sustainability

Review

Framing Concepts of Agriculture 5.0 via Bipartite Analysis

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Abstract: Cultural diversity often complicates the understanding of sustainability, sometimes making its concepts seem vague. This issue is particularly evident in food systems, which rely on both renewable and nonrenewable resources and drive significant environmental changes. The widespread impacts of climate change, aggravated by the overuse of natural resources, have highlighted the urgency of balancing food production with environmental preservation. Society faces a pivotal challenge: ensuring that food systems produce ample, accessible, and nutritious food while also reducing their carbon footprint and protecting ecosystems. Agriculture 5.0, an innovative approach, combines digital advancements with sustainability principles. This study reviews current knowledge on digital agriculture, analyzing scientific data through an undirected bipartite network that links journals and author keywords from articles retrieved from Clarivate Web of Science. The main goal is to outline a framework that integrates various sustainability concepts, emphasizing both well-studied (economic) and underexplored (socioenvironmental) aspects of Agriculture 5.0. This framework categorizes sustainability concepts into material (tangible) and immaterial (intangible) values based on their supporting or influencing roles within the agriculture domain, as documented in the scientific literature.

Keywords: digital; food; nexus; ontology; socioenvironmental; sustainability

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1. Introduction

Significant advancements in computer science are driving digital innovations across industries [1], including agriculture [2]. Digital and Precision Agriculture (Agriculture 4.0) relies on technologies like proximal (near target) sensors, which include electrical resistors, isotope detectors, and various types of spectrometers (e.g., visible, near-infrared, and laser-based) [3–5]. These sensors are also mounted on aerial and satellite platforms, equipped with multispectral and hyperspectral capabilities, LIDAR (Light Detection and Ranging), and radar systems like SAR (Synthetic Aperture Radar), which capture data in the microwave spectrum.

Modern monitoring devices produce vast amounts of data across a range of spatial (millimeters to meters) and temporal (fractions of a second to weeks) scales [6]. Looking forward, if these agricultural datasets can be integrated through interoperable big data platforms [7], allowing diverse datasets to be easily shared and analyzed across different platforms, they could enable complex analytics and data-driven decision-making through advanced machine learning (ML) and artificial intelligence (AI) techniques [8,9]. Future big data systems may rely on platforms-as-a-service (PaaS), edge computing, quantum computing, and fast 5G and 6G networks [10].

Technology-driven approaches like Industry 4.0 have become accessible to small- and medium-sized enterprises [11]. More recently, the European Commission introduced Industry 5.0, a concept that focuses on value-oriented economies that serve humanity within planetary boundaries [12]. This shift parallels the move from Agriculture 4.0 to Agriculture 5.0, which aims to address socioenvironmental issues. While Agriculture 4.0 primarily emphasizes data collection [2,13,14], Agriculture 5.0 seeks to use digital transformation to enhance decision-making, data precision, and accessibility, especially for smallholder farmers [9]. By supporting social equity and digital inclusion, Agriculture 5.0 can help produce and distribute culturally relevant, carbon-neutral food across diverse cultural, economic, and political landscapes [15,16].

Agriculture 4.0 already encompasses numerous developments, particularly for pre-harvest and harvest stages, which are applied to both annual crops (e.g., wheat, soybeans, corn) and perennial crops (e.g., fruit and timber). Innovations include improved water management, soil fertility and carbon adjustment, pest control, and advanced monitoring for plant and livestock health [17]. For annual crops, techniques like vegetation health and climate indices from satellite imagery allow AI-based assessments of plant health and targeted fertilizer or amendment application [18–22]. For perennial crops, digital tools like mechanized pruning and automated pest control enhance productivity [23–28]. In precision livestock farming [29], sensor technologies track grazing patterns and animal health [30–33], while UAV imagery estimates forage biomass [34] and increases the productivity [35,36] of integrated crop–livestock systems (ICLS) or crop–livestock–forestry systems (ICLFS) [37,38]. These systems, where crops and livestock are managed together for mutual benefits [39–41], foster sustainable interactions, thus protecting native ecosystems and supporting conservation [42,43].

Connecting Agriculture 4.0 with ICLS, ICLFS, and agroforestry systems (AFS) could also repurpose degraded lands into productive landscapes [44–46]. However, challenges in infrastructure, aging farmer populations, data accessibility, and market dynamics limit adoption [47–49]. Addressing these challenges is essential [15], especially as climate change and resource depletion threaten the sustainability of food systems [9,12,24]. Moving from Agriculture 4.0 to 5.0 calls for a comprehensive approach where data collection, analytics, and decision-making are integrated to enhance sustainable agriculture. This shift can support food security, environmental preservation, and economic prosperity in a world with complex socioenvironmental demands [16].

This study aims to identify knowledge gaps in Agriculture 5.0 through an analysis of current scientific data, using a bipartite network to associate scientific journals with key(words) terms from articles in the Clarivate Web of Science database. By establishing a framework that connects concepts within Agriculture 5.0, this study highlights the balance between technology and socioenvironmental sustainability, offering a value-oriented framework [12,50] to guide future research and policy toward sustainable agriculture [8,14,16,51].

2. Materials and Methods

2.1. Data Source

Data for this analysis were collected from publications indexed in the Clarivate Web of Science (WoS) database. The search, conducted on 29 January 2024, included all fields for publications from 1945 to 2023, following PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines for systematic reviews [52]. PRISMA is a standard method for systematic reviews used to track article extraction. Figure 1 provides the PRISMA diagram, with each step of the systematic process.

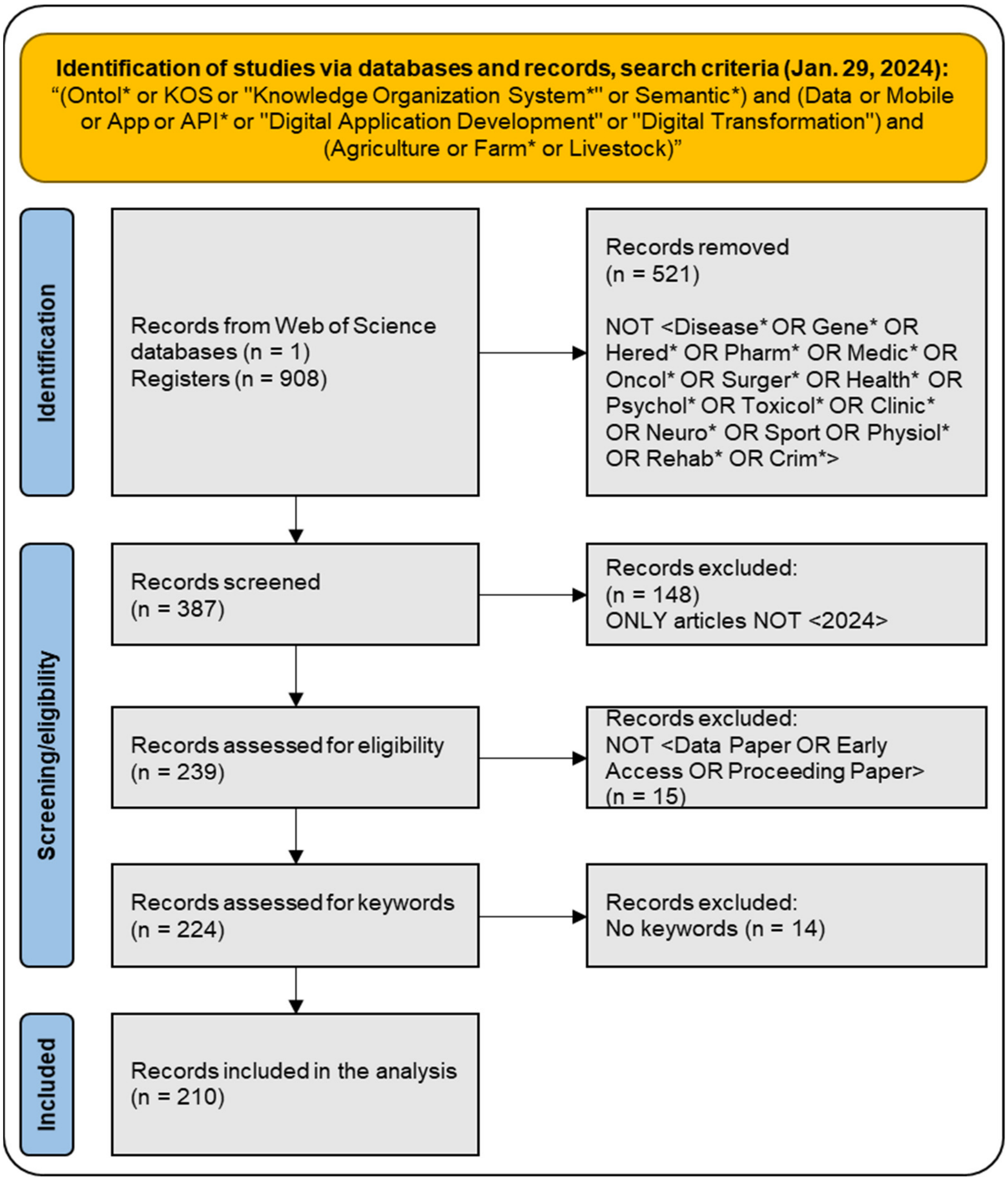

Figure 1. PRISMA methodology for extracting relevant articles in Web of Science. The symbol * stands for any additional character.

2.2. Identification

The search terms were grouped into three major categories to capture relevant publications, as follows:

- (Class 1) Knowledge organization—keywords focused on terms associated with knowledge structuring, including ontologies and semantic networks [53,54] designed to structure and classify knowledge;
- (Class 2) Terms representing digital advancements, such as "API" (Application Programming Interface) [51];
- (Class 3) Agriculture—terms related to land use, plant, and livestock systems.

"Agriculture 5.0" was not included in the search to avoid bias, as it is an emerging term.

The search strategy combined relevant terms from each class, using a logical string, as follows:

- Class 1—<Ontol* or KOS or "Knowledge Organization System*" or Semantic*>;

- Class 2—<Data or Mobile or App or API* or "Digital Application Development" or "Digital Transformation">;
- Class 3—<Agriculture or Farm* or Livestock>.

2.3. Screening, Eligibility and Inclusion

To minimize irrelevant results, especially from health-related studies, terms associated with medical or psychological fields were excluded. Only full articles were included, and publications from 2024 or those without author keywords were omitted. Keywords Plus, an algorithm-generated keyword list from WoS, was excluded to prioritize author-provided terms. Following these criteria, 210 articles were extracted, including 120 journal titles and their author keywords for the bibliometric network analysis.

2.4. Network Analysis

A bibliometric analysis was conducted on a bipartite network—called a keyword–journal network—consisting of two node types, keywords (D) and journals (J), linked by published articles [55]. The network's properties include:

- Bipartite—nodes link only between keywords and journals, not between nodes within the same set;
- Undirected—relationships lack hierarchy and reflect shared topics;
- Weighted—edges include information on how frequently a keyword appears in a particular journal.

Bipartite network analysis is a powerful tool for constructing the semantic framework of Agriculture 5.0, as it effectively captures relationships between two distinct entities—keywords (concepts) and journals. This method ensures an unbiased exploration of sustainability dimensions, integrating technological and socioenvironmental aspects critical to Agriculture 5.0. The separation of domains in bipartite analysis prevents artificial links within the same set (e.g., between keywords or journals), focusing instead on how journals act as conduits for specific concepts. By mapping keywords to journals, the analysis identifies high-degree nodes or "superhubs", which represent influential journals disseminating critical knowledge. These superhubs highlight dominant themes, while less frequent themes may be associated with little-explored concepts.

The keywords underwent a disambiguation process to group similar terms (e.g., CNN and Convolutional Neural Network). After this process, the final set included 823 keywords. The bipartite keyword–journal network was represented as a graph $G = (D, J, E)$, where D and J are the keyword and journal sets, and E is the weighted edges. Starting from matrix A ($n \times m$), where n represents keywords and m represents journals, the adjacency matrix M of G is defined as follows [55]:

$$M = \begin{bmatrix} 0 & A \\ A^T & 0 \end{bmatrix}$$

Graphical representations of the network were generated using Gephi (v. 0.10, https://gephi.org/, accessed on 1 October 2024), applying algorithms to calculate centrality measures (i.e., the importance of a node) betweenness, weighted node degree (k_w), and clustering. Node clustering was achieved with default settings of "Modularity Class" [56], and bipartite analysis was carried out with default settings of the plugin "MultiMode Network Projection" (https://github.com/jaroslav-kuchar/Multimode-Networks, accessed on 1 October 2024). The combined method allows for deriving two new networks, as depicted in the intuitive example below (Figure 2). When decomposed into two new networks, the thickness of an edge between two nodes of the same set reflects the frequency at which they were previously connected with nodes of the other set.

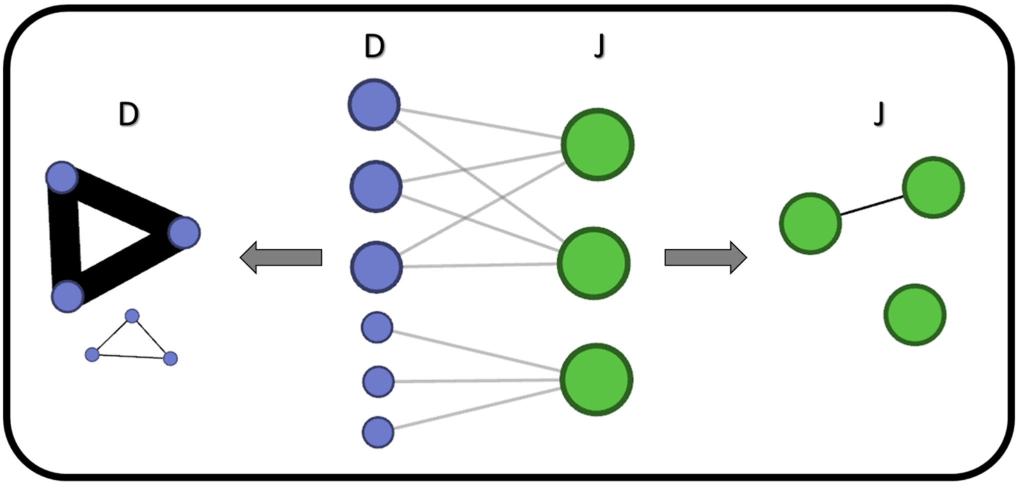

Figure 2. Schematic representation of a bipartite analysis of two sets of nodes, *D* (purple) and *J* (green).

The network's modularity class algorithm can reveal clusters of keywords (*D* set) with high and low centrality. Keywords with high centrality are generally related to economic applications of digital transformation, while keywords with low centrality suggest emerging socioenvironmental topics within Agriculture 5.0.

As a result, key sustainability concepts were extracted from the bipartite keyword–journal network analysis and integrated into a dynamic social framework [15,57]. To minimize epistemological biases, this value-oriented framework for Agriculture 5.0 was constructed by linking multidimensional sustainability concepts through semantic relationships found in the scientific literature. By structuring the framework as a directed network, it highlights both the direction and strength of connections among sustainability concepts, with nodes and node labels sized by weighted in-degree and out-degree centralities [58]. These weighted centrality measures offer insights into each concept's role, with in-degree centrality indicating support and out-degree centrality representing influence within the network. This nexus-driven approach helps reveal how different sustainability concepts interact and contribute to the overall framework.

3. Results

Figure 3 illustrates the growth in citations of the selected articles, showing an increase from 2004 to 2023. These 210 articles were cited a total of 3,466 times. The exponential trend in citations, with an annual increase rate of around 30%, highlights growing interest in the field. The uptick in citations starting around 2004 aligns with the release of the Millennium Ecosystem Assessment report (http://www.millenniumassessment.org, accessed on 1 October 2024), which examined the impacts of ecosystem changes on human well-being and recommended policies to promote the sustainable use of ecosystems.

Figure 4 displays two visualizations of the undirected bipartite network, which consists of 943 nodes and 1129 edges, linking 120 journal nodes (in blue) and 823 keyword nodes (in red). The larger network layout uses the Force Atlas 2 algorithm with settings to reduce hub formation and prevent node overlap. The inset image uses the Circle Pack Layout algorithm, grouping nodes based on hierarchy (node type and centralities), followed by the Expansion algorithm. Due to the network's bipartite structure, direct links between two keywords or two journals do not exist; rather, connections between keywords and journals occur indirectly via shared topics.

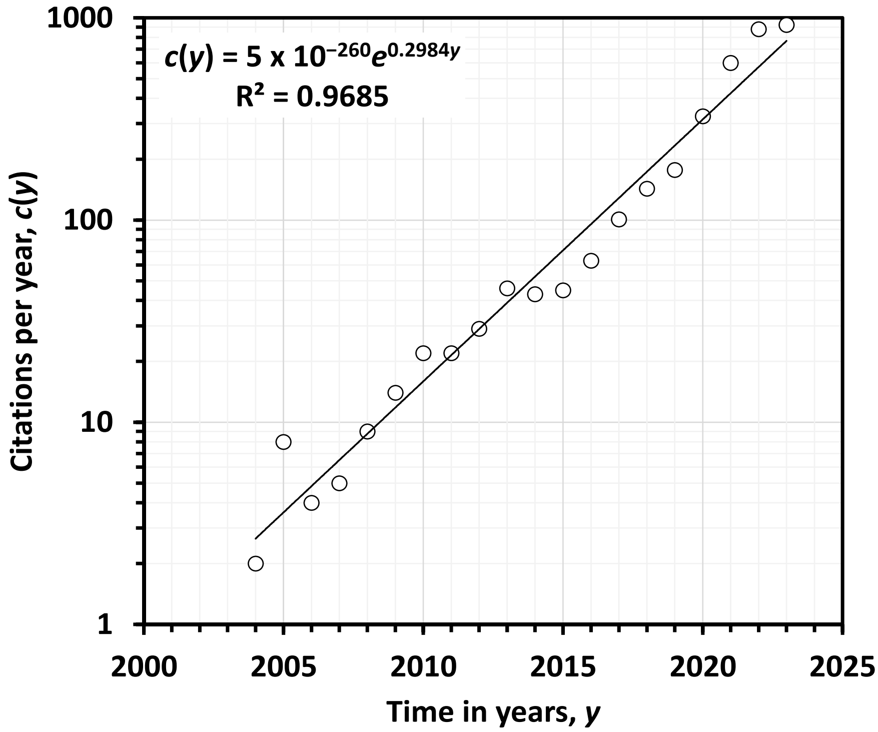

Figure 3. Exponential growth rate (~30%.y^{-1}) of scientific interest in included articles.

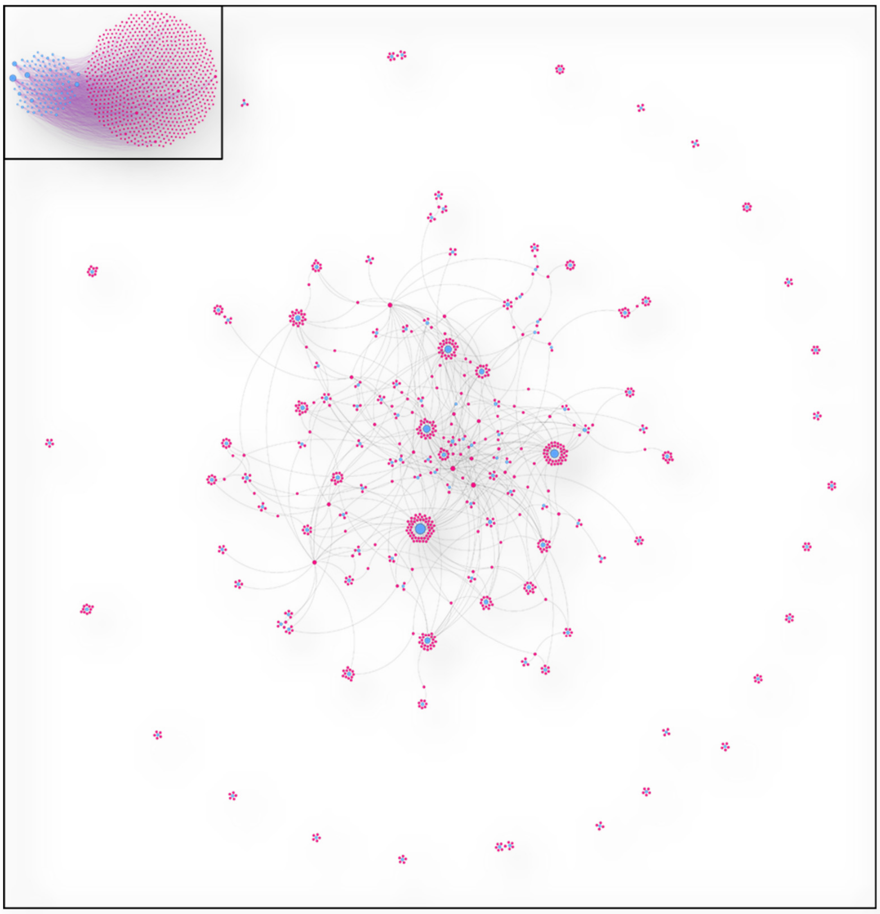

Figure 4. Two representations of the same undirected bipartite graph with 943 nodes and 1129 links between journals (in blue, 120 nodes) and keywords (in red, 823 nodes). The size of the nodes is proportional to the weighted degree centrality.

Figure 5 presents the distribution of weighted degrees (k_w) in the network. This distribution likely (out of two points, in black) follows a power-law decay, indicating that a few high-degree nodes serve as central hubs in the network, while many others have lower connectivity [59]. Five key journal nodes (superhubs) were identified with a high k_w value (>64), attracting keywords across articles and establishing them as prominent sources in this knowledge domain [60].

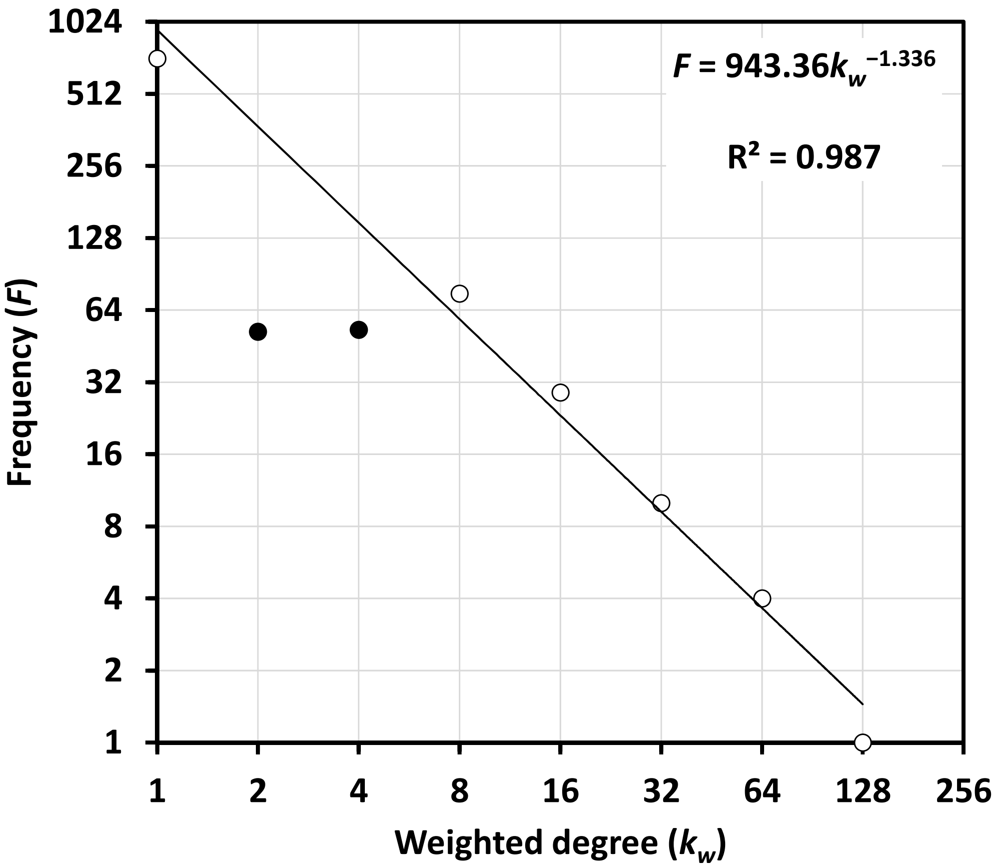

Figure 5. Log-binned (2^n for $n = 0, 1, \ldots, 7$) node degree distribution of the keyword–journal network extracted from the 210 selected publications. Dark circles were disregarded in the statistical regression.

3.1. Identification and Selection of Conceptual Assets from the Bipartite Keyword–Journal Network

Figure A1 (Appendix A) presents the one-partition J set of journals, while the one-partition D set of keywords are shown in Figures 6 and 7. The undirected network graph of keywords comprises 823 nodes linked by 11,259 edges, with an average k_w of 28.5. Clustering analysis (26 clusters) identifies high k_w clusters, particularly a large blue cluster in Figure 6. This cluster represents keywords with high connectivity, typically linked to the economic and technological aspects of sustainability. The lower k_w clusters, shown in detail in Figure 7, contain keywords associated with emerging socioenvironmental aspects of Agriculture 5.0.

Conceptual assets were selected based on these clusters, representing both high-centrality (economic) and low-centrality (socioenvironmental) sustainability dimensions (Table 1). These assets were screened for their roles within Agriculture 5.0, allowing for a preliminary framework that differentiates between technological (economic) and socioenvironmental concepts. The screening was deliberately limited to manage complexity and focus on key insights. This pragmatic approach allowed for a clear and actionable preliminary framework while leaving room for future refinement and expansion as the field evolves.

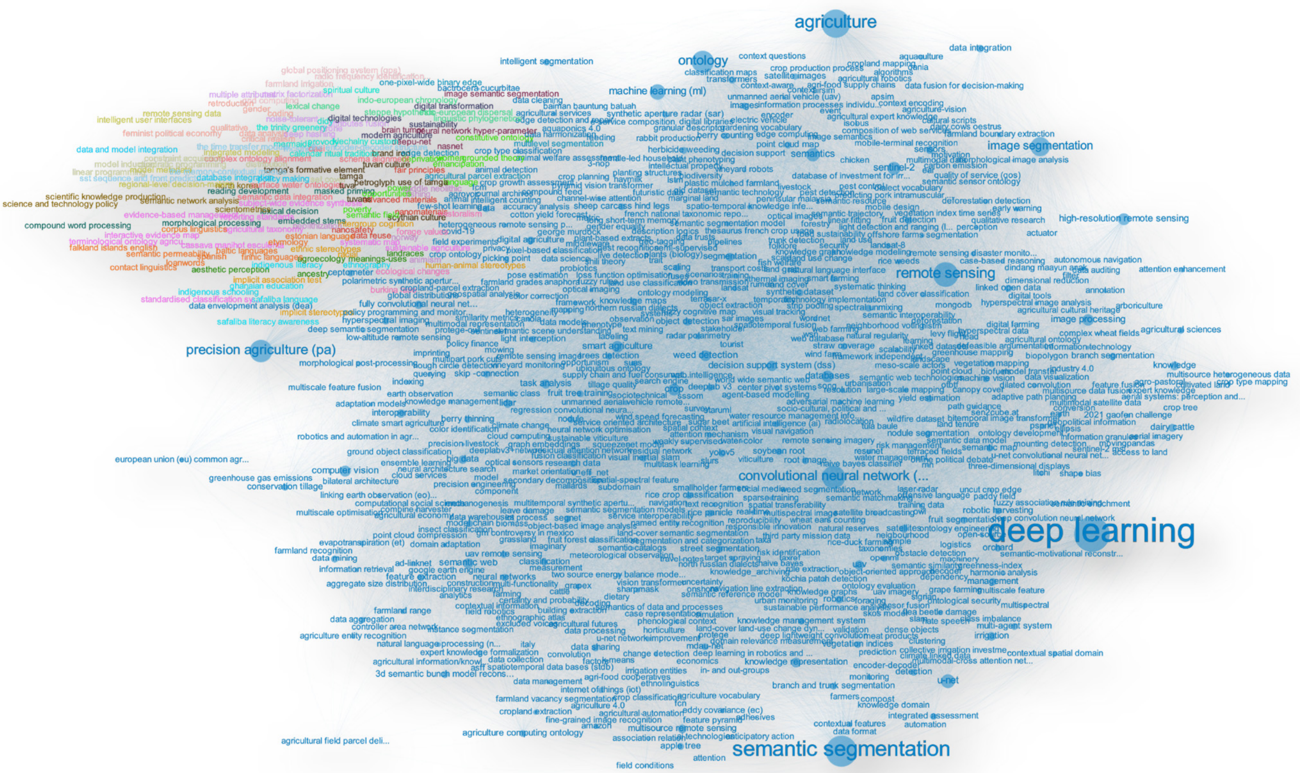

Figure 6. Keywords semantics from the bipartite analysis. The size of the nodes (labels) is proportional to the weighted degree (betweeness) centrality.

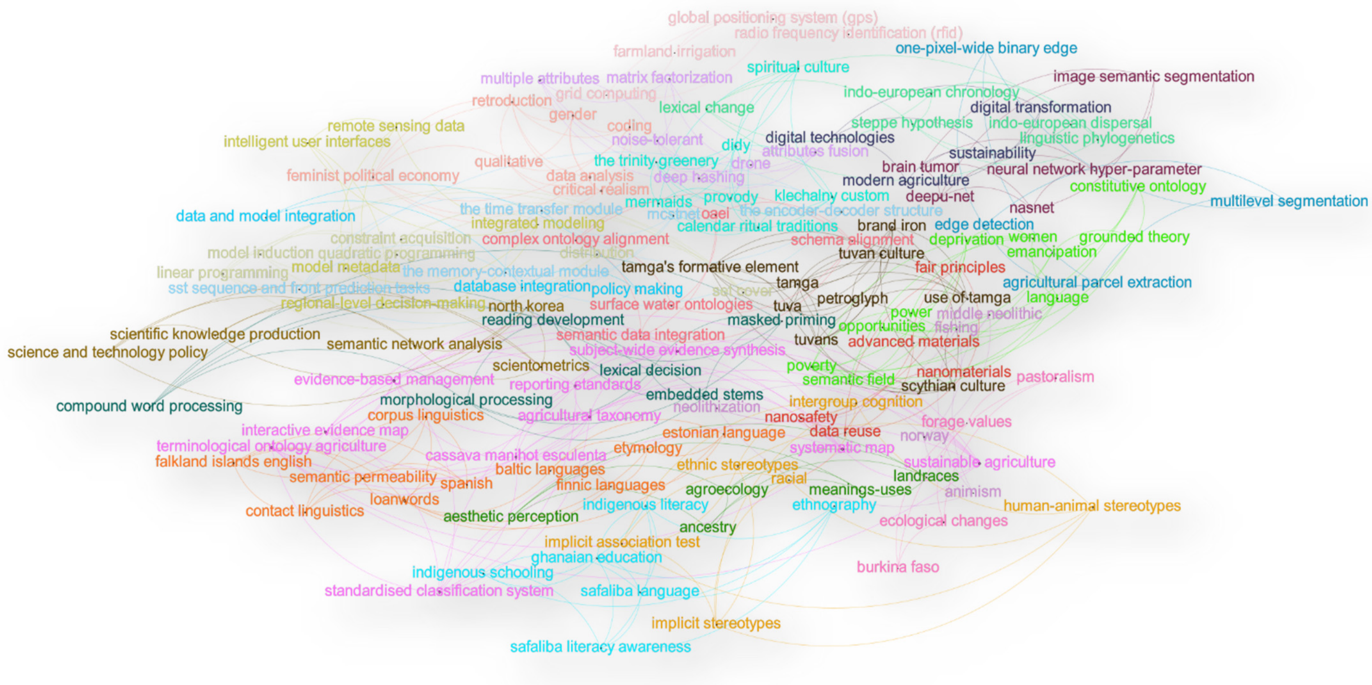

Figure 7. Details of subsets of underexplored keywords among journals.

Table 1. Major conceptual preliminary assets extracted and selected from k_w extreme values (very small and very large) obtained in 26 clusters. Most relevant concepts for screening preliminary assets are highlighted in bold (n = 31). * k_w values between $167 \leq k_w \leq 430$ shown in parenthesis. ** all k_w values shown in parenthesis.

Cluster	k_w	Extracted Concepts	Selected Assets	Selected References
0	1–430 *	**deep learning** (430), **semantic segmentation** (377), **agriculture** (344), **remote sensing** (301), convolutional neural network (cnn) (278), **precision agriculture** (272), ontology (267), **image segmentation** (233), **machine learning** (187), u-net (167)	7	n = 95 publications, see Table A1
1	2	**data** and model integration, **database integration**, **policy making**	3	58 citations [61]
2	3	agricultural parcel extraction, edge detection, multilevel segmentation, one-pixel-wide binary edge	0	-
3	3	farmland irrigation, global positioning system (gps), grid computing, radio frequency identification (rfid)	0	-
4	3	burkina faso, ecological changes, forage values, pastoralism	0	-
5	3	digital technologies, digital transformation, modern agriculture, **sustainability**	1	2 citations [62]; uncited [63]
6	4	mcstnet, sst sequence and front prediction tasks, the encoder-decoder structure, the memory-contextual module, the time transfer module	0	-
7	4	complex ontology alignment, oaei, schema alignment, semantic data integration, surface water ontologies	0	-
8	4	north korea, **science and technology policy**, **scientific knowledge production**, scientometrics, **semantic network analysis**	3	7 citations [64]
9	4	integrated modeling, intelligent user interfaces, model **metadata**, regional-level **decision-making**, remote sensing data	2	12 citations [65]
10	4	FAIR principles, nanomaterials, **data reuse**, nanosafety, advanced materials	1	3 citations [66]
11	4	animism, fishing, middle neolithic, neolithization, norway	0	-
12	4	indo-european chronology, indo-european dispersal, lexical change, linguistic phylogenetics, steppe hypothesis	0	-
13	4	brain tumor, deep u-net, image semantic segmentation, nasnet, neural network hyper-parameter	0	unrelated
14	4	aesthetic perception, agroecology, **ancestry**, landraces, meanings-use	1	uncited [67]
15	5	attributes fusion, deep hashing, drone, matrix factorization, multiple attributes, noise-tolerant	0	-
16	5	compound word processing, embedded stems, lexical decision, masked priming, morphological processing, reading development	0	-
17	5	constraint acquisition, distribution, linear programming, model induction, quadratic programming, set cover	0	-
18	5	ethnography, ghanaian education, indigenous literacy, indigenous schooling, safaliba language, safaliba literacy awareness	0	-
19	5	**ethnic** stereotypes, human-animal stereotypes, implicit association test, implicit stereotypes, intergroup cognition, **racial**	2	1 citation [68]
20	6	coding, **critical realism**, **data analysis**, feminist political economy, **gender**, qualitative, retroduction	3	492 citations [53]
21	6	calendar **ritual traditions**, didy, klechalny custom, mermaids, provody, spiritual culture, the trinity greenery	1	uncited [69]
22	8	brand iron, petroglyph, scythian **culture**, tamga, tamga's formative element, tuva, tuvan culture, tuvans, use of tamga	1	1 citation [70]
23	9	agricultural taxonomy, cassava manihot esculenta, evidence-based management, interactive evidence map, reporting **standards**, standardised classification system, subject-wide evidence synthesis, sustainable agriculture, systematic map, terminological ontology agriculture	1	uncited [71]
24	4–9 **	**poverty** (9), deprivation (5), **language** (5), **power** (5), **women** (5), semantic field (5), constitutive ontology (4), grounded theory (4), **emancipation** (4), opportunities (4)	5	2 citations [72]; 18 citations [73]
25	5–9 **	loanwords (9), contact linguistics (5), corpus linguistics (5), falkland islands english (5), semantic permeability (5), spanish (5), finnic languages (4), baltic languages (4), estonian language (4), etymology (4)	0	-
Total	-	-	31	-

3.2. *Economy: The Core Dimension of Sustainability in Agriculture 4.0*

The main assets from Cluster 0 in Table 1—"deep learning", "semantic segmentation", "agriculture", "remote sensing", "precision agriculture", "image segmentation", and "machine learning"—were mapped into nine conceptual assets that define the economic dimension of sustainability. These assets represent applications within Agriculture

4.0 that support technological advancements, enabling better monitoring, analysis, and management practices. The conceptual applications include the following:

- Detection—identifying or detecting beneficial or harmful elements within agricultural systems;
- Forecasting—using historical data to predict future trends or events;
- Framework—providing guidelines for building useful systems or solutions;
- Mapping—assigning geographic locations to specific land cover or crop classes;
- Modeling—creating representations that accurately reflect reality;
- Monitoring—recording and analyzing data over time to track processes;
- Policy—developing principles, rules, or guidelines to achieve long-term sustainability goals;
- Privacy—ensuring individuals' control over how their data are collected and utilized;
- Security—providing reliability, safety, and trust in the use of technological applications.

The association between these conceptual assets and their applications in digital agriculture was established through a detailed review of 95 articles that referenced these keywords (Table A1 in Appendix A). Figure A2 shows the mapping between these keywords and the nine economic sustainability concepts, illustrating a "domain-to-range" relationship, i.e., linking specific keywords to broader conceptual categories.

Figure 8 illustrates the new bipartite analysis of the mapping in Figure A2, resulting in a semantic network of economic sustainability concepts in Agriculture 4.0, where edges represent the connections between these economic conceptual assets. Node and label sizes reflect weighted degree and betweenness centrality distributions, respectively, to emphasize the role of each concept within the network.

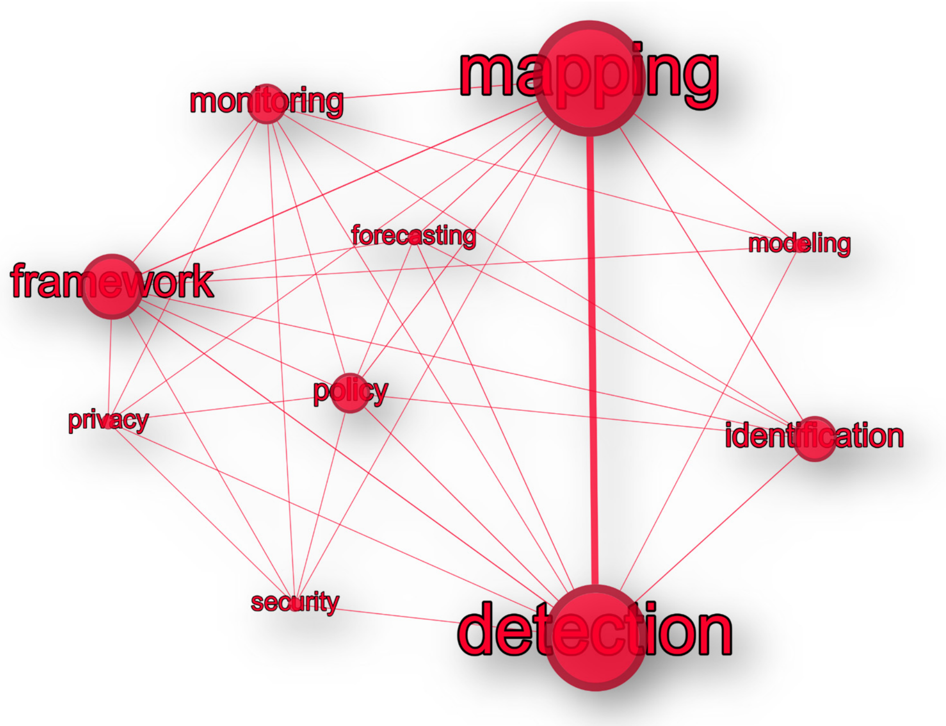

Figure 8. Network of conceptual assets of the Economic (technological application) dimension of Sustainability obtained from the bipartite analysis between "economic keywords" and the nine conceptual assets of the economic dimension of sustainability. The bipartite network is shown in Figure A2. The size of the nodes (labels) is proportional to the weighted degree (betweeness) centrality.

In Figure 8, notable connections exist between mapping (through remote and proximal sensing) and detection (primarily via proximal sensing). These connections are key for identifying specific targets and monitoring environmental changes. Modeling (through simulations of real-world processes) and forecasting (predicting future conditions) are linked as well, supporting the construction of comprehensive frameworks for sustainable knowledge organization. Together, these processes inform policy creation, guiding both public and private sectors in addressing sustainability challenges.

While the importance of privacy and data security is recognized, these concepts are among the lower-centrality nodes in the network. This suggests that while essential, they are less frequently addressed within the current technological applications of Agriculture 4.0, possibly indicating an area for future development as digital agriculture evolves.

4. Discussion

4.1. Socioenvironmental Dimensions of Sustainability in Agriculture 5.0

There is an urgent need for interdisciplinary research and synthesis focused on food and farming systems. Such efforts should produce culturally, economically, and politically appropriate insights to ensure that food production and distribution address both economic and ecological sustainability [15]. For example, cluster 1 (Table 1) highlights keywords like "data", "model integration" and "policy making" [61], which underscore the importance of agriculture databases structured with semantic relationships, based on meaning or conceptual similarity, and shared ontologies. Such structured datasets enable more reliable data-driven decision-making.

The broader concept of "sustainability" (cluster 5) emerges from recent literature emphasizing strategic planning as essential for integrating diverse data required for sustainable agriculture [62,63]. Additionally, studies reveal the critical role of smallholder farmers, especially women-led agricultural enterprises [63], in aligning with the Sustainable Development Goals (SDGs) set by the United Nations [43].

Other clusters reveal emerging socioenvironmental aspects of Agriculture 5.0. For instance, cluster 8 highlights the use of semantic networks to enhance scientific and technological policymaking (cluster 8). Similarly, cluster 9 emphasizes structured data and metadata for process-based modeling, particularly in addressing human impacts on natural resources [46]. Cluster 10 highlights data reuse, advocating for governance frameworks based on F.A.I.R. (Findable, Accessible, Interoperable, and Reusable) principles to support socioenvironmental goals [66].

Notably, cluster 14 introduces the concept of ancestry and its relationship to cultural aspects in agriculture [65], while cluster 19 adds concepts like ethnic and racial diversity [67]. These socio-cultural elements impact how communities perceive agricultural practices and the adoption of sustainable technologies [74,75]. Clusters 21 and 22 address cultural traditions and rituals [69,70], with examples like cereal production practices from Ukrainian folklore and the symbolic role of animal marking in nomadic societies [76]. Together, these findings highlight the challenges of integrating diverse cultural contexts into standardized (cluster 23) frameworks for sustainable agriculture [71].

Finally, clusters 20 [53] and 24 [72,73] address themes of gender, poverty, power, and emancipation, reinforcing the importance of fair representation and inclusivity in sustainable development. The inclusion of these socioenvironmental dimensions underscores the need for a value-oriented framework in Agriculture 5.0 that recognizes both material (tangible) and immaterial (intangible) factors influencing sustainability [53,72,73,77].

4.2. Developing a Framework of Conceptual Assets of Agriculture 5.0

The digital transformation of agriculture relies on precision and digital technologies that, if adapted to local contexts, can generate high-value agricultural products and address socioenvironmental challenges [10]. From a critical realism perspective [53], this framework needs to be rooted in the recognition that reality (ontology) cannot be simplified into our knowledge of it (epistemology). Critical realism promotes an ontological approach that minimizes biases [53], acknowledging the inherent complexity of sustainability concepts [57].

In Agriculture 5.0, the conceptual assets framework distinguishes between material and immaterial values [12]. Achieving sustainability in agriculture involves addressing not only tangible (economic) needs, but also intangible (socioenvironmental) factors such as user values, cultural connections, and well-being [77]. Prototyping the framework as a directed network allows the relationships between these assets to be structured according to weighted in-degree (support) and out-degree (influence) centralities, clarifying each asset's role within the network [58].

Table 2 summarizes the value-oriented conceptual assets for Agriculture 5.0, categorizing them based on support and influence roles derived from scientific literature. The framework highlights that certain assets—such as technology, sustainability, and policy-making—are pivotal, influencing other dimensions and guiding sustainable agricultural practices.

Table 2. Value-oriented conceptual assets in Agriculture 5.0 and their semantics based on the nexus of "support" and "influence" in the scientific literature. The symbol * indicates incremental material assets.

Conceptual Asset	Value	Support (In-Degree)	Influence (Out-Degree)
Agriculture	Material	Ethnic, Language, Policy-making [78–85]	Language, Ritual tradition, Technology [79,80,82,83,85–89] and see also Table A1
Ancestry	Immaterial	-	Culture, Ethnic [74]
Certification *	Material	Sustainability [90]	Information [90]
Culture	Immaterial	Ancestry, Language, Ritual tradition [74,83,85,91,92]	Agriculture, Language, Ritual tradition [74,83,85]
Data	Material	Metadata standard, Privacy, Security, Technology [93–96]	Information [94]
Decision making	Material	Knowledge [97]	Policy making [90,98,99]
Detection	Material	Technology (Table A1)	Technology (Table A1)
Education	Material	Policy making [99]	Ethic, Sustainability [100,101]
Equality	Immaterial	Gender, Race, Ethic [102–104]	Sustainability [105]
Ethic	Immaterial	Education [106]	Equality [100,101]
Ethnic	Immaterial	Ancestry, Race, Ritual tradition [74,83,91,92]	Agriculture [78,90]
Vocabulary *	Material	Language [107]	Metadata standard [108]
Forecasting	Material	Modeling (Table A1)	Knowledge (Table A1)
Gender	Immaterial	-	Equality [109]
Identification	Material	Technology (Table A1)	Technology (Table A1)
Information	Material	Data (Table A1)	Modeling (Table A1)
Intellectual property *	Material	Technology (Table A1)	Technology (Table A1)
Knowledge	Material	Forecasting (Table A1)	Decision making (Table A1)
Language	Immaterial	Agriculture, Culture, Vocabulary [74,83,91,92,107]	Agriculture [79,80,85]
Mapping	Material	Technology (Table A1)	Technology (Table A1)
Metadata standard	Material	Language, Privacy, Security, Technology [95,110–112]	Data [93], Information technology—Metadata registries (MDR)—Part 6: Registration
Modeling	Material	Information (Table A1)	Forecasting (Table A1)
Monitoring	Material	Technology (Table A1)	Technology (Table A1)
Privacy	Immaterial	Sustainability [113]	Data, Metadata standard [93,95,112,113]
Policy making	Material	Decision making [98]	Agriculture, Education, Sustainability, Technology [84,99,114]
Race	Immaterial	-	Equality, Ethnic [102–104]
Ritual tradition	Immaterial	Agriculture [87,89,92]	Culture, Ethnic [74]
Security	Immaterial	Sustainability [113]	Data, Metadata standard [93,95,112]
Sustainability	Immaterial	Education, Equality, Policy making [84,99,105,109]	Agriculture [84]
Technology	Material	Detection, Identification, Intellectual property, Mapping, Monitoring, Policy making [114] and Table A1	Data, Detection, Identification, Intellectual property, Mapping, Monitoring, Metadata standard [112]

In the corresponding graph of the directed network (Figure 9), agriculture influences elements like language, ritual traditions, and technology, while being supported by policy [99] and ethnic factors [78]. For instance, agricultural practices are often shaped by traditional languages and rituals, as seen in the deep-rooted agricultural societies of South America [79] and East Asia [83], where language and agricultural knowledge evolved together [68,74,91,93]. This co-evolution has been observed in civilizations across different regions, underscoring the historical and cultural (heritage) significance of agricultural practices [75,85,87–89].

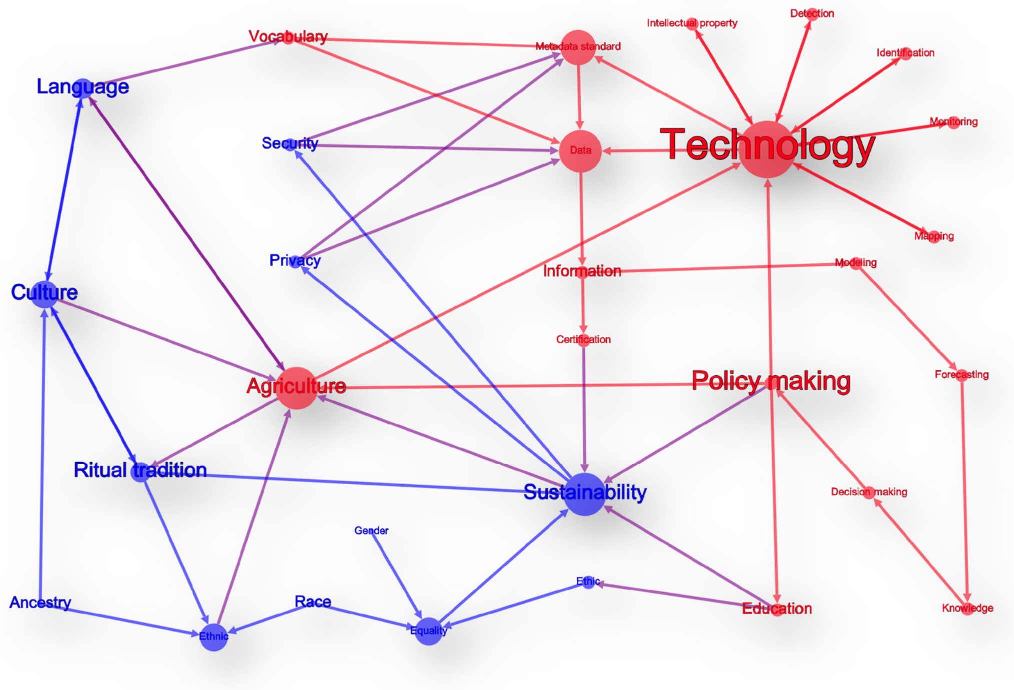

Figure 9. Framework of material (red) and immaterial (blue) conceptual assets in Agriculture 5.0 as a directed network graph of weighted support (larger labels) and influence (larger nodes).

Assets such as privacy and security [93–96] are fundamental in the current technological landscape, ensuring that agricultural data collection respects individual rights [81,82]. As digital transformation progresses, concepts like metadata standards [108] and controlled vocabularies [95,107,110–112] will play crucial roles in structuring agricultural data for certification [90], while education [100,101] will remain vital for cultivating knowledge on sustainable practices [102–104,113].

The framework's integration of diverse conceptual assets reflects the complex interplay of economic, social, and environmental elements essential to Agriculture 5.0 [78,84,97]. A value-oriented approach to Agriculture 5.0 will need to consider not only the practical applications of technology, but also the broader socioenvironmental contexts in which agricultural practices occur [98,99,105,114], particularly in the context of climate change [10,13] and smallholders [90].

Table 3 summarizes the main roles of conceptual assets in Agriculture 5.0. "Technology" stands out as the primary supporter and influencer of other key assets. Overall, major supporters include Technology, Sustainability, Agriculture, Data, Metadata Standards, Culture, Equality, and Ethnic Diversity. In contrast, major influencers are Technology, Policy Making, Sustainability, Agriculture, Culture, Language, and Ritual Tradition. These findings suggest that focusing research and development on these key assets could significantly advance a value-oriented Agriculture 5.0.

Table 3. Weighted influencer (supported by) and supporter roles of Agriculture 5.0 conceptual assets.

Conceptual Asset	Value	Influence	Support
Technology	Material	7	7
Sustainability	Immaterial	5	3
Agriculture	Material	5	3
Data	Material	5	1
Metadata standard	Material	4	1
Culture	Immaterial	3	3
Equality	Immaterial	3	1
Ethnic	Immaterial	3	1
Language	Immaterial	2	3
Ritual tradition	Immaterial	2	3
Ethic	Immaterial	1	1
Vocabulary	Material	1	2
Privacy	Immaterial	1	2
Security	Immaterial	1	2
Decision making	Material	1	1
Detection	Material	1	1
Education	Material	1	2
Forecasting	Material	1	1
Identification	Material	1	1
Information	Material	1	2
Knowledge	Material	1	1
Mapping	Material	1	1
Modeling	Material	1	1
Monitoring	Material	1	1
Policy making	Material	1	4
Intellectual property	Material	1	1
Certification	Material	1	1
Ancestry (Heritage)	Immaterial	0	2
Gender	Immaterial	0	1
Race	Immaterial	0	2

5. Conclusions

The digital transformation in agriculture holds potential not only for economic gains, but also for fostering sustainable practices. Agriculture 5.0 aims to go beyond data collection to develop actionable insights that provide real-world benefits. However, there is concern that concentrating large volumes of data and analytical power within a few entities could exacerbate inequalities, excluding those with fewer resources and increasing the risk of environmental degradation unless well-regulated.

In this study, a bipartite network analysis was applied to identify core sustainability concepts in Agriculture 5.0, proposing a framework that connects economic and socioenvironmental dimensions. This preliminary framework underscores the need for a balanced approach that integrates both technological advancements and socioenvironmental priorities. The shift from Agriculture 4.0 to 5.0 represents a promising pathway to enhance food security and environmental stewardship, aligning with the United Nations Sustainable Development Goals (SDGs).

While technological advancements will continue to drive progress, establishing shared standards, semantic agreements, and protocols for socioenvironmental data is likely essential for long-term sustainability. This study's approach provides an initial structure for such a framework, though further development and formalization, possibly through Web Semantics or ontology-based methods, will be needed to refine it.

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Appendix A

Figure A1 displays the J set of journals, as structured in Figure 2. Generated with the Force Atlas 2 layout, the graph includes 120 journal nodes connected by 977 edges, with an average weighted degree (k_w) of 23.9. Node sizes and labels represent k_w and betweenness centralities, while colors indicate 26 clusters derived from the modularity class algorithm. Within the largest blue cluster in Figure 5, key "superhub" journals are highlighted, including Computers and Electronics in Agriculture (k_w = 180), IEEE Access (k_w = 143), Remote Sensing (k_w = 102), IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing (k_w = 97), and IEEE Sensors Journal (k_w = 88).

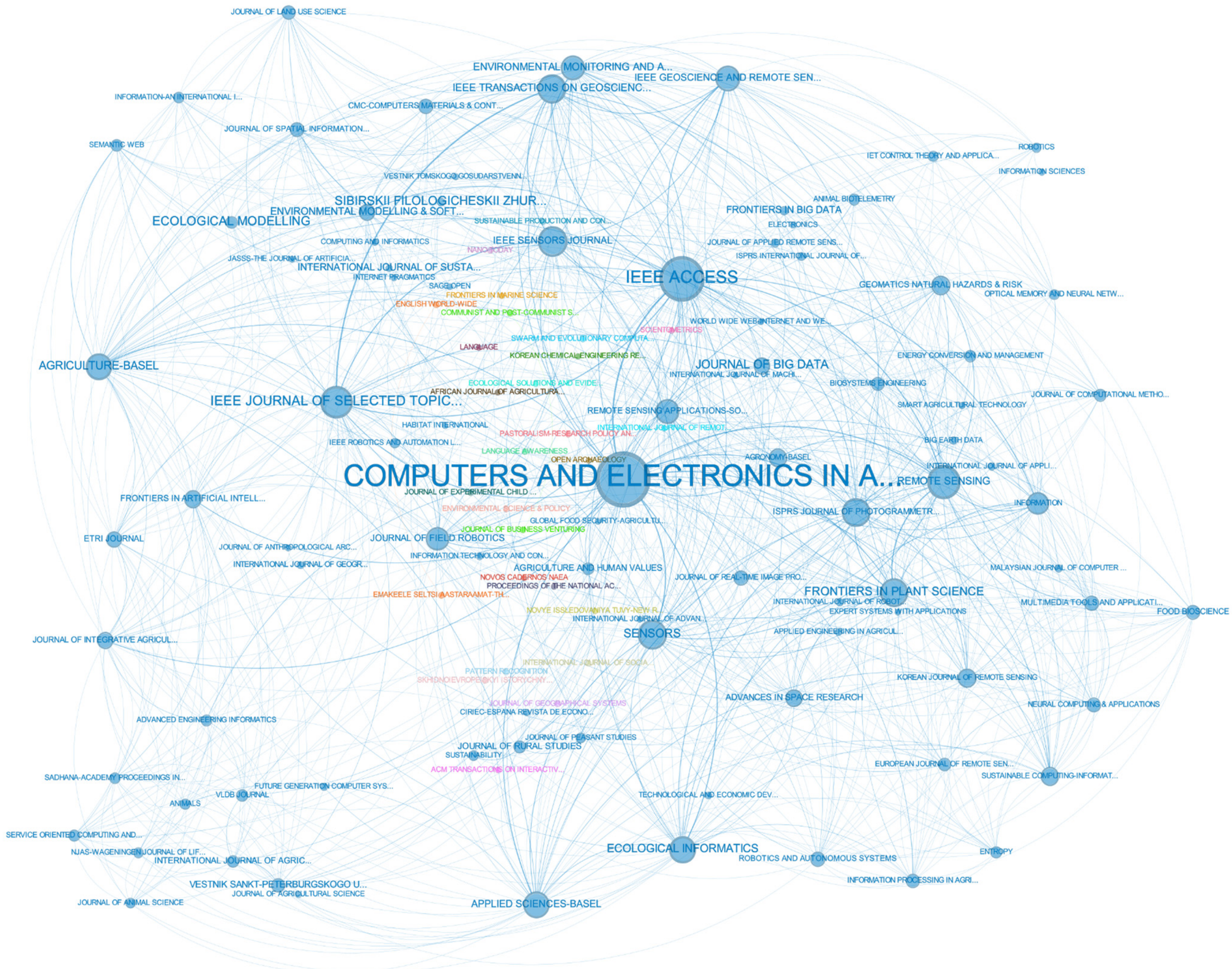

Figure A1. *J* (journals) set from the bipartite analysis of the keyword–journal network.

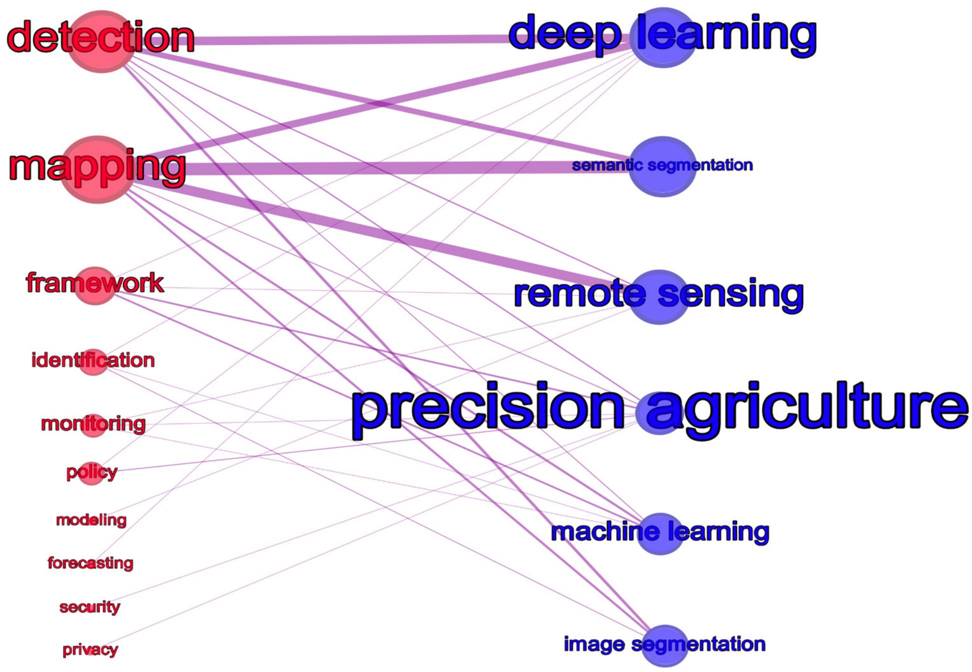

Figure A2. Bipartite undirected network between superhub keywords (blue) and application categories (red). The size of nodes (labels) is proportional to weighted degree (betweeness) centrality, while the thickness of the edges is related to ties strength.

Table A1. Bipartite correspondence between applications and superhub keywords in 95 publications from cluster 0 (Table 1).

Application	Publication DOI	Publication Year	Superhub Keywords
detection	10.1007/s11554-023-01264-0	2023	deep learning, precision agriculture
detection	10.1016/j.compag.2020.105302	2020	deep learning
detection	10.1016/j.compag.2020.105504	2020	deep learning
detection	10.1016/j.compag.2020.105760	2020	precision agriculture
detection	10.1016/j.compag.2023.107881	2023	deep learning, semantic segmentation
detection	10.1016/j.inpa.2022.05.002	2023	semantic segmentation
detection	10.1016/j.isprsjprs.2023.09.021	2023	deep learning
detection	10.1016/j.rsase.2021.100627	2021	deep learning, semantic segmentation
detection	10.1016/j.suscom.2022.100759	2022	deep learning, semantic segmentation
detection	10.1109/ACCESS.2020.2991354	2020	deep learning, semantic segmentation, precision agriculture
detection	10.1109/ACCESS.2021.3108003	2021	deep learning, semantic segmentation
detection	10.1109/JSEN.2021.3071290	2021	deep learning, semantic segmentation, image segmentation
detection	10.1109/LRA.2023.3320018	2023	image segmentation
detection	10.3390/agriculture11020131	2021	deep learning
detection	10.3390/rs15215124	2023	deep learning, semantic segmentation, remote sensing
detection	10.3390/s20185292	2020	deep learning, remote sensing, image segmentation
detection	10.3390/s21144801	2021	semantic segmentation
detection	10.3390/s22197131	2022	image segmentation
detection	10.7780/kjrs.2021.37.3.1	2021	deep learning, semantic segmentation
detection & identification	10.1016/j.compag.2021.106451	2021	image segmentation, machine learning
detection & identification	10.1109/TGRS.2021.3093041	2022	deep learning, image segmentation

Table A1. *Cont.*

Application	Publication DOI	Publication Year	Superhub Keywords
detection & identification	10.3390/rs14092004	2022	deep learning
detection & mapping	10.1016/j.biosystemseng.2020.05.022	2020	deep learning
detection & mapping	10.1016/j.compag.2019.03.028	2019	machine learning
detection & mapping	10.1016/j.compag.2023.108217	2023	semantic segmentation
detection & mapping	10.1016/j.isprsjprs.2021.08.024	2021	deep learning, semantic segmentation
detection & mapping	10.1080/19475705.2023.2196370	2023	deep learning, semantic segmentation, remote sensing
detection & mapping	10.1109/LRA.2019.2901987	2019	deep learning
forecasting	10.1016/j.enconman.2020.113098	2020	deep learning
framework	10.1109/ACCESS.2021.3128178	2021	deep learning
framework	10.1109/ACCESS.2022.3198099	2022	precision agriculture
framework	10.1109/JSTARS.2021.3139155	2022	precision agriculture
framework	10.1117/1.JRS.16.024519	2022	machine learning
framework	10.1145/3453172	2021	remote sensing
framework	10.1186/s40537-023-00729-0	2023	precision agriculture, machine learning
framework	10.21638/11701/spbu10.2022.206	2022	precision agriculture
framework	10.32604/cmc.2023.030924	2023	machine learning
framework	10.3389/fdata.2020.00012	2020	machine learning
mapping	10.1007/s00521-020-05561-8	2023	semantic segmentation
mapping	10.1007/s10661-022-10848-5	2023	deep learning, semantic segmentation, remote sensing, image segmentation
mapping	10.1007/s11042-022-12141-6	2022	semantic segmentation
mapping	10.1016/j.asr.2023.05.007	2023	semantic segmentation, remote sensing
mapping	10.1016/j.compag.2020.105277	2020	deep learning
mapping	10.1016/j.compag.2020.105369	2020	semantic segmentation, remote sensing
mapping	10.1016/j.compag.2021.106482	2021	deep learning, semantic segmentation
mapping	10.1016/j.compag.2022.106731	2022	deep learning, remote sensing
mapping	10.1016/j.compag.2023.107754	2023	semantic segmentation
mapping	10.1016/j.ecoinf.2023.102078	2023	deep learning, semantic segmentation
mapping	10.1016/j.fbio.2023.102848	2023	semantic segmentation, machine learning
mapping	10.1016/j.isprsjprs.2021.09.005	2021	deep learning, semantic segmentation
mapping	10.1016/j.isprsjprs.2022.01.007	2022	deep learning, semantic segmentation
mapping	10.1016/j.isprsjprs.2023.06.014	2023	semantic segmentation
mapping	10.1016/j.jag.2021.102511	2021	remote sensing
mapping	10.1016/j.robot.2023.104581	2024	semantic segmentation, precision agriculture
mapping	10.1080/03066150.2012.665890	2012	remote sensing
mapping	10.1080/22797254.2023.2181874	2023	semantic segmentation
mapping	10.1109/ACCESS.2019.2913442	2019	semantic segmentation
mapping	10.1109/ACCESS.2021.3069882	2021	remote sensing
mapping	10.1109/JSTARS.2021.3132259	2022	image segmentation, machine learning
mapping	10.1109/JSTARS.2022.3208185	2022	remote sensing, image segmentation
mapping	10.1109/JSTARS.2023.3301158	2023	remote sensing
mapping	10.1109/LGRS.2020.3037976	2022	semantic segmentation, image segmentation
mapping	10.2316/J.2022.206-0730	2022	remote sensing
mapping	10.3389/fpls.2022.1030595	2023	semantic segmentation, remote sensing
mapping	10.3389/fpls.2023.1196634	2023	deep learning, remote sensing
mapping	10.3389/fpls.2023.1228590	2023	deep learning, semantic segmentation, remote sensing
mapping	10.3390/agriculture12111894	2022	machine learning
mapping	10.3390/app12168234	2022	deep learning, semantic segmentation, remote sensing
mapping	10.3390/e23040435	2021	semantic segmentation
mapping	10.3390/ijgi12020081	2023	machine learning
mapping	10.3390/info12060230	2021	deep learning, semantic segmentation, remote sensing

Table A1. *Cont.*

Application	Publication DOI	Publication Year	Superhub Keywords
mapping	10.3390/info13050259	2022	deep learning
mapping	10.3390/rs11172008	2019	semantic segmentation, remote sensing
mapping	10.3390/rs12132159	2020	deep learning
mapping	10.3390/rs13040612	2021	deep learning, semantic segmentation
mapping	10.3390/rs13214370	2021	semantic segmentation, remote sensing
mapping	10.3390/rs13214411	2021	remote sensing
mapping	10.3390/rs14092157	2022	remote sensing
mapping	10.3390/rs14194694	2022	semantic segmentation
mapping	10.3390/rs15102500	2023	deep learning, semantic segmentation, remote sensing
mapping	10.3390/sens12060230	2020	deep learning
mapping	10.9713/kcer.2019.57.2.274	2019	semantic segmentation
mapping & detection	10.1109/TGRS.2020.3029841	2021	image segmentation
mapping & detection	10.3390/agronomy13030635	2023	deep learning, remote sensing
mapping & detection	10.1002/rob.21877	2020	semantic segmentation, precision agriculture
mapping & detection	10.1109/ACCESS.2023.3308909	2023	semantic segmentation, remote sensing, machine learning
mapping & modeling	10.1080/1747423X.2021.1879296	2021	remote sensing
modeling	10.3390/rs12030342	2020	remote sensing
monitoring	10.1186/s40317-021-00248-w	2021	machine learning
monitoring	10.3390/rs15184403	2023	remote sensing
monitoring	10.3390/s20205768	2020	precision agriculture
policy	10.1016/j.jrurstud.2020.10.040	2022	precision agriculture
policy	10.1016/j.jrurstud.2020.10.040	2020	precision agriculture
policy	10.3233/JCM-226522	2023	deep learning
privacy & security	10.3390/su151310264	2023	precision agriculture

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