibliometrix; biblioshiny; sustainability and productivity; knowledge mapping

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1. Introduction

There is increasing attention in scientific studies to the values of social–ecological systems (SESs) and their contribution to sustainable food production and improving livelihoods in the context of global environmental changes [1–3]. The term social–ecological system was first introduced by Retzlaff in 1970. The term has since been applied by many scholars across several disciplines [2,4–6].

This study is a systematic review of the published research on SESs, with particular focus on the Village Tank Cascade Systems (VTCSs) of Sri Lanka. VTCSs were designated as Globally Important Agricultural Heritage Systems (GIAHS) by the Food and Agriculture Organization of the United Nations in 2017 [7]. VTCSs are terrestrial SESs, characterised by traditional farming systems that are rich in agrobiodiversity and biocultural values and embedded in an expansive area of wetlands [8]. VTCSs are recognised as some of the earliest and most sophisticated rainwater-harvesting irrigation systems globally, with their origin dating back to the 4th century Before the Common Era (BCE) [9,10]. These ancient irrigated systems exist within cascades of small tanks and use micro (or meso) watershed management systems that have evolved through the co-adaptation of rural communities to their surrounding environment [11]. The most sustainable feature of VTCSs is the ecosystem services provided by the land use system to support food production and the social well-being of rural communities facing climate and other stresses, whilst simultaneously maintaining the ecological productivity of their ecosystems [12]. However, regional investigations have uncovered a variety of ancient rainwater harvesting irrigation systems equipped with small reservoirs in Asian and African regions, which are known by various names, such as 'cascade tanks', 'pond' or 'pond wetland', and 'small-dams' [13,14].

Similar to global trends, the systematic research on VTCSs has increased over the last decade [14–18]. The earliest studies on VTCSs and their properties date back to 1923 [15]. To the authors' knowledge, only three review studies of VTCS research were conducted prior to this bibliometric analysis, by Perera [15], Kumara et al. [19], and Nianthi and Jayakumara [16]. Perera [15] studied the evolution and provided an overview of VTCS research studies conducted from 1923 to 2017. Nianthi and Jayakumara [16] assessed the progress of VTCS studies conducted in different locations from 1951 to 2009. More recently, Kumara et al. [19] performed a systematic bibliometric analysis and science mapping of VTCS research trends between 2000 and 2023 using 17 articles downloaded from the Science Direct database. These trends indicate greater attention to exploring the system properties of VTCSs, which were neglected in previous studies [19].

Over the last century, VTCSs have often been neglected in the research fields; more attention was paid to agricultural development aiming to increase economic production, while the crucial social, cultural, and ecological factors that are necessary for sustainability were ignored. This oversight underscores the current need to manage VTCSs by striving for a balance between sustainability and productivity, which is vital for the long-term health and effectiveness of VTCS landscapes [20,21]. Thus, a new approach is essential to enhance VTCS productivity without sacrificing sustainability [22–28]. To achieve sustainability, VTCSs must maintain optimal levels of ecological, cultural, social, and economic productivity, identified in this study as key dimensions of sustainability and productivity [3,20,29,30]. In this approach, the different aspects of ecological, cultural, social, and economic productivity play a role in either sustaining resource systems, such as natural ecosystems and biodiversity, to enhance ecological and cultural productivity, or in utilising resources like water and land to boost economic and social productivity. Thus, an in-depth understanding of the factors that maintain both sustainability and productivity is crucial to promoting sustainable production within these globally important agricultural heritage landscapes, aligning with the 2030 Agenda for Sustainable Development's objectives [21,31–34]. As highlighted by the United Nations Sustainable Development Goals (UN-SDGs) of the 2030 Agenda, maintaining VTCSs in an optimal condition is critical for sustainable land and water resource management in agriculture, especially in dry and arid areas. Therefore, a transdisciplinary framework to evaluate the sustainability and productivity dimensions of VTCSs is crucial, as depicted in Figure 1 [35–37].

This study reviews the development of a conceptual knowledge structure (themes and trend) and assesses the degree of inclusion of the sustainability and productivity dimensions of VTCS research in studies published between 1985 and 2023. The review focuses on the following research questions:

Q1. What are the annual trends of SES and VTCS research production?
Q2. What are the dominant and emerging research themes regarding VTCSs?
Q3. What are the key clusters of VTCS research and their relationships?
Q4. What is the degree of inclusion of sustainability and productivity in VTCS research?
Q5. What are the research gaps and directions for future VTCS research?

This study is the first systematic bibliometric analysis and mapping of a knowledge structure in the field of VTCS research. This research and analysis could help to establish a robust foundation to evaluate past research as well as future research needs.

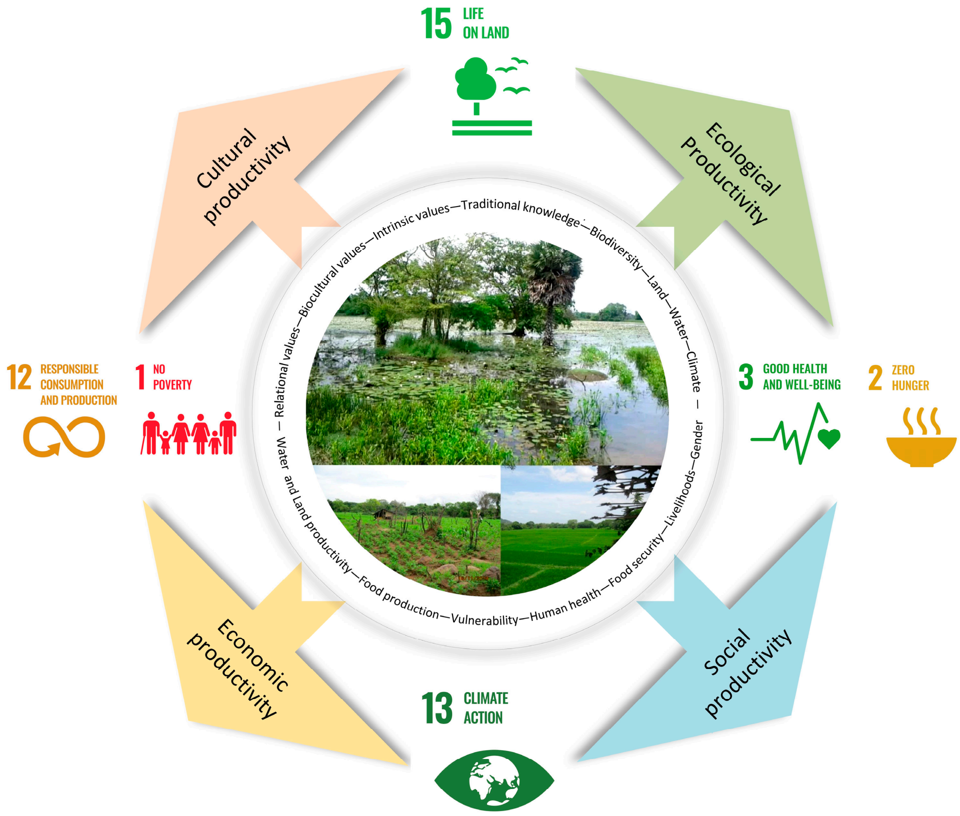


Figure 1. A conceptual diagram illustrates the dimensions of sustainability and productivity within VTCSs, aligning with the pertinent United Nations Sustainable Development Goals (UN-SDGs) of the 2030 Agenda for Sustainable Development. To achieve sustainability in VTCSs, it is necessary to uphold optimal levels across the ecological, cultural, social, and economic productivity dimensions. Source: inspired by Dubey et al. [21], McNeill [34]. Image: water and agricultural ecosystems of a VTCS; photo credit: Sujith S. Ratnayake.

2. Materials and Methods

2.1. Analysis of Global Trend of SES Publications

Global trends in publications related to SESs between 1992 and 2023 were analysed using 8225 records downloaded from the Web of Science (WoS) core collection and the Scopus databases on 18 November 2023 using the bibliometrix package and biblioshiny app of the R software [38]. The search was limited to the 'Article Title', 'Abstract', and 'Keywords' of peer-reviewed publications. The following search string was used to identify relevant publications in the databases: "social-ecological systems" OR "socio-ecological systems" OR "socio-ecological production landscapes" OR "Satoyama Landscapes" OR "Globally Important Agricultural Heritage Systems".

2.2. Analysis of VTCS Research Publications

2.2.1. Data Sources and Search Strategy

This study adopted the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework [39] and utilised the bibliometrix package of the R software environment [38] for a systematic search, merging, and duplicate removal of the literature data [40,41]. Searches were conducted through the two prominent multidisciplinary online science databases: the WoS Core Collection and Scopus. Searches targeted research articles frequently used by researchers across a range of disciplines, such as Environmental Science, Social Science, Agricultural Science, Biological Science, Earth and Planetary Sciences Economics, Econometrics and Finance, and Arts and Humanities. The search criteria were limited to peer-reviewed journal articles, book chapters, research reports, and conference proceedings that were published between 1985 and 2023 relating to VTCSs in Sri Lanka.

The search terms used for this study were: "Village Tanks", "Tank Cascade", "Cascade Tank", "Tank Irrigation", "Ancient Irrigation", "Ancient Reservoir", "Cascade system", "Cascade Reservoir", and "Cascade Restoration". The Boolean operator 'OR' was used to optimise the search results of possible studies containing the search criteria. In addition, the search was conducted to include the article title, abstract, or keywords in Scopus and all fields in WoS Core Collection. Review papers were excluded from this study, with the selection limited to peer-reviewed articles written in English and limited to Sri Lanka in the database search query. The selected documents from the two databases were then exported, with all information provided in BibTex format. The WoS Core Collection generated 33 records whilst the Scopus generated 49 records. The database search was undertaken on 18 November 2023. After a thorough search of the available literature obtained using other sources, such as Google Scholar and ResearchGate, 77 additional records were identified (search date 19 November 2023).

2.2.2. Screening

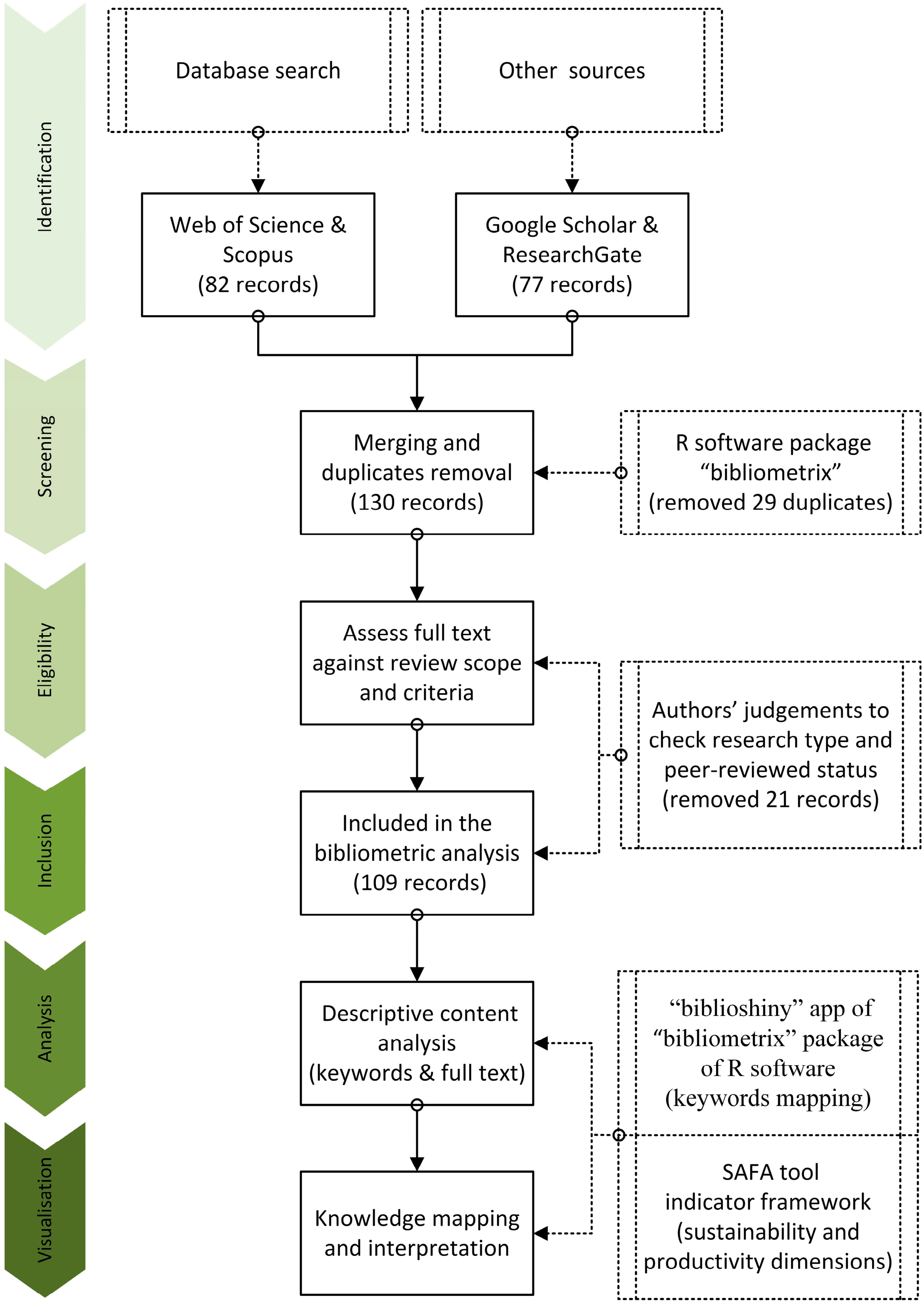
The two downloaded files, one from each database, were merged into a single file using the bibliometrix package of the R software (4.3.2 Version) [38]. Merging removed 29 duplicated records and resulted in a single Excel file of 130 records. The peer-review status of the cited journals was verified in Serial Solution's Ulrichsweb database, accessed on 22 November 2023 via UNE Library Databases A–Z (https://une.au.libguides.com/az.php). In certain instances, the peer-review status of conference proceedings and research reports downloaded from Google Scholar and ResearchGate was verified by contacting the respective publishing authorities.

2.2.3. Eligibility

The 130 selected records were reviewed to determine the eligibility of the paper in relation to the scope of the study. This study followed the method outlined by Pahlevan-Sharif et al. [42] for screening the records. The screening of 130 records involved examining the full-text version of the paper and concluding its eligibility as a research study. As a result of the eligibility check, 21 records were excluded, resulting in a total of 109 papers being included in the review process. A flowchart of the bibliometric analysis and the knowledge mapping process is shown in Figure 2.

2.2.4. Research Categorisation

The research in the 109 publications reviewed in this study was categorised as follows: (i) empirical; (ii) exploratory; (iii) descriptive; and (iv) conceptual. Empirical research is defined in this study as research that is entirely reliant on experiments or observations designed to study the relationships between variables, without relying on a system or theory. Data in this research type were primarily obtained in the form of observation or experimentation [43]. Exploratory research is defined as research regarding specific situations or contexts and their associated variables or facts, whether or not it answers the issue at hand. For this research type, data are generally obtained through primary and secondary sources such as scholarly writings, observation, social enquiry, and government and non-government reports. It is often the case that an exploratory research approach is implemented to uncover 'new' or 'valuable' findings or facts [44]. Descriptive research is defined as a study of the relationship between different variables, which is used to describe phenomena without disturbances. Enquiries of the descriptive type generally take the form of, but are not limited to, observation and population enquiries such as surveys or group information and interview sessions. However, whilst this research type shares similarities with exploratory research, descriptive research mainly deals with accurately and precisely depicting the characteristics and components of phenomena, while exploratory research may provide new insights and ideas about a given study [45]. Finally, conceptual research in this study is defined as inquiries of abstract or conceptual nature regarding specific issues or contexts. The primary function of conceptual research is to explore, develop, and clarify abstract ideas to enhance understanding and develop new frameworks or models to guide further research. In this context, there is little reliance on observational data and secondary sources are most often utilised [46].



SAFA= Sustainability Assessment of Food and Agriculture systems

Figure 2. Flowchart showing the integrated process of data mining and science mapping of the literature data of VTCS research. Source: Adapted from Aria and Cuccurullo [38], Page et al. [39].

2.2.5. Thematic Areas Analysis and Knowledge Mapping

High-Frequency Keyword Mapping

Keywords provide a simple summary of the main themes addressed in a given study [47]. Thus, an analysis of relevant keywords helps to identify research hotspots and the emergence of research themes and typologies in different periods, in line with the scope and objectives of this literature review [48]. This study used the biblioshiny app (version 4.1) of the bibliometrix package [38] to map high-frequency keywords in the 109 research studies using bibliometrics indicators. These maps comprise the keywords most frequently used by the authors in their publications during the evaluated period. An analysis of knowledge structures through the bibliometrix package enables the discovery of hidden patterns, and dominant themes and trends in scientific publications [49,50]. The biblioshiny app allows users to select relevant bibliometrix functions for keyword co-occurrence or network analyses and use bibliometric mapping to detect the most frequently highlighted themes in a given study [51]. For example, co-occurrence analysis uses the keywords extracted from an article (title, abstract or intext) to study the co-occurrence of important terms and themes to understand the conceptual structure of the research, allowing for a quantification and visualisation of the thematic evolution within an interactive web interface [52]. Word TreeMap and word CloudMap of the biblioshiny app were used to extract high-frequency keywords to provide a high-level summary of the research themes and trends and reflect diverse research hotspots [48].

Factorial Analysis

Similar to keyword network analysis, a factorial analysis in biblioshiny was used to create a conceptual structure by clustering keywords based on multiple correspondence and hierarchical cluster analyses. A factorial analysis of keywords was used to reduce the number of factors through statistical methods. This represents the relationship between several categorical variables, such as research categories or authors and institutions. In multiple correspondence analysis, highly correlated keywords are represented in close proximity, forming clusters. These clusters are graphically represented by their relative position or distribution in a two-dimensional plot. The relative position of each keyword in the multiple correspondence analysis graph reflects the relationship (similarity or divergence) among keywords [47,50,53,54]. Highly correlated keywords will lie closer together in the plot, whereas keywords that are less correlated lie further apart. Likewise, a hierarchical cluster analysis was used to cluster close keywords that explain a similar 'concept' or 'topic' of the research area [48]. Then, a word tree dendrogram map was used to describe keywords' closeness to or distance from each other, treating neighbouring keywords as subfields or clusters of the main research topic [49,55–57]. The height of the tree dendrogram measures the distance among keywords or clusters of keywords [47].

Analysis of Sustainability and Productivity

The first step in this process involved the development of 16 key themes and potential keywords related to sustainability and productivity dimensions based on the SAFA tool version 2.2.40 [58,59] (Figure 3). This was followed by a determination of the degree of inclusion of 16 themes in the 109 research studies, obtained by analysing author keywords and full texts (Table S1). The total number of research studies that fell under each theme was then calculated for analysis and to map the research knowledge.

	Related potential keywords
A. ECOLOGICAL PRODUCTIVITY	
1. Biodiversity	ecosystems; species; ecosystem functions; ecosystem services; interactions; ecosystem services valuation; conservation; restoration; impacts on biodiversity; ecological resilience; deforestation; ecological productivity.
2. Land habitats	landscape variability; landscape heterogeneity; habitat quality; land use change; land degradation; fragmentation; soil health; ecological restoration; ecosystem services; conservation and governance.
3. Water habitats	water pollution; water quality; water regulation services; water governance; invasive species; water governance; ecosystem services.
4. Atmosphere/Climate	climate change impacts on ecosystems; air pollution; air quality; air quality regulation; greenhouse gas emissions; energy; forest productivity; ecosystem services.
B. CULTURAL PRODUCTIVITY	
5. Traditional knowledge	Protection and use; repositories; ancient chronicles; intellectual property rights; access and benefit sharing.
6. Biocultural values	traditional practices and use; ethnobiology; biocultural "keystone" species and functional groups; medicinal plants; biocultural approaches in conservation.
7. Intrinsic values	nature's right to exit or nature's own value independent of human uses: species conservation; protection of ecologically sensitive habitats; assessment and monitoring tools.
8. Relational values	human relation fostered by nature: social-ecological functions; aesthetic values; sense of place; amenity values; spiritual values; environmental justice; political ecology; social co-production of ecosystem services; ecotourism.
C. ECONOMIC PRODUCTIVITY	
9. Food production	crops; fisheries; livestock; agrobiodiversity; economic productivity; economic viability; resource-use efficiency; cropping intensity; marketing; supply and value chains; pest and diseases; extension and technology; policy.
10. Water	water productivity and farm water balance; irrigation water availability; water harvesting; irrigation water quality; groundwater; water policy and governance; watersheds; invasive species; village tanks; technology.
11. Land	land productivity; land suitability; resource-use efficiency; land use change; soil fertility; land policy and governance; land tenure; wildlife conflicts; technology; structure and pattern; sustainable land management.
12. Climate vulnerability	climate change and variability parameters; exposure; sensitivity; hazards; adaptive capacity; impact quantification; adaptation strategies and policies.
D. SOCIAL PRODUCTIVITY	
13. Food security	food availability, access and utilisation; nutrition; dietary diversity and pattern; sustainable food systems; food environment; climate adaptation; agrobiodiversity; food policy and governance.
14. Human health	health impacts; non-communicable diseases; waterborne diseases; ecosystem services; well-being; healthy diets.
15. People/Livelihoods	Knowledge; extension services; local economy; social well-being; social governance; social resilience; social vulnerability; socio-demography; migration; energy; waste; participation; maintenance; adaptive co-management.
16. Gender	gender roles; gender inclusion; gender perceptions; gender-environment nexus; gender knowledge and empowerment; gender equality; access to resources and decision-making; gender mainstreaming.

Figure 3. Sustainability and productivity dimensions, themes, and related keywords, assessed using SAFA tool. Source: adapted from the SAFA tool of FAO [58,59]. The dimensions of ecological, cultural, economic, and social productivity can be associated with enhancing either the sustainability or productivity of VTCSs. This association depends on their role in either sustaining resource systems to enhance ecological and cultural productivity or in utilising resources to boost the economic and social productivity of VTCSs.

3. Results

3.1. Trends in Published SES and VTCS Studies

Figure 4 shows the global trend in publications over the study period and shows a clear trend of a global increase in scientific publications on SESs after 2000. The country-specific production map (Figure 4a) shows the articles published by different countries between 1992 and 2023. This reflects the importance and influence of a given nation in the scientific assessment of SESs' characteristics over the period. The countries with the greatest number of SES publications are developed nations (USA, Australia, Germany, the UK, Canada, Spain and Sweden) and, overall, developed nations account for a disproportionate level of scientific studies related to SESs. Sri Lanka is ranked 36th among the 137 analysed nations and sits second to India among South Asian countries. Figure 4b presents a word cloud map of the 50 most frequently used keywords in global SES studies. According to the map, the 10 most frequently used keywords are "ecosystem", "sustainability", "climate change", "biodiversity", "sustainable development", "decision making", "adaptive management", "ecology", "ecosystem services", and "human". These 10 words accounted for 43.68% of the uses among the 50 keywords. Other keywords that can be considered relevant to the sustainability and productivity dimensions are "governance", "land use change", "resilience", "water management", "knowledge", "adaptation", "participatory approach", "environment policy", "environmental protection", and "risk assessment". The keywords "food security" and "human health", which are among the most significant social productivity dimensions in SES studies in relation to current global environmental change issues [60–63], were not among the first 50 keywords.

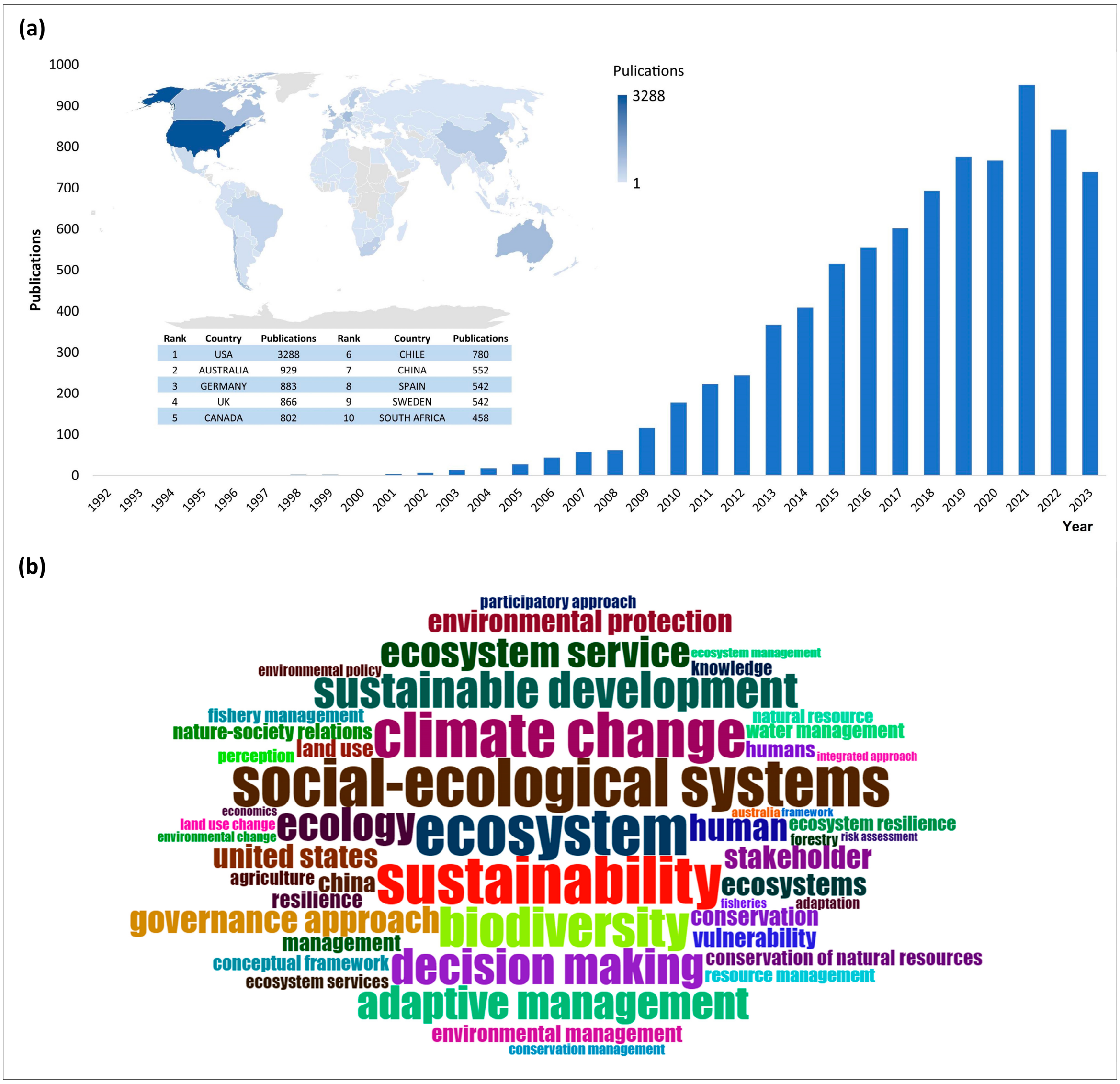


Figure 4. Global trends in the scientific production of publications in the field of SESs between 1992 and 2023: (**a**) annual and nation-specific production; (**b**) word-cloud map of the 50 most frequently used keywords by authors in the global studies. The maps were generated through the biblioshiny web interface of the bibliometrix package using the R programming language.

A summary of the core information regarding the bibliometric review of VTCS research publications is shown in Table 1. The annual production of VTCS research between 1985 and 2023 was analysed using 109 peer-reviewed research publications. Figure 5 shows the trend in research publications on VTCSs over the period. There was a noticeable increase in VTCS research in Sri Lanka after 2010 and a significant increase in 2021 and 2023. Of these studies, 78% are categorised as empirical research and 44%, 21%, and 40% of studies are categorised as quantitative, qualitative, and mixed methods research, respectively. A recent bibliometric analysis of 17 VTCS research articles published between 2000 and 2023 revealed substantial international collaboration in this research, with researchers based in Australia making the most substantial contribution [19].

Table 1. Summary of the main information regarding the bibliometric data of research publications in Sri Lanka.

Main Information	Description	Results
Key statistics	Timespan	1985–2023
	Sources (journals, books, etc.)	68
	Documents	109
	Annual Growth Rate %	7.74
	Author's keywords	404
Authors	Authors	230
	Single-authored docs	9
	Authors of single-authored docs	6
Publication category	Journal article	71
	Book chapter	10
	Conference paper	19
	Research report	9
Research design	Quantitative methods	48
	Qualitative methods	21
	Mixed methods	40
Research type	Empirical research	85
	Exploratory research *	10
	Descriptive research *	13
	Conceptual research *	11

* numbers are not mutually exclusive as some of the research contained more than one research type. Source: biblioshiny app and authors' judgements.

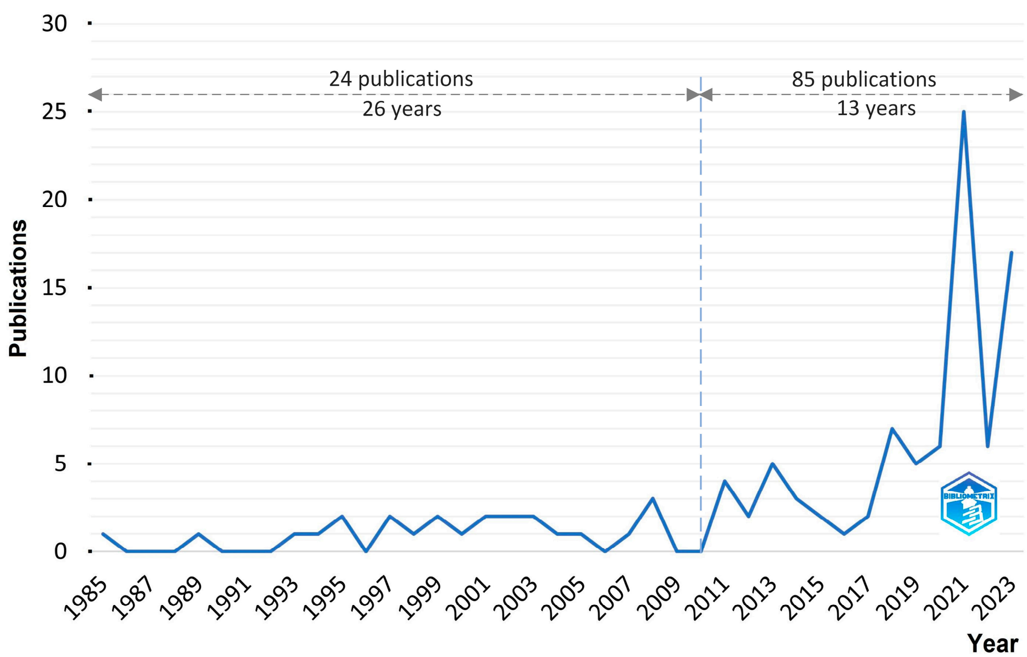


Figure 5. The trend in the annual production of VTCS research publications in Sri Lanka between 1985 and 2023.

3.2. Mapping of High-Frequency Keywords

3.2.1. Research Hotspots

Figure 6a presents a word TreeMap of the top 30 keywords in VTCS research. Figure 6b presents a word cloud map of the top 50 keywords. The top 10 keywords accounted for 56% of the cumulative frequency of keywords in the top 30 keywords (Figure 6a). Of the top 10 keywords, 21% related to water management ("water management") and irrigation management ("tank irrigation", "irrigation", and "irrigation management"). Similar to the global pattern in SES research, the terms "climate change" and "sustainability" were also among the top 10 keywords in VTCS research.

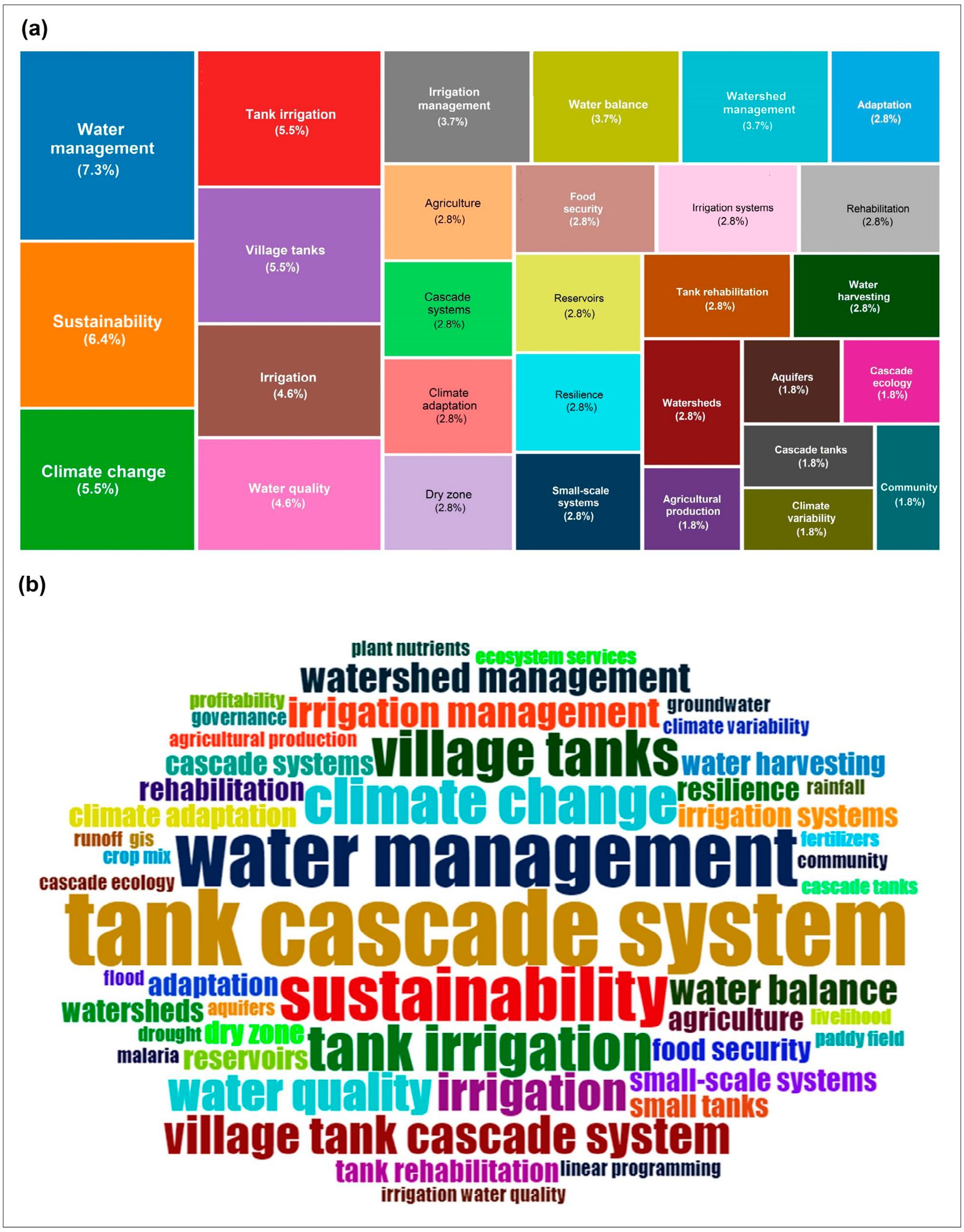


Figure 6. Word TreeMap chart of the 30 most frequently used keywords by authors with percentages (**a**) and a word cloud map of the 50 most frequently used keywords (**b**) in the field of VTCS research between 1985 and 2023, derived from the biblioshiny app of the bibliometrix package in the R software environment.

3.2.2. Trends in Emerging Keywords in VTCS Research

Figure 7 shows the temporal patterns of trending keywords used in VTCS research between 1985 and 2023. The use of these keywords during the early years of VTCS research was vital for the enhancement of water productivity and irrigation management. However, in the later stages, keywords regarding the enhancement of sustainability became more relevant. Among these were traditional knowledge, water quality, water governance, food security, climate change, ecosystem services, and climate adaptation, which became apparent in VTCS research.

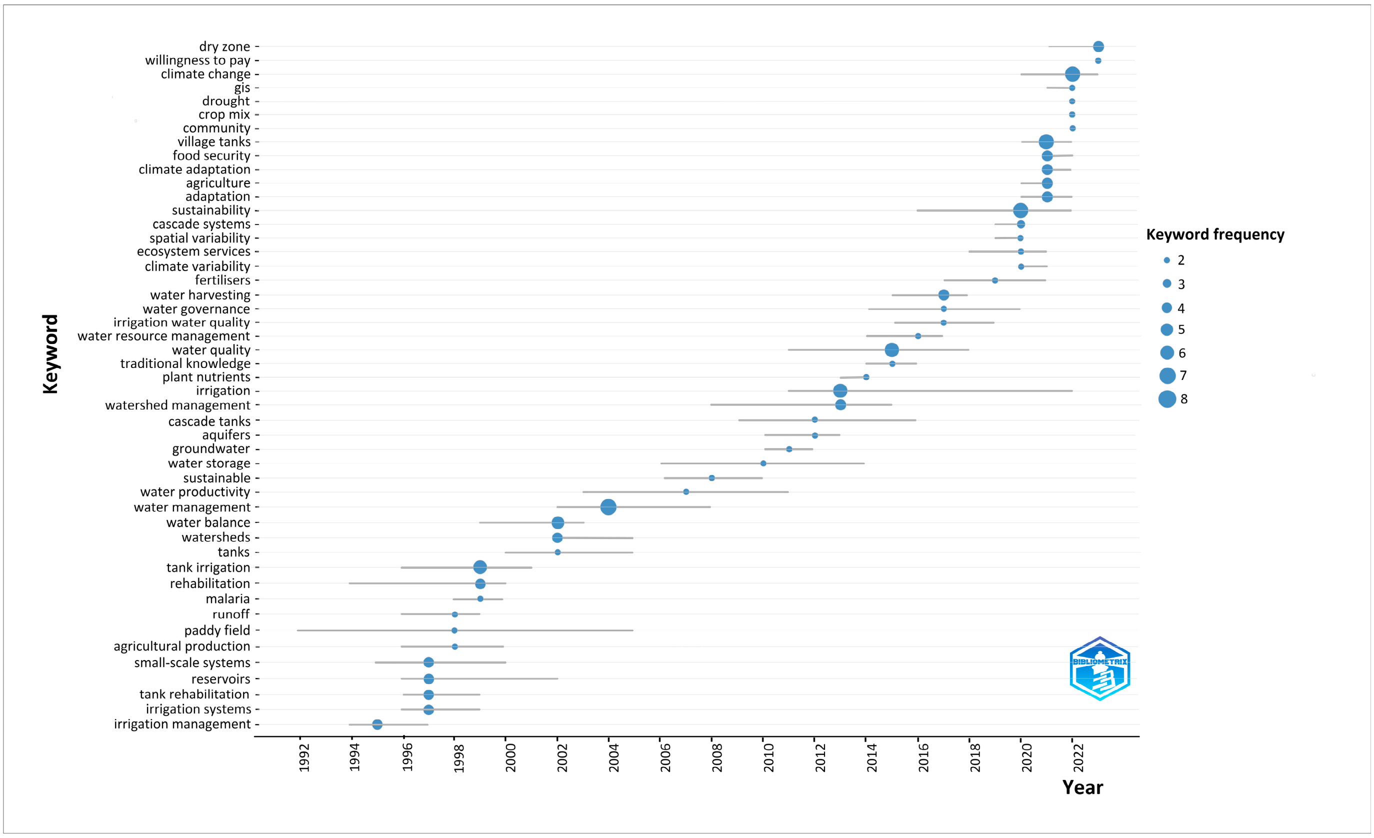


Figure 7. Trending keywords of VTCS research between 1985 and 2023, derived from the biblioshiny app of the bibliometrix package in the R software environment. Parameters were set to minimum word frequency = 2 and number of words per year = 5.

3.2.3. Mapping of Research Clusters

The factorial analysis of peer-reviewed published data of VTCS research recognised four dominating clusters or subfields in the VTCS research domain. Four clusters are displayed in Figure 8: cluster 1 (green), cluster 2 (purple), cluster 3 (red), and cluster 4 (blue). The two conceptual structure maps—the words map (Figure 8a) and tree dendrogram map (Figure 8b)—offer an in-depth perspective of the interrelationships among various research themes. These maps categorise VTCS research into clusters focusing on different topics: climate change and food security (cluster 1); irrigation water supply and management (cluster 2); agricultural water demand and supply (cluster 3); and the spatial characterisation and sustainability performance of landscapes (cluster 4). These clusters illustrate the diverse research directions within VTCS studies.

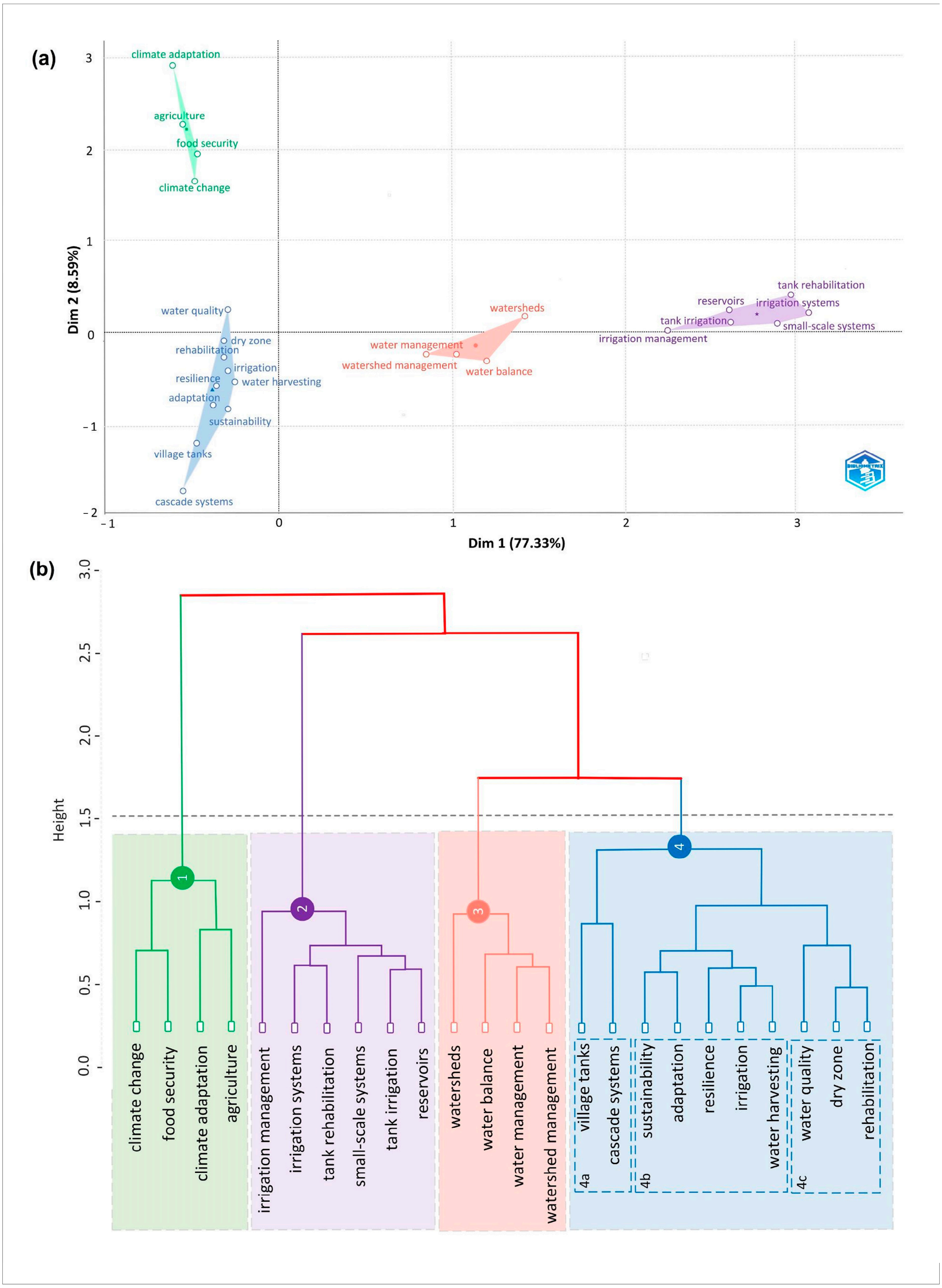


Figure 8. Multiple correspondence analysis of high-frequency keywords in the fields of VTCS research (**a**), and tree dendrogram of hierarchical cluster analysis of high-frequency keywords in the fields of VTCS research (**b**), derived from the biblioshiny app of the bibliometrix package in the R software environment.

3.2.4. Mapping of Sustainability and Productivity Dimensions

The radar map presented in Figure 9 serves as a visual summary of how aspects of the sustainability and productivity dimensions (ecological, cultural, social, and economic productivity) have been incorporated into VTCS research. This analysis is based on a review of 109 research publications, which identified 16 thematic areas reflecting the dimensions of sustainability and productivity. The extent to which these themes are represented in VTCS research was categorised into five levels: Best; Good; Moderate; Limited; Poor. A comprehensive classification of the 109 studies is detailed in Table S1. From the map, it is evident that themes related to economic productivity, especially those concerning water and food production, have received considerable attention in VTCS research, scoring highly on the map. In contrast, themes related to cultural productivity, such as traditional knowledge and biocultural values, are underrepresented. Meanwhile, themes pertaining to social and ecological productivity were given slightly more emphasis in previous VTCS studies.

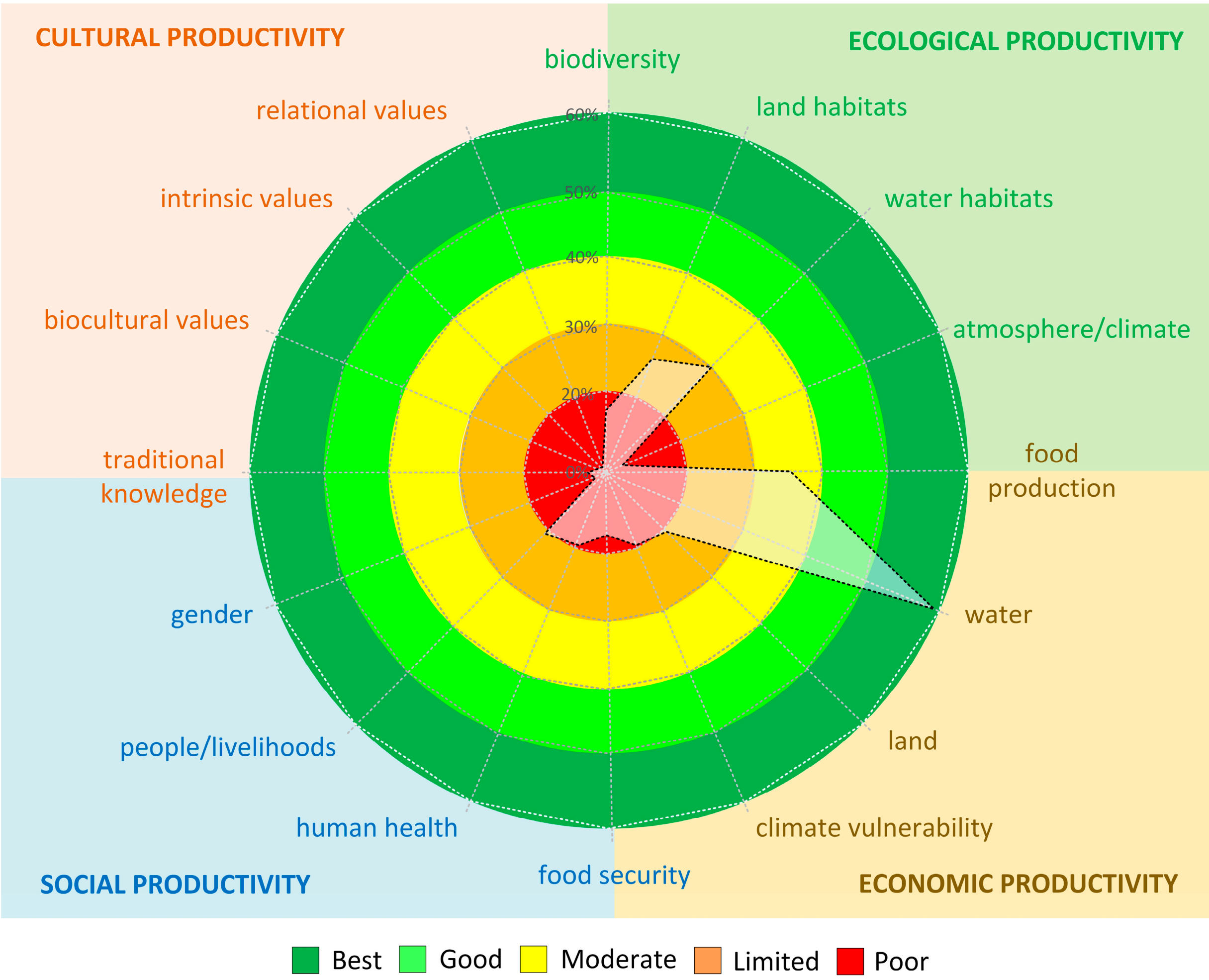


Figure 9. Radar graph showing the inclusion of sustainability and productivity dimensions in VTCS-based research conducted between 1985 and 2023. Source: Developed by the authors, inspired by de Oliveira et al. [32], FAO [59].

4. Discussion

4.1. Trends in Publications of SES and VTCS Studies

A causal factor for the growing number of scientific publications on SESs globally after 2000 may be the adoption of the three Rio Conventions in the United Nations Conference on Environment and Development in June 1992. The Rio Conventions resulted in global sustainable initiatives and funding mechanisms, such as UN-SDGs and the Global Environment Facility (GEF), prompting greater attention and the provision of finances to explore SESs. The capacity of SESs to promote and improve sustainable rural livelihoods contributed to this heightened focus and to addressing the interconnected challenges of climate change, land degradation, and biodiversity loss [25,26,64–66]. The country-specific production map (Figure 4a) suggests that developing countries do not have robust research capacities to explore and produce scientific studies on SESs. This capacity shortfall is particularly problematic because food production in many of the SESs found in developing countries is projected to be at risk as a result of future global environmental changes [60,61,67,68]. Figure 5 illustrates a significant increase in publications related to VTCSs in 2021 and 2023, suggesting that this surge may result from the dissemination of doctoral research findings and global financial support aiming to develop knowledge products in this field [18,69–72].

4.2. Mapping of High-Frequency Keywords

An analysis of the most frequently used keywords revealed that water management, sustainability, and climate change were the research hotspots in the field of VTCS research development over the last three decades. However, additional terms central to the sustainability and productivity dimensions, such as "biodiversity", "ecosystem services", "traditional knowledge", "biocultural diversity", "land use change", "ecological restoration", "human health, "groundwater", "livelihoods", and "governance" were not among the top 30 keywords, and thus were not research hotspots in past VTCS research. Therefore, more research is needed to integrate these concepts and topics into VTCS research.

4.3. Mapping of Research Clusters

According to a factorial analysis of research data, cluster 1 (green) is a more distant or separated cluster from the other three clusters and consists of research targeting climate change and food security themes in VTCS research. This cluster is most strongly aligned with ecological productivity and contrasts with the other three clusters, which are more focused on economic productivity. The impact of climate change on agriculture, including crops, fisheries, livestock, and biodiversity, is critical to maintain the sustainability of food systems in VTCSs [73]. For example, Ratnayake et al. [74] explored the impact of climate change on the suitability of land for paddy production in the VTCSs. The results indicated that future paddy production will be at risk due to the changing climate and limited adaptation capacity. Further, Ranasinghe et al. [75] found that climate change impacts livestock production in VTCSs due to pasture shortages leading to a reduced milk yield and the deterioration of animals' health. Wickramasinghe et al. [76] and Saase et al. [77] verified the negative impacts of climate change on land and water productivity potentials, respectively. It was also found that the increased growth of invasive aquatic plants due to climate change can lead to a loss of tank capacity, thus impacting food production [78,79]. Further, several studies confirmed that the food system and food security of the VTCSs are vulnerable to climate changes, leading to nutritional insecurity in these communities [62,63]. Sustainable local food systems and the food environment of the VTCSs are likely to be important for communities adapting to the negative impacts of climate change. For example, Ratnayake et al. [80] explored the neglected, underutilised, and wild food plants grown in the wild environments of SESs and provided options to increase the adaptive capacity of communities to cope with food insecurity issues. Moreover, the food environment of the north–central VTCSs studied by Nayanathara and Hemachandra [81] revealed supply chain issues in market food crops other than paddy. The study also highlights the weak connection between the built and natural food environments of the VTCSs.

Cluster 2 (purple) brings together research publications based on keywords relevant to irrigation water supply and management. Water is a critical factor for agriculture (food) production in VTCSs, mainly due to the erratic water availability. Thus, this cluster is related to water-production-focused research publications. For example, a study by Senaratne and Wickramasinghe [82] revealed that the temporal scarcity of water has been the major challenge for VTCSs, and this has shaped irrigation water management strategies.

The rehabilitation of tanks has been practised for a long period to improve tank water capacity and irrigation in the VTCSs. For example, studies conducted by Sakthivadivel et al. [83], Sakthivadivel and Brewer [84], Itakura and Abernethy [85], and Kariyawasam [86] provided recommendations for effective tank rehabilitation through innovative methods, tools and techniques. Groundwater is an important source of water for irrigation in VTCSs, especially in upland areas where surface water is scarce. Examples of studies that focused on groundwater use related to this cluster include those by Kumari et al. [87], which produced a groundwater quality zoning map, and De Silva [88], which developed a model to monitor the fluctuations in groundwater levels. Quantifying agricultural water productivity is an important measure in irrigation scheduling decisions. Water productivity could have substantial implications for irrigation water demand and supply budgets. There are several quantitative studies that evaluate the agricultural water productivity in the VTCS areas [89–91]. Furthermore, studies have evaluated the impact of external factors, such as aquatic weed infestation and siltation, as well as wild elephant encroachment, on the agricultural water productivity of VTCSs [89,92,93].

Cluster 3 includes studies focused on modelling agricultural water demand and supply in VTCSs. This cluster is closest to the centre of the multiple correspondence analysis plot, indicating its core status (Figure 8a). Research within this cluster addresses both sustainability and productivity in relation to VTCSs. Studying the water balance is critical due to the scarcity of water resources for agriculture in VTCSs, and allows for assessments of agricultural water demand and supply and the implementation of improved agriculture productivity strategies in the face of potential climate change. In addition, the outcome of water balance studies contributes to goals aligned with sustainability and productivity, such as designing optimal adaptation strategies and improved irrigation management and effective tank restoration projects to reduce water stress. Cluster 3 includes several water balance modelling studies focussed on tank rehabilitation [94], improving climate resilience [73], simulating the dynamics of the hydrology of different tank components [95], accounting and improving irrigation water use [96,97], water resource planning and predicting irrigation water availability [98–100], and understanding the role of return flows in tank cascade systems [101]. Studies focussed on the importance of cascade watershed management and the protection of vegetation cover in agricultural water balance were also included in the cluster [102,103]. Micro-watershed areas of VTCSs are critical to maintaining optimal irrigation water demand and supply for food production. Moreover, sustainable land use and cover management in tank micro-watersheds and agricultural production areas are important elements of the demand and supply budgets of irrigation water [102]. VTCS landscapes are experiencing rapid land use and cover changes with impacts on their sustainability and productivity [72]. However, according to this review, only a few peer-reviewed quantitative studies have been carried out to evaluate land use and cover change pressures in the tank cascade catchment areas to date [76,104].

Cluster 4 is the largest and can be divided into three sub-clusters related to studies focused on (4a) spatial characteristics, (4b) sustainability performance, and (4c) water quality and governance. However, interrelationships can be seen within each of the three sub-clusters. The first sub-cluster (4a) includes studies concerned with the spatial characterisation and investigation of patterns of VTCS landscapes. These studies help us to understand the broad issues affecting VTCS landscapes and guide the design of studies on specific issues to address socio-economic and ecological dimensions [11,64,105–107]. Spatial characteristics and heterogeneity are key to maintaining the biodiversity and ecosystem services of VTCSs. However, systematic assessments and the monitoring of biodiversity status in VTCSs are limited. The few studies that fit to this sub-cluster include those by Ratnayake et al. [80], Hettiarachchi et al. [108], Geekiyanage and Pushpakumara [109], and Marambe et al. [110]. Further, Ratnayake et al. [24] provided a methodological framework for the detailed assessment and mapping of ecosystem services in VTCS landscapes [36]. Dissanayake and Vidanage [111] used choice experiment surveys to conduct a valuation of ecosystem services to assist in the restoration of VTCSs.

The second sub-cluster (4b) includes studies of sustainability performance, system resilience, and adaptation capacities. Only three studies focused on measuring landscape sustainability performance, particularly emphasising economic productivity. In one of these studies, Hemachandra et al. [112] developed a sustainability index that integrated 21 parameters (8 physical–environmental and 13 socio-economic parameters) to measure the physical–environment and socio-economic sustainability. This index can be used for the rapid assessment of cascade components for the prioritisation of rehabilitation in future research or assessments. In another study, Sirimanna et al. [113] evaluated eight parameters (agricultural water productivity, hydrological endowment, irrigation water demand, tank water supply adequacy, tank water storage adequacy, the performance of the tank's physical components, cascade tank capacity, and the structural balance ratio of the cascade components) to access their efficacy for food production in the VTCSs. This study revealed that all the above parameters, except land and water productivity, do not meet the sustainability performance requirements in the VTCSs. In the third study, Dayananda et al. [114] explored resource-use efficiency and environmental sustainability in the VTCSs using a bio-economic model. The model revealed that water and labour are the key determinants of the sustainability and productivity of the system. These studies emphasise the need to maintain ecological sustainability by enhancing the adaptive capacity and resilience of a system to restore its original functions. Furthermore, Kulasinghe and Dharmakeerthi [115] assessed the ecological sustainability of various land use systems of VTCS by employing the soil organic carbon management index as a surrogate measure. Their research unveiled a noteworthy decrease ($p < 0.01$) of 33% in total organic carbon content within paddy lands compared to forest lands. Studies relevant to system resilience are an integral part of the sub-cluster linked with sustainability and adaptation. However, no studies have been conducted to quantitatively assess the system resilience of VTCS landscapes; instead, several qualitative studies explored the aspects of system resilience that are important for sustainable food production [116,117]. In addition, Kekulandala [70] investigated the potential to incorporate an adaptive co-management of VTCSs under the impact of climate change.

The third sub-cluster (4c) centres on studies of water quality in VTCSs. Water quality is an important parameter for both the productivity and sustainability dimensions and is linked to many other social, economic, and ecological factors, including human health, ecological productivity, agricultural water productivity, and food production. Abeysingha et al. [118] studied the drinking and irrigation water quality parameters of Thirappane VTCS and found that water quality is appropriate for irrigation but unsuitable for drinking. Abeysingha et al. [119] and Dharma-Wardana et al. [120] investigated the relationship between water quality and the occurrence of chronic kidney disease of unknown aetiology (CKDu) in VTCS areas. Their studies highlighted the problem of the pollution of drinking water resources due to high ionicity and the potential benefits of maintaining the ecological functions of tank components that help with water purification. Other studies on water quality focussed on the importance of spatial and temporal variations in groundwater quality for both drinking water and irrigation purposes. A study conducted by Kumari et al. [121] provides a methodological framework to develop a groundwater classification and zonation of the Ulagalla cascade to monitor spatial and temporal variations in groundwater quality. Reducing chemical pollution is critical to maintain water quality. An over-reliance on agrochemicals and subsidised fertiliser has resulted in major impacts on the VTCS environments, particularly on water quality and soil health [122–124]. The diminishing surface and groundwater quality due to human activities, such as the excessive use of pesticides, fertiliser, detergents, and waste dumping, puts the sustainability of the system at risk [9,119,125–130]. Water governance is another key topic in this sub-cluster that is important for the sustainable management of water resources, as it delivers water ecosystem services to communities reliant on VTCSs. There are several studies related to this cluster, investigating historical and present water governance systems and different management approaches and how they contribute to the long-term sustainability and productivity dimensions of VTCSs [131–134].

4.4. Mapping of Sustainability and Productivity Dimensions

The review revealed that the 16 sustainability and productivity themes were not equally represented, especially in past VTCS research. The cultural, ecological, and social productivity themes of VTCSs were scarcely addressed in peer-reviewed research over the last four decades. The VTCSs are deeply interlinked with the traditional knowledge, practices, and cultural values in various different livelihoods and food systems [20]. However, these cultural values have already been depleted, are in the process of deterioration, or are being neglected [72]. Thus, the inclusion of traditional knowledge and cultural values is crucial for future research addressing the sustainability of VTCSs. In relation to social productivity, the map shows that the food security and human health themes were not well addressed in past VTCS research, except for a few studies that assessed healthy food consumption patterns and dietary diversity through community perceptions and the prevalence of non-communicable diseases among VTCS communities [62,63,135]. This review also revealed that few research studies addressed the land and water themes of ecological productivity. Most of these studies assessed the impact of habitat destruction on ecosystem functions. Only one study focused on systematically quantifying the impacts of land use changes; however, this study was limited to a single VTCS area [76]. Most of the research concerning water investigated water quality parameters in relation to surface and groundwater pollution [9,119,125–130]. Reductions in the ecological productivity of land habitats due to soil erosion were highlighted by Dharmasena [103], and the loss of ecosystem services as a result of land degradation was assessed by Ratnayake et al. [24]. VTCS biodiversity research was poorly represented. The literature review found that the majority of biodiversity studies focused on the identification and listing of species and measuring diversity [80,110]. The impacts of climate change on biodiversity are critical, as they directly influence the ecological productivity of VTCS landscapes [64]. However, quantitative assessments of the impact of climate change on ecological productivity in VTCS habitats are very limited [79].

Keywords related to the "water" and "food production" themes of economic productivity were most frequently included in VTCS research. Modelling irrigation water demand and supply for agricultural production in VTCS areas was the dominant research theme regarding economic productivity. However, quantitative research addressing climate vulnerability and land use changes, along with their subsequent impact on food production and water productivity, is also scarce [74,79].

4.5. Limitations of the Study

Similar to many systematic reviews, this study faces certain limitations. Notably, it relies exclusively on the SAFA framework to assess the sustainability and productivity of VTCSs, omitting alternative conceptual frameworks that have been developed and utilised in related research. Such frameworks include the sustainable livelihood framework [136]; adaptive capacities and resilience assessment frameworks [137–140]; frameworks for evaluating the cascade effects of ecosystem services on human well-being [141,142]; and Ostrom's framework for analysing the sustainability of SESs [143]. These approaches could be explored in future research on VTCSs to enhance the assessment of sustainability and productivity, thereby advancing the field. Additionally, this study does not explore the connections between the sustainability and productivity dimensions or the integration of research knowledge, a gap that is also observed in many global reviews of SES research that fail to merge the social and ecological domains of SESs [144]. An interactive analysis of the economic, social, ecological, and cultural productivity dimensions is crucial for the development of more effective governance, policy, and management strategies for VTCS sustainability. Furthermore, the study does not conduct a thorough examination of the methodologies, tools, and techniques employed in the reviewed research articles.

Analysing VTCS studies through the lens of diverse methodologies could lead to more nuanced policy recommendations and options [144]. The identification of crosscutting sustainability and productivity dimensions in this study opens up additional avenues for a more integrated analysis of VTCS research in future endeavours.

5. Conclusions

This study presents a systematic review that used a bibliometric analysis to undertake a knowledge mapping of peer-reviewed publications that focused on VTCS research between 1985 and 2023, and the use of the SAFA tool to analyse the sustainability and productivity dimensions. The results of this study not only inform knowledge structures and trends in past VTCS research based on a keywords analysis, but also highlight the degree of inclusion and gaps in relation to the sustainability and productivity dimensions within VTCS research over the period. Further, the findings of this study can guide the use of research data and indicators for future studies regarding restoration efforts in VTCSs. The main conclusions of this study in relation to the research questions presented earlier are as follows:

Q1. A global increase in scientific publications on SESs occurred after 2000. VTCS research publications also increased over this period, with most of the increase occurring after 2012.

Q2. Water-productivity-management-related research was the most common focus of past VTCS research, whilst climate change, adaptation, ecosystem services, and food security themes became emerging research themes in both global SES and VTCS studies in the last decade to integrate more sustainability dimensions and themes.

Q3. Four dominant research clusters were identified in VTCS research based on the following keywords: (i) food security and climate change; (ii) irrigation water supply and management; (iii) agricultural water demand and supply; and iv) spatial characterisation and landscape sustainability performance. These clusters can be aligned with the four dimentions of sustainability and productivity.

Q4. Research focussing on the themes within the economic productivity dimensions was most common in past VTCS resercah. Research focussed on themes regarding cultural productivity was very rare, and research focussed on themes within the social and ecological productivity dimensions was limited. Thus, studies focussing on themes within the cultural, ecological, and social dimensions, integrating transdisciplinary perspectives, and contributions aiming to maintain the sustainability of the overall system need more emphasis in future VTCS research.

Q5. Although some dominant areas (hotspots) of research focus were found in the past, VTCS research still needs to address several neglected areas that are important to the sustainability dimensions. This has not yet received enough attention among the scientific community and policymakers. This could be a result of the absence of a national VTCS research strategy in Sri Lanka, which should be formulated by integrating both top-down and bottom-up approaches to VTCS research. Thus, key recommendations are as follows:

    1. To improve and increase research on ecosystem services: The ecosystem functions of VTCS landscapes are not independent, and exhibit nexus relationships with multiple VTCS resources. Thus, it is necessary for future research to explore multiple values of ecosystem services in order to obtain optimal benefits.
    2. To streamline the integration of biodiversity and landscape ecology: Biodiversity and landscape ecology remain poorly recognised and are not reflected well in the VTCS research to date. Thus, future research should address the indicators proposed by global sustainability agendas, such as the Convention on Biological Diversity (UNCBD), The Ramsar Convention on Wetlands, and the new Kunming-Montreal Global Biodiversity Framework (GBF).

3. Systematic assessments of land use change impacts need to be expanded: The landscape pattern dynamics due to land use/cover conversions should be analysed and quantified, as well as the ecological impacts.
4. Refine climate change research in VTCSs: Research should prioritise examining the shifts in landscape patterns driven by seasonal weather variations, focusing on quantifying their effects on sustainability and productivity. This approach goes beyond merely analysing trends in rainfall and temperature, offering a more comprehensive understanding of environmental impacts.
5. Strengthen research on local food systems linked with climate change: Traditional food systems of VTCSs are now disappearing from the VTCS food environment for various reasons, including changes in land use and the climate. Thus, future research should be expanded to strengthen local food systems' resilience and sustainability in VTCS landscapes.
6. Recognise cultural values linked with sustainability dimensions: VTCS landscapes are rich in traditional knowledge and biocultural values that can help to achieve sustainable food production. However, studies on traditional knowledge and biocultural values were found to be the most neglected area of VTCS research and should be considered as a future research topic, as well as the development of scientific indicators to monitor and assess these factors.
7. Integrate green governance into VTCS research: Several crosscutting research areas can be identified between the four sustainability and productivity dimensions. Thus, research on policy and institutional aspects related to the green governance of VTCS resource systems needs to be strengthened.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su16083360/s1, Table S1: Key characteristics of past VTCS research, with special reference to the sustainability and productivity dimensions.

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