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Systematic Review

Assessing Agricultural Systems Using Emergy Analysis: A Bibliometric Review

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Abstract

Sustainable intensification requires metrics that are able to capture both economic performance and the often-hidden environmental inputs that support agriculture. Emergy analysis (EmA) meets this need by converting all inputs—free environmental flows and purchased goods/services—into a common unit (solar emjoules, sej). We conducted a PRISMA-documented bibliometric review of EmA in agroecosystems (Web of Science + Scopus, 2000–2022) using Bibliometrix and synthesized farm-scale indicators (ELR, EYR, ESI, %R). Our results show output has grown but is concentrated in a few countries (China, Italy and Brazil) and journals, with farm-level assessments dominating over regional and national assessments. Across cases, mixed crop–livestock systems tend to show lower environmental loading (ELR) and higher sustainability (ESI) than crop-only or livestock-only systems. %R is generally modest, indicating continued reliance on non-renewables, with fertilizers (crops) and purchased feed (livestock) identified as recurrent drivers. Thematic mapping reveals well-developed niche clusters but no single motor theme, consistent with the presence of incongruous baselines, transformities and boundaries that limit comparability. We recommend adoption of the 12.1×10^{24} sej yr^{-1} baseline, transparent transformity reporting and multi-scale designs that link farm diagnostics to basin and national trajectories. Co-reporting with complementary sustainability assessment methods (such as LCA and carbon footprint), along with appropriate UEV resources, would increase its reputation among policymakers while preserving EmA's systems perspective, converting dispersed case evidence into cumulative knowledge for circular, resilient agroecosystems.

Keywords: emergy; bibliometric review; agricultural ecosystems

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1. Introduction

The sustainable intensification of agriculture, aiming to increase yields while minimizing environmental impact, is a central topic of debate. This discussion is informed by a growing body of literature that highlights the complexities and trade-offs associated with intensification pathways [1–3]. As such, understanding the current state of research is crucial for developing effective strategies for sustainable agriculture.

A key aspect involves a more efficient use of resources, with a special focus on food with resource-intensive needs. Reducing agricultural waste by returning these flows into the system [4] and rescaling landscape for multiproduction or even integrated production are possible solutions to improve yield using fewer resources and less space. For instance, Pimentel et al. concluded that organic crop production required 30% less energy inputs than a conventional one [5]. Not only are unconventional ways of production receiving more attention, but integrated production systems are also demonstrating smart resource use and improved yields, along with valuable co-products [6].

Increasing agricultural production can be achieved through improved management practices. Efficient resource management in agriculture involves controlling overexploitation while maximizing the potential of natural resources. This approach aims to optimize the farm-scale economy by reducing investments and enhancing the value of the final products (e.g., food production). Conceptual models are widely applied at the farm scale to achieve these goals. These often perceive agricultural inputs as flows of materials, money, energy, labor and information, or a combination thereof. However, these models often focus only on inputs for a given use, failing to integrate other perspectives. For instance, energetic assessments typically focus on biofuel production and the impact of greenhouse gas emissions [7,8] but fail to include other parallel activities.

Emergy assessment (EmA) is a valuable tool for evaluating production systems, as it integrates all inputs into a single, common unit—solar emjoules (sej). By categorizing inputs, EmA can account for both free environmental contributions and economic resources, thereby providing insights into environmental and economic performance. Developed by Odum in 1983 [9], the emergy methodology captures the total energy required to produce a product or service, based on principles of thermodynamics and ecological systems theory.

Bibliometric studies have shown that emergy research has expanded rapidly since the mid 1990s and is increasingly diversifying [10]. Early reviews covering 1996–2014 identified the United States and China as the most productive countries and highlighted methodological development and ecosystem sustainability as core themes [11]. Subsequent analyses have examined 2008–2020 publications and reported an exponential increase in output, stronger collaboration networks, and a shift toward integrating emergy with other sustainability tools [12]. More recently, specialized bibliometric surveys have focused on emergy applications in wastewater treatment [13] and ecosystem services [14]. Across these reviews, the literature remains concentrated in a handful of countries and journals, and there is ongoing debate about standardizing accounting frameworks and indicator definitions.

Our review narrows the lens to agroecosystems, which have been reported as one of the most popular fields of interest after wetlands in a bibliographic review of emergy applications in ecosystems [14]. We collate and analyze peer-reviewed studies (2000–2022) applying EmA to crop, livestock and mixed farming systems to better understand their efficiency, both economically and ecologically. To this end, we first (i) conducted a literature review on the implementation of EmA in agroecosystems and (ii) a bibliometric analysis focused on different production systems at farm scale. The latter aims to aggregate all the published information on EmA by analyzing the patterns and outcomes through emergy indicators.

2. Materials and Methods

2.1. Bibliometric Analysis

We performed a quantitative summary focused on the available literature on EmA for agroecosystems using the open-source R package Bibliometrix (version 4.1.2) [15]. Bibliometrix enables the quantification and statistical analysis of publications and, in this case, the evaluation of the relevance of EmA to agricultural production. We used Web of Science (WoS) and Scopus, since both contain a large collection of bibliometric databases, citations and references from scientific publications. We retrieved all scientific publications using the following queries for WoS and Scopus platforms, respectively, to include a wide variety of agricultural contexts:

TS = ("emergy agriculture" OR "emergy sustainable production" OR "emergy farming" OR "emergy land management agriculture");

TITLE-ABS-KEY ("emergy agriculture" OR "emergy sustainable production" OR "emergy farming" OR "emergy land management agriculture").

We focused on the period between 1 January 2000 and 31 April 2022 to filter outdated publications, with the final search being performed on the 31 April 2022. While we acknowledge that a more recent cut-off year could provide additional perspectives, the selected timeframe still encompasses two decades of research, capturing key methodological developments and applications of EmA.

This review was not registered in a public registry. As an exploratory bibliometric study, the research questions and screening/classification procedures were refined iteratively during initial searches, making prospective registration impractical. Nevertheless, we adhered to PRISMA 2020 [16] guidelines and have provided the PRISMA flow diagram (Figure S1) and a detailed Methods section to maximize transparency and reproducibility. The initial search retrieved 750 records (Web of Science = 693; Scopus = 57) using the queries reported above. Records were exported and deduplicated using the R package Bibliometrix (automated DOI/title matching followed by manual verification). Titles and abstracts and full texts were then manually assessed for eligibility. Inclusion required peer-reviewed, English-language studies applying emergy analysis to agricultural systems. After removing duplicates (WoS = 492; Scopus = 54; total n = 504), 295 records were excluded at the screening/eligibility stage, and 209 studies were retained for the bibliometric analysis. For the farm-scale indicator synthesis we further required studies to report emergy indicators (ELR, EYR, ESI and %R) and to state the global baseline; n = 28 studies met these additional criteria.

2.2. Agricultural Subsystems: An Overview of Emergy Indicators

We classified publications according to two criteria: spatial scale and production type. Spatial scale included farm-level, sub-national (e.g., watersheds) and national assessments. Production type distinguished crops, livestock, mixed systems (integrated crop–livestock configurations implemented at the parcel or whole-farm level), forestry (provided that a harvestable product such as timber or cork was involved), and co-production systems in which agricultural output is coupled with bioenergy generation.

Apart from the quantitative analysis, 28 articles from farm-scale classification—involving crop, livestock and mixed production—were selected (Table S1). With approximately 10 articles for each production approach, a further analysis involving emergy indicators was conducted. The selection was based on the availability of the chosen emergy indicators, specifically those listed in Table 1.

All production systems were based on local renewable and non-renewables inputs, including both free and purchased inflows. These inflows were combined in different emergetic indices to assess the sustainability of the system. To understand the overall sustainability of different agricultural production systems, indicators such as the environmental loading ratio (ELR), emergy yield ratio (EYR), the emergy sustainability index (ESI) and the percentage of renewability (%R) were used. These emergetic indicators are functions of the inflows of the system.

Table 1. Emergy indicators selected for further analysis of the collected literature.

Indicator	Expression	Description
Emergy Yield Ratio (EYR)	Y/F	The EYR measures the net contribution of a process to the economy beyond what is required for its own operation [17] and is the result of dividing the outputs emergy (Y) by the purchased emergy (F).
Environmental Loading Ratio (ELR)	(F+N)/R	The ecosystem's stress related to the production activity can be evaluated through the ELR, calculated by dividing the non-renewable inputs (N) and F by renewable inputs (R).
Emergy Sustainability Index (ESI)	EYR/ELR	The ratio between EYR and ELR yields the sustainability index, which indicates if a process provides a suitable contribution to the user with a low environmental pressure [18].
Renewability (R%)	R/Y	Renewability of a system indicates the quantity of renewable resources required by the production system to produce its output.

3. Results

3.1. Overview of Research on Emergy Assessments

We collated data spanning 196 articles, 10 proceeding papers and three reviews during the period 2000–2022. This resulted in a total of 209 documents published across 69 sources, reflecting an annual growth rate of 5.1%. This collection has 606 authors contributing to the body of work, but only six authors produced single-authored papers, indicating a high level of collaboration within the field. On average, each document had 4.8 co-authors, with 36.4% of all publications being internationally co-authored, highlighting the global nature of emergy research in agricultural contexts.

In terms of impact, each document obtained an average citation of 23.4 ± 28.4, corresponding to 6.8 years for an article to be cited, with an annual average citation of 2.7. The average age of the documents is 8.8 years, suggesting that while foundational work remains relevant, newer research is also being integrated. The most frequently cited document was "Emergy Analysis on Chinese Agriculture" by G.Q. Chen, published in 2006. Notably, all the top 10 most-cited documents globally were from the 2000s, indicating that these works have had sufficient time to accrue citations and establish their influence within the field.

There was an increase in the annual growth rate of scientific production of agroecosystems analysis of 26.4% in the last five years (2017–2021) (Figure 1). Until April 2022, six articles had been published. Starting from two papers published per year in 2000 and rising to 23 in 2021, this trend indicates a clear increase in interest in the emergy–agriculture field during the last decade.

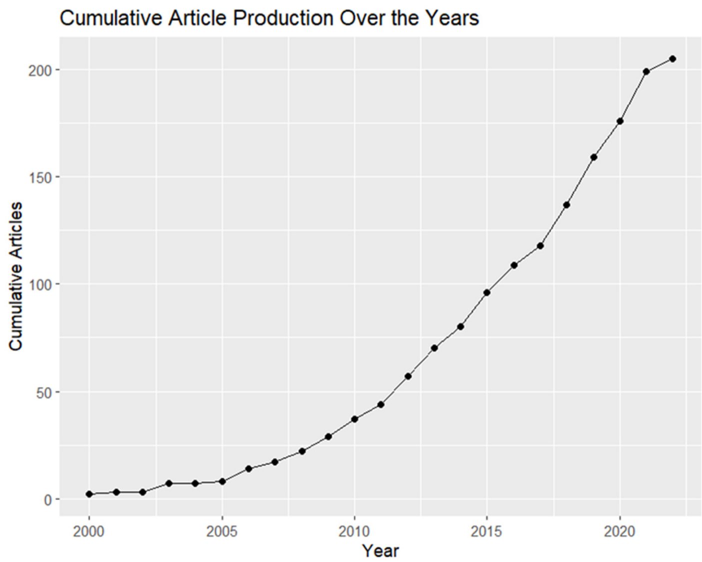

Figure 1. Cumulative annual scientific production from 2000 to 2022 (April).

3.2. Journals

The literature on EmA applied to agricultural systems was published in a total of 68 journals. According to *SCImago Journal & Country Rank* [19], all these sources are environmentally oriented, as the main categories for the journals listed in Table 2 are Agricultural and Biological Sciences; Environmental Sciences; Energy; Engineering; and Business, Management and Accounting. *The Journal of Cleaner Production* was the source with the second highest impact factor (11.1) and number of citations (1005). It presents the highest h-index (21), which takes both quantity and quality into consideration, followed by the journals *Ecological Indicators* (12) and *Ecological Modelling* (11). These last three sources represent the core of the literature on EmA applied to agricultural systems, with 36% of the total publications. Furthermore, the top 10 sources contained 63% of all publications. From the 68 journals, only 22 published more than one article related to the topic.

Table 2. Most relevant sources and the respective number of articles (n), % of total collected articles, h-index, total citations (TCs), first published year (PY) and impact factor (IF).

Sources	Articles (%)	h-Index	TC	PY Start	IF
Journal of Cleaner Production (n = 45)	21.5	21	1005	2008	11.1
Ecological Indicators (n = 16)	7.	12	478	2007	6.3
Ecological Modelling (n = 16)	7.7	11	744	2007	3.0
Sustainability (n = 14)	6.7	6	93	2007	3.9
Ecological Engineering (n = 9)	4.3	9	226	2000	4.4
Agricultural Systems (n = 8)	3.8	7	220	2009	6.7
Agriculture Ecosystems & Environment (n = 7)	3.4	7	558	2010	5.6
Energy Policy (n = 7)	3.4	7	333	2006	6.1
Environmental Science and Pollution Research (n = 3)	2.4	2	28	2018	5.2
Renewable and Sustainable Energy Reviews (n = 5)	2.4	3	104	2010	16.8

3.3. Authors Analysis

Similarly to the journals with higher h-index and more citations, our data shows the top 10 authors published 107 scientific papers (Table 3). About 70% of authors in the database wrote one article on EmA applied to agricultural production, while 0.5% wrote above 10 articles. One of these authors is Ulgiati S, with 13 publications, of which 11 were cited at least 11 times (h-index), followed by Ortega E and Wang X, with 13 and 19 published articles, respectively, and an h-index of 10.

Table 3. Top 10 authors based on total publications % and their respective h-index, total citations (TCs) and the first publication year (PY).

Authors	Institution	Articles (%)	Authors	h-Index	TC	PY Start
Wang X	China Agr Uni.	9.1	Ulgiati S	11	539	2001
Ulgiati S	Uni. Siena	6.2	Ortega E	10	585	2003
Campbell D	Uni. Rhode Island	5.7	Wang X	10	344	2014
Ortega E	Uni. Estadual de Campinas	5.7	Chen B	8	566	2006
Chen Y	Nanjing Agr Uni.	4.8	Campbell D	7	200	2009
Giannetti B	Uni. Paulista	4.3	Chen Y	7	238	2014
Agostinho F	Uni. Estadual de Campinas	3.8	Wu X	7	296	2013
Chen B	Beijing Normal Uni.	3.8	Zhang X	7	237	2008
Wu X	Northwest AANDF Uni.	3.8	Zhang Y	6	143	2011
Zhang X	Wuhan Uni. of Science and Technology	3.8	Agostinho F	5	202	2008

3.4. Country Contribution

The most relevant countries in this study correspond to the affiliations of the main authors. Those data were unavailable for eight of the 209 articles. Among these, the most relevant countries are Italy, Brazil, with a special emphasis on China, with 111 published articles (Figure 2). While China is the country with the most publications in this area, Italy was the first country to publish one article in 2000, followed by Australia and Egypt in 2003. A noticeable expansion occurred in 2006, when a broader range of countries began contributing more extensively to this research area. In terms of first-author affiliations, China accounts for 53% of the total documents, followed by Brazil and Italy, with 11%.

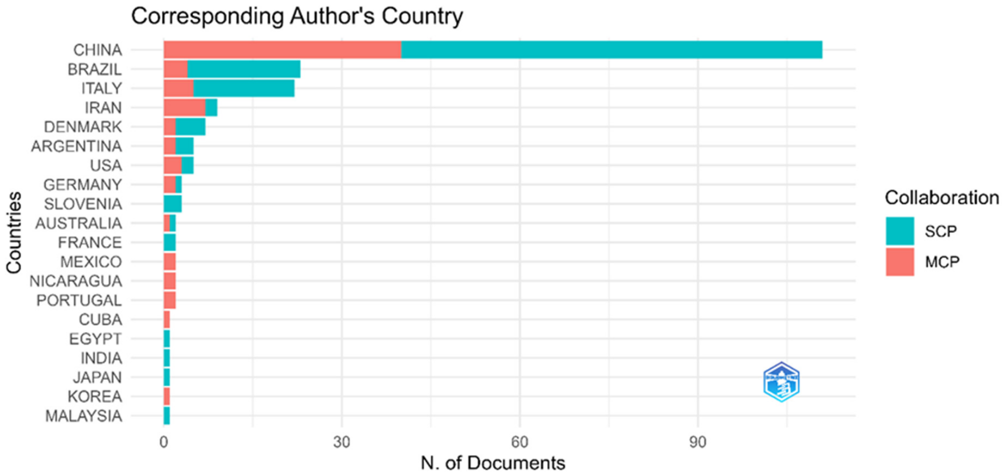

Figure 2. Number of published articles per country with single-country participation (SCP) or multi-country participation (MCP).

The articles published exhibit a higher rate of intra-country collaboration compared to inter-country collaboration, with a total of 127 and 74 collaborations, respectively. China has, for instance, several articles under MCP, indicating that the first authors are from China, but there are several participations from other countries. Essentially, there are more countries with publications under SCP. However, some countries published exclusively under MCP. This might indicate the need for expert support when using the emergy tool. All in all, there is a higher number of single-country publications, representing 63% of the total articles.

Figure 3 shows that countries with the highest number of publications are predominantly involved in multi-country collaborations. While not all of these publications result from direct collaborations between these countries, a significant portion does. Thus, most of the documents under the MCP might be involving experts from the main publishing countries—China, Brazil, Italy and the USA. The latter might not contribute as much in terms of first authorship, but according to Figure 2, there is an indication that the USA contributes mostly as a co-author in articles from other countries.

3.5. Keyword Analysis

From the 209 documents, 603 individual keywords were gathered and quantified to identify the purposes behind the main themes. It is also important to highlight that certain concepts appear under similar terminologies, although they share the same definition: "emergy assessment" versus "emergy evaluation", "emergy accounting", "emergy synthesis". Keywords plus represent the words extracted from the titles of an article's references, emphasizing the research methods and techniques used by the authors [20]. "Sustainability" and "energy" were the main highlighted keywords from the total of 450 individual keywords presented in Figure 4. Their mentions have been increasing at a rate of 46 and 64% in the last five years (2017–2022), respectively. These words are followed by the terms "ecosystem services", "agriculture", "systems", "management", "farms", "production systems" and others. When analyzing the trend of the keywords (Figure 5), sustainable agriculture was the most frequent term in the last few years (2019–2021), as gleaned from the gathered documents. Not only are these terms representative of the main topic under study, but they also relate to the methodology in question: "emergy", "transformity", "emergy evaluation", "emergy assessment" and "emergy analysis". "Life-cycle assessment" (LCA), which has been used alongside EmA since 2014, is also present, but with a low frequency (17 occurrences), in comparison to "Sustainability", with 77 occurrences.

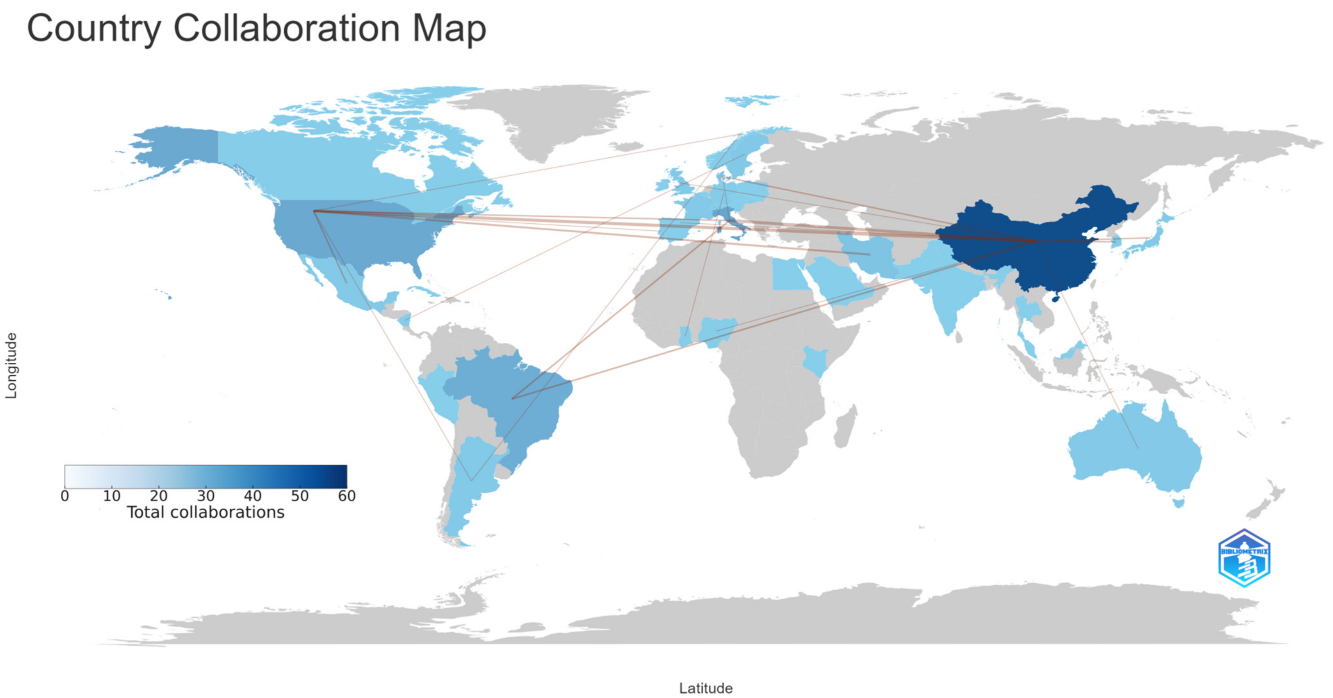

Figure 3. The map illustrates collaborations between countries via co-authorship, with country shading indicating total collaborations.

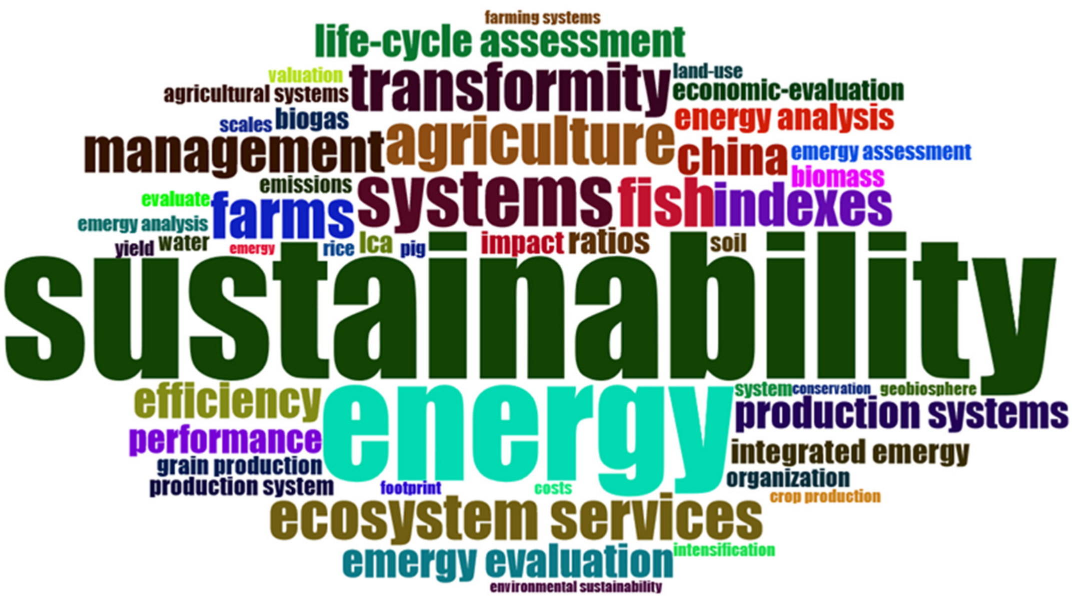

Figure 4. Word cloud of keywords plus, words or phrases appearing frequently in titles from an article's references.

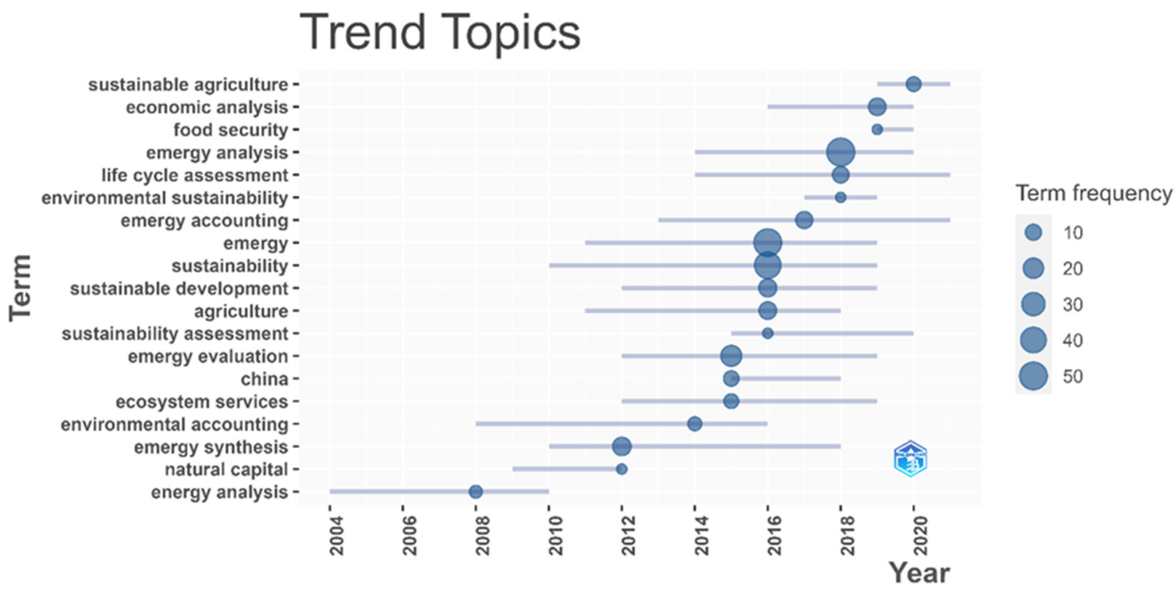

Figure 5. Most common keywords used by the authors in the collected literature. Each horizontal line spans from its first to last occurrence, each dot marks the year peak use with respective overall frequency.

To explore how these terms are conceptually related, we analyzed keyword co-occurrence using a thematic map (Figure 6). In this diagram, clusters are positioned according to density, indicating the internal cohesion of the cluster, and centrality, reflecting its degree of connection to other clusters [21–23].

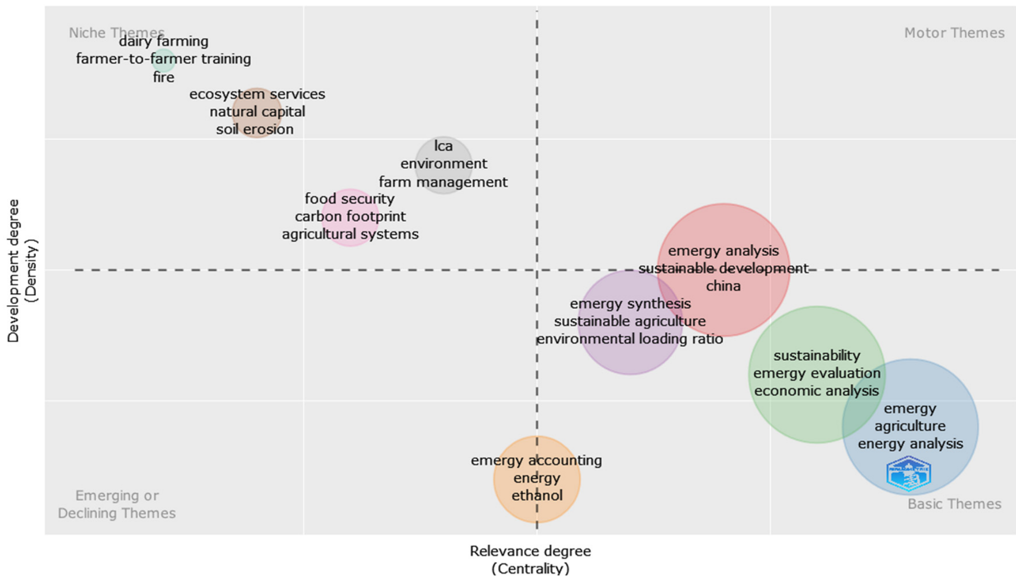

Figure 6. Thematic map of authors' keywords.

The niche theme quadrant (upper left) contained four different clusters. These are well developed but relatively specialized research groups. The brown cluster—linking "ecosystem services", "natural capital" and "soil erosion"—reveals how well studied the soil erosion theme is, as it constitutes an important component of ecosystem services, as a regulating service related to erosion control and soil retention. Likewise, the grey cluster—"life cycle assessment", "farm management", and "environment"—shows how LCA functions as an environmental performance tool compliant with farm management and emergy. Another tool highlighted here is the cluster with "carbon footprint", along with "food security" and "agricultural systems". The fourth, more context-specific, includes "dairy farming," "farmer-to-farmer training," and "fire," representing targeted applications of emergy in livestock systems and rural development contexts.

No clusters are located entirely within the emerging or declining themes quadrant (lower left), although the cluster with "emergy accounting", "energy" and "ethanol" lies close to this boundary. Its position suggests that it is weakly connected and not well developed, possibly indicating declining interest or poor integration into emergy–agriculture research. The same applies to the motor quadrant (upper right), where the red cluster ("emergy analysis", "sustainable development", and "China") is positioned between quadrants. Its high centrality indicates strong connections to other topics, while its moderate density suggests it is still consolidating internally, possibly indicating that Chinese-led contributions are playing a significant role in the discourse on EmA. The basic themes quadrant (lower right) identifies the core and transversal concepts in this study area, with three fully integrated clusters, indicating the main purpose of this tool in the literature: to assess sustainability and economic performance in agricultural ecosystems.

3.6. Scope of Analysis: Spatial Scale and Production Types

Different spatial scales capture distinct levels of complexity, resource flows and heterogeneity in agricultural systems, which can influence the outcomes of an emergy assessment. To explore how scale shapes the application of EmA in agroecosystems, we categorized the reviewed publications into national, regional and farm-level analyses (Figure 7).

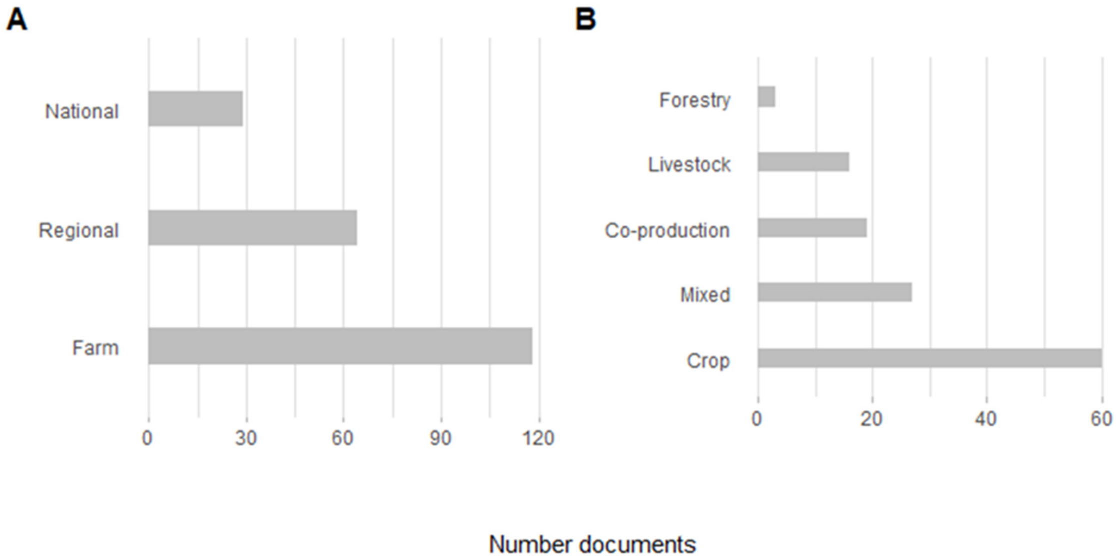

Figure 7. Number of articles, characterized by their dimension scale (**A**) and the production type related to farm-scale analysis (**B**).

Farm-scale studies dominated the dataset. This likely reflects the methodological compatibility of EmA with detailed, site-specific data, as well as the research interest in comparing management practices at the production-unit level. Regional-scale studies, the second most frequent category, covered diverse spatial units: from individual watersheds to multi-province territories. This highlights the flexibility of EmA in assessing aggregated agricultural systems within a defined landscape. National-scale assessments were the least represented and often formed part of broader EmA studies encompassing entire economies, where agriculture was only one sector among many.

Within farm-scale studies, crop production systems were by far the most frequently assessed (Figure 7B), reflecting both the global prominence of cropping systems and the availability of production and input data necessary for emergy accounting. Mixed crop–livestock systems formed the second-largest group, underscoring interest in integrated resource flows between plant and animal production. Co-production systems—where agricultural outputs are coupled with bioenergy production such as biofuels or bioethanol—appeared less frequently but represent an emerging niche linking agriculture to renewable energy transitions. Livestock-only systems were comparatively rare, while forestry systems (with harvestable products such as timber or cork) were minimally represented, possibly due to the longer temporal scales required for evaluation.

3.7. Agricultural Productions and Emergy Indicators

Emergy indicators are frequently used to quantify the sustainability of one system, since many other assessment methods cannot measure the contribution of natural ecosystem to economic development. Figure 8 shows the collected emergy indicators from a subset of publications (Table S1), as explained in Section 2.2. There were studies that assessed more than one system. This explains why there are different numbers of studies (n) for each type of system. Among all production types, livestock production has the highest EYR and ELR; consequently, its ESI indicator is the lowest compared to other agricultural systems. The environmental loading ratio of crop production is closer to that of livestock than to mixed production, which has the lowest ELR. On the other hand, the ESI of crop production is closer to that of mixed production, which has the highest value.

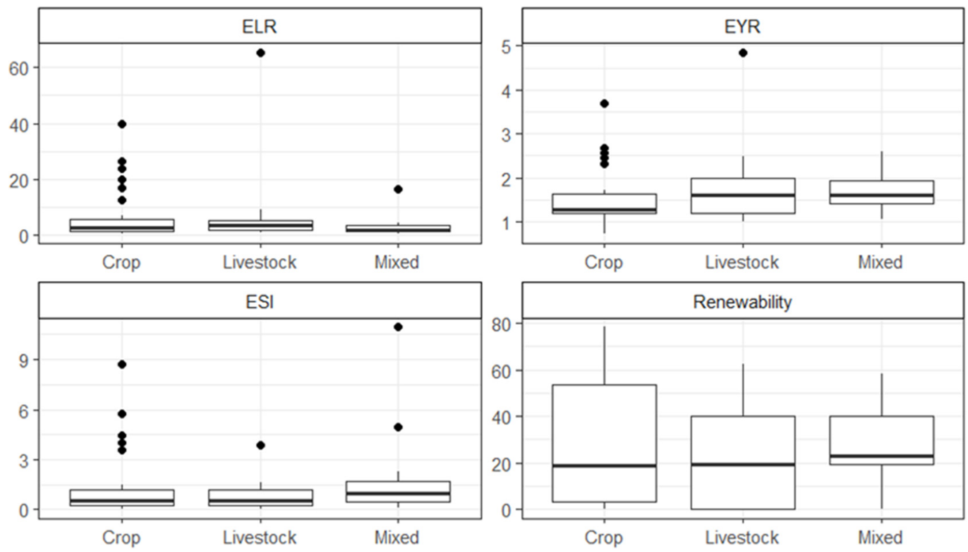

Figure 8. Emergy indicators collected from a subset of publications and categorized by type of agriculture: crop, mixed and livestock systems. Observations (n) for ELR, EYR, ESI: crop = 21, livestock = 16, mixed = 16; observations (n) for renewability: crop = 21, livestock = 11, mixed = 11.

The average percentage of renewable resource use is higher for mixed production, although the maximum values are higher for crops, followed by livestock.

4. Discussion

Our bibliometric analysis shows how recent and unexplored the link between emergy and agriculture is. Although still considered a novel topic, the field has shown a progressive increase in scientific publications since 2000, particularly from China, followed by Italy and Brazil. Collaboration is common, and just a handful of journals concentrate most of the output, notably *Journal of Cleaner Production*, *Ecological Indicators* and *Ecological Modelling*. These patterns indicate both a growing community and a degree of concentration in where, and by whom, this work is published.

An earlier bibliometric study (1999–2014) [11] reported very few agriculture-focused EmA papers, 13 from a total of 668 publications, versus the approximately 80 agro EmA items for 2000–2014 from our study. This could be attributed to broad searches for "emergy" [24–29], followed by the tallying of subfields, whereas our search strategy specifically targeted agriculture-related terms and screened the full text/abstract rather than relying on titles alone. Thus, several publications do not include the word "emergy" in their titles, and there are variant terms (assessment/evaluation/accounting/synthesis) that fragment the retrieval, underscoring how search syntax and field-specific synonyms shape the evidence base.

The popularization of EmA applied to agricultural production is growing, particularly in countries where this tool is being disclosed and taught. For instance, a university in China (Normal Beijing University) and one in Brazil (University of Campinas) are two examples of institutions where courses on emergy are offered, increasing its popularity in the region. The USA, Florida, (University of Florida Gainesville) also has an active role considering that H.T. Odum served as a Graduate Research Professor there and it now hosts the Emergy Research Conferences [30]. In Europe, Italy stands out as a major contributor, with a substantial number of scientific publications and active research groups focused on emergy applications in agriculture and sustainability. In contrast, the adoption of EmA in Africa and Oceania appears limited, with only isolated studies identified in the literature, suggesting that the methodology remains relatively underutilized in these regions.

4.1. Production Scales

Although farm-scale studies more than doubled those at the national scale in our study, relying on farm-level evidence alone might be insufficient. Farm studies excel at identifying management levers (input substitution, internal cycling and co-products) because they use detailed data and tight boundaries. Yet, they cannot capture cross-scale feedback such as the cumulative pressure of many farms on basins or whether national trade actually compensates local resource depletion. We argue that a multi-scale approach may provide the best overall picture of the various factors at play.

National evaluation of agriculture through emergy analysis provides a comprehensive assessment of a country's investments in resource management and aids in long-term planning by projecting future scenarios based on current trends in resource use and sustainability indicators. Cuadra & Rydberg used EmA in their study to evaluate the fair trade of coffee from Nicaragua, revealing that the revenue from product exportation did not compensate for the depletion of local resources [31]. Similarly, Cavalett & Ortega found that soybean production and processing in Brazil also failed to compensate for local resource depletion, particularly in international markets [32]. Additionally, national assessments of agricultural systems can identify trends in resource use over time. The increasing prevalence of production systems with intensive resource use, such as livestock production, correlates with higher ELR and EYR values, indicating an overreliance on non-renewable resources and a decrease in self-sufficiency [33,34]. Overall, national scale emergy assessments highlight critical trends and dependencies, informing strategies for sustainable resource management and policy development.

When considering the regional scale, the collected documents showed EmA being applied to evaluate specific sub-system issues, with an agricultural influence. Several studies focused on river basins, examining how economic structures and sub-system functions impact basin dynamics [35]. For instance, Guogang and colleagues assessed the agricultural systems surrounding a river basin between 1988 and 2008, revealing how the basin was affected by an increasing dependence on purchased resources, reflecting an increase in the ELR and a decrease in ESI indicators [36]. This highlights how regions are often characterized by specific types of agricultural production, and studies at this scale can provide a comprehensive understanding of the impact of these agricultural dynamics. Oliveira evaluated the direct and indirect environmental support for milk production in the Campania Region of Italy, demonstrating the importance of circular-like production systems [37]. Such assessments at the regional level can help identify different agricultural policy paradigms and their impacts. For example, Kocjančič developed a decision-making model incorporating EmA with an economic optimization model, providing both anthropocentric and ecocentric perspectives on the milk sector in Scandinavia and emphasizing the importance of organic production [38]. These studies collectively illustrate how regional scale analyses can offer valuable insights into the sustainability and dynamics of agricultural systems.

Farm-scale emergy analyses, with their detailed focus and ability to compare conventional and alternative production systems, provide critical insights that are essential for developing targeted, sustainable agricultural policies and practices that can effectively address specific local challenges.

Crop production had the highest number of study cases at farm level, highlighting comparisons between conventional high-input production and alternatives such as ecological low-input systems. Approximately 23% of these farm-level studies focus on mixed production systems, while 16% examine co-production systems. These agricultural models represent potential examples of circular agriculture, balancing circular economy principles with sustainable development goals. EmA offers a valuable approach for these systems by using a set of indicators, enabling meaningful comparisons both within and between different systems.

All in all, these scales are complementary rather than interchangeable: farm-level evidence identifies what to change, regional studies show where aggregation and heterogeneity matter, and national assessments test whether the overall trajectory is sustainable.

4.2. Farm-Scale Emergy Indicators

We used four indicators to (i) explore the relevance of EmA on agroecosystems' management by comparing different systems at the farm scale and (ii) to highlight the environmental performance in mixed production. Because crop production was the most recurrent type to be assessed, the subset used for indicator collection yielded more results than other agricultural types. Livestock was the production type with the highest impact on the environment (ELR = 8.1), followed by crop production (ELR = 6.7). Both of these production systems are largely intensive and dependent on industrialized non-renewable resource inputs, such as fertilizers and machinery. For instance, in the long-term, the higher the %R, the higher the resilience of a system to economic stress, considering the lower dependence on non-renewables. The average %R did not differ significantly between production types, and the relatively low values point out to the reliance these systems still have on non-renewables. These results also help to clarify the critical role of agricultural systems in supporting non-agricultural sectors, particularly through the services they require [39].

Local free non-renewable resources from agricultural production are related to groundwater and topsoil loss. Topsoil loss emergy is calculated based on the erosion rate and organic matter content, multiplied by its UEV. The UEVs should vary by region to reflect the amount of environmental work embodied in the process of SOM production [40]. Soil depletion in agricultural production is a critical subject needing more attention, as evidenced by its identification as a niche theme in Figure 6.

Mixed production proved to be the system with the lowest pressure on the environment (ELR = 2.1). In other words, since the ELR assumes that a higher reliance on non-renewable components indicates greater environmental pressure, mixed production systems demonstrate a higher capacity for natural development and, consequently, self-sustainability. However, these systems need to be resilient to avoid climate change vulnerability. A high EYR indicates that there are more contributions from free emergy flows rather than purchased outputs. However, on its own, it does not reflect production efficiency [41]. The highest maximum value collected corresponds to the livestock system of a large-scale dairy farm following a circular economy model, with a great amount of resources being re-circulated within the system [42]. These types of systems could arguably be classified as mixed systems, to a certain extent. Martin and colleagues emphasize that mixed systems could vary spatially and temporally, arguing that systems could be considered mixed based on complementary production [43].

Mixed production systems exert, in general, lower pressure on the environment and show higher sustainability [44–46]. On the other hand, they have lower productivity, which can be compensated for by internal resource cycling and greater product diversity. Several emergy analyses to alternative crop production indicate higher sustainability but lower yield [47]. The decrease in yield can be offset by production diversity in integrated production systems. ESI is an indicator which can reflect a system's resilience based on how efficiently a system utilizes its resources relative to the environmental stress it imposes. For values under 1, the business relies heavily on external economic resources, focusing primarily on meeting customer consumption needs [48], leading to a higher requirement of external inputs to meet high demand, rather than aligning with the natural cycle of the ecosystem. Livestock system's average is the lowest and under 1, evidencing a system which relies on inputs. Processes with an ESI higher than 1, such as crops and mixed systems, indicate a capacity to contribute to society and to evolve naturally, with few external resources.

Fertilizers, particularly N and P, are the inputs with the largest emergy contribution in terms of purchased resources in crop production systems [49]. These could be substantially reduced with the integration of locally available organic fertilizers, such as manure, or through the incorporation of crop by-products (e.g., straw). For example, the maximum for ESI value (8.5) was observed in rice production systems that incorporated the straw back into the soil [50]. This practice reduces the need to purchase/use fertilizers while enhancing the systems' self-sustainability and exerting less pressure on the environment (ELR = 0.4). Meanwhile, in livestock production, purchased feed represents one of the main contributors to the final emergy [51]. When feed for livestock is produced locally, this flow can be highly reduced, depending on the number of animals per unit of area.

4.3. Further Considerations

EmA is still faces several challenges that it needs to overcome. One of the main inaccuracies lies in the comparison of systems analyzed under different global baselines. This issue was raised in 2016, when a consensus on adopting a global baseline of 12.1 × 1024 sej/yr was established after three different publications arrived at similar estimates [52–54]. Uncertainty also arises from transformity (Unit Emergy Value) choices—although a large part comes from energy/mass input estimations [55]. Together with data intensity, allocation rules and uneven reporting, this makes replication difficult and impairs cross-study comparability. Moreover, the selected transformities in each study may not be fully representative of the system under analysis. In other words, the total emergy required to produce a product or service depends on the particularities of each production system. The Tiangong Unit Emergy Value Database [56] has been announced (2025) as a platform intended to address several long-standing issues in EmA. According to the public description, it consolidates dispersed UEVs, records whether labor and services are included and assigns identifiers and metadata related to region, process and assumptions. It has also been reported to interface with an LCA environment, so emergy flows can be linked to upstream life-cycle processes. We did not assess this resource. We note it only as an ongoing standardization effort. Its suitability and use should be evaluated in future work. More broadly, recent syntheses of emergy research point to complementary directions that could accelerate standardization and uptake [57]: open, regional UEV repositories, AI-assisted workflows to support transformity estimation and harmonization and dynamic emergy models for scenario analysis—all of which would complement initiatives such as Tiangong, while remaining subject to independent evaluation.

Our results also show where EmA adds most value. At the farm scale, the standard indicators (ELR, EYR, ESI and %R) make management choices visible, particularly the gains from internal cycling in mixed systems. At regional and national scales, EmA reveals aggregate pressures and market linkages that farm studies cannot capture. Yet, these strengths have not fused into a single, dominant research front on the thematic map. On the thematic map, several clusters lie in the niche quadrant. They are well developed but not central to the wider network. The lack of a motor theme reflects the field's current stage: specialized strands exist, but none has yet emerged to lead the broader agenda. This also indicates a clear path for consolidation. For instance, capacity building (i.e., co-authorships beyond current hubs, shared transformity libraries and regional short courses) and a greater share of regional and national applications can connect case-level insights to policy scales. In parallel, systematically integrating EmA with LCA and other tools, such as the C footprint, can raise the centrality of these specialized strands by making results legible to wider audiences and directly comparable with mainstream impact metrics. Moreover, EmA retains the accounting of free environmental support, while LCA provides impact categories and greenhouse gas indicators that policymakers and journals commonly expect.

5. Conclusions

This review shows that the application of emergy analysis (EmA) to agroecosystems expanded steadily from 2000 to 2022, with a marked contribution from China, Italy and Brazil and a concentration of publications in a small set of sustainability journals. The field is collaborative but unevenly distributed, and the thematic map indicates mature, specialized strands without a single, dominant research front. Within this landscape, EmA's value is most evident where it translates resource use into comparable indicators and reveals hidden dependencies across scales.

Three findings stand out. First, scale matters: farm, regional and national studies are complementary rather than interchangeable. Farm-level analyses identify concrete management levers—input substitution, internal cycling and co-products—while regional and national assessments capture aggregation effects, trade linkages and long-term trajectories that single-farm studies cannot. Second, the indicator synthesis is consistent across cases: mixed crop–livestock systems generally show lower ELR and higher ESI than crop or livestock systems alone, reflecting gains from internal resource cycling; %R values remain modest overall, signaling continued reliance on non-renewables; and fertilizers in crops and purchased feed in livestock are recurrent drivers that policy and management can target. Third, the bibliometric structure itself offers guidance: journals are open to well-designed EmA work, but wider impact requires designs that speak beyond the emergy community.

Looking forward, two routes can help consolidate the field and enhance its centrality. (i) Method integration: systematically pair EmA with complementary sustainability assessment methods so that emergy's accounting of free environmental support is reported alongside the impact categories and GHG metrics that policymakers and generalist journals expect. (ii) Capacity building: extend co-authorships beyond current hubs and share practical assets to diversify geographies and production contexts and to encourage more regional and national assessments that connect farm diagnostics to policy scales. The Tiangong–LCA linkage makes such integration feasible in routine workflows.

In sum, EmA already delivers actionable insight for sustainable intensification—especially for mixed systems and circular practices—while its broader policy relevance will grow with clearer standards, multi-scale designs and integrated reporting. These steps move the field from specialized niches toward a more coherent, widely connected research front without compromising the systems perspective that constitutes EmA's distinctive strength.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/agronomy15092110/s1; Figure S1. PRISMA flow diagram illustrating the literature search and selection process for emergy-based agricultural studies. Table S1. Key characteristics of the 28 studies included in the qualitative analysis of emergy indicators [41,42,47,49–51,58–79].

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