Worldwide Research Trends in Agrivoltaic Systems

Subjects: Others

Contributor: Aidana Chalgynbayeva, Zoltán Gabnai, Péter Lengyel, Albiona Pestisha, Attila Bai

An agrovoltaic system combines agricultural crop production and energy production in the same place, emphasizing the dual use of land. Researchers provided a bibliometric analysis of agrivoltaic topics based on publications indexed in SCOPUS, in which either economic assessments of agrivoltaics, agrivoltaic systems for crops and livestock animals, photovoltaic greenhouse and agrivoltaics with open field discussed, or its ideas are used to analyze certain locations. It is shown that scientific publications in recent years mainly focus on short-term predictions, there is no recognized evaluation standard for various prediction analyses, and it is difficult to evaluate various prediction methods so far.

Keywords: APV ; agrophotovoltaics ; trend ; thematic map ; correspondence analysis ; solar farming ; SLR

1. Emerging Trends in the Literature on Agrivoltaic Systems

Figure 1 shows that there was no high-level scientific publication activity before 2011 related to AV. However, Prof. Dr. Adolf Goetzberger, founder of the Fraunhofer Institute for Solar Energy Systems (ISE), and Dr. Armin Zastrow were the pioneers in the establishment of Agrivoltaics in 1981, when it was aimed at optimizing the utilization of the land [1]. Since then, this technique has been considered a prototype until 2011, when it was first published as agrivoltaic (AV). All over the world, the method is known under different names. The authors propose different terminologies for the concept of an AV system. For instance, in the German research context, it is known as “agrophotovoltaics (APVs)”, in French, Italian and American research contexts it is known as “agrovoltaics”, and in the Asian research context, “photovoltaic agriculture” and “solar sharing” are mentioned [2]. Currently, “Agrivoltaic” is the internationally recognized term, as well as the well-established acronym for Agrivoltaics, “AV". Over the years, innovations have been used to supply the needed power for different agricultural applications such as crop drying, cultivation in a greenhouse, irrigation, desalination, etc. Moreover, it enables the production of food and energy, providing benefits for farmers.

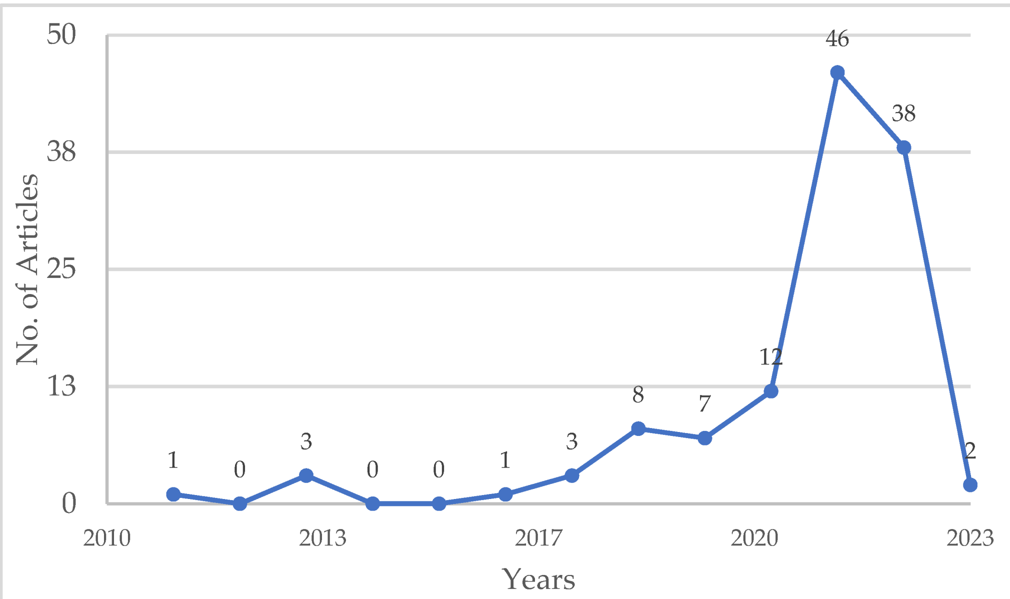

Figure 1. Annual scientific production. Source: created by the authors.

Attention to the implications of agrivoltaics in renewable energy has risen from 2011 (**Figure 1**). In the 2010s, the first agrivoltaic-pilot plants were built and researched in Japan and then in Germany and France [1]. Agri-PV is interdisciplinary, and as such, researchers expected to find a wide variety of disciplines represented in the study. Most studies are seeking to address questions such as the long-term impact of solar energy infrastructure on soil quality, suitable crops, etc. [3]. There is very little scientific research examining their agriculture parameters, such as crop performance, crop yields and quality of the harvestable products. Meanwhile, economic, social and political implementation of AV systems have also been researched since 2020 [4][5][6]. Nevertheless, agrivoltaic systems are gradually being installed around the world, and there is very little scientific research examining their local acceptance in society, the economic factors for the market launch of agrivoltaic systems and farmers' motivation for agrivoltaic systems. **Figure 1** presents the annual scientific production of agrivoltaics research by year. After screening this research field, it can be stated that the research activity related to agrivoltaic systems emerged after 2011 and started to grow rapidly in 2021 and beyond. The number of articles published from 2011 to 2020 climbed very gradually, peaking in 2021 and dipping drastically in the following years. The difference in publication between 2020 and 2021 is 35.4%, and between 2021 and 2022, it is 8.3%. One of the reasons for this might be the topic under development and the experimental stage of APV, as well as little experience with other popular crops such as rapeseed, turnips and legumes [7], the high concentration of studies in specific regions and lower citation rate.

2. Top 10 Most Relevant Journals

One of the most interesting aspects of bibliometric analysis is the identification of journals that researchers most often use to disseminate their research work. Regarding the most relevant journals based on the number of publications, based on the H-index, **Table 1** lists the top 10 journals that cover a wide range of research disciplines and shows that the three most relevant journals account for over 46.6% of publications. The articles were issued by seven different publishers, and the largest production of articles was found in the AIP conference proceedings journal, published by the American Institute of Physics, with 11 conference papers, followed by Applied Energy from Elsevier, with 9 articles. AIP conference proceedings journal and Applied Energy are considered the most influential sources of publication related to agrivoltaic systems in an emerging interdisciplinary research area, so researchers don't need to be limited to a specific area. **Table 1** represents other sources with scores of 8 or less. It shows that AV-specialized scientific conferences are the best way to get relevant and up-to-date information about this research area. The majority of the journals in **Table 1** have Q1 ranking, which means that the topic is interesting for the highest-level publishers. Sustainability and Energies are two of the few exceptions; they are also excellent sources of AV. This also indicates that there is a growing propensity for interdisciplinary research in agrivoltaic systems that could make agriculture more sustainable and use green energy in the future.

Table 1. Most productive scientific sources.

Journal/Proceedings	Publisher	Country	H Index	SJR	TP
AIP CONFERENCE PROCEEDINGS	American Institute of Physics	United States	75	0.19 (Not yet assigned quartile)	11
APPLIED ENERGY	Elsevier	United Kingdom	235	3.06 (Q1)	9
AGRONOMY	John Wiley & Sons.	United States	138	0.69 (Q1)	8
ENERGIES	MDPI	Switzerland	111	0.65 (Q1/Q2)	7
SUSTAINABILITY (SWITZERLAND)	MDPI	Switzerland	109	0.66 (Q1/Q2)	7
IOP CONFERENCE SERIES: EARTH AND ENVIRONMENTAL SCIENCE	IOP Publishing Ltd.	United Kingdom	34	0.2 (Not yet assigned quartile)	4
RENEWABLE ENERGY	Elsevier	United Kingdom	210	1.88 (Q1)	4
SCIENTIFIC REPORTS	Nature Publishing Group	United Kingdom	242	1.01 (Q1)	4
JOURNAL OF CLEANER PRODUCTION	Elsevier	United Kingdom	232	1.92 (Q1)	3
PLOS ONE	Public Library of Science	United States	367	0.85 (Q1)	3

TP: the number of total publications. Source: Created by the Authors.

3. Distribution of Production by Countries and Authors

In general, agrivoltaics publications related to agriculture activities and green electricity are written by authors representing 32 countries. **Table 2** lists the ten most productive countries in terms of this indicator, along with such an indicator as the number of articles. This can partly be explained by the fact that SCOPUS primarily indexes publications published in English. The latter also explains the fact that most of the publications included in the study database (90%) are written in English.

Table 2. Top 20—Most productive countries (based on first author's affiliation).

Region	No. of Articles	Region	No. of Articles
USA	**15**	**SPAIN**	**4**
CHINA	**11**	**AUSTRALIA**	**3**
GERMANY	**9**	**BELGIUM**	**3**
FRANCE	**8**	**FINLAND**	**3**
SOUTH KOREA	**8**	**PAKISTAN**	**3**
JAPAN	**7**	**NETHERLANDS**	**2**
ITALY	**6**	**SINGAPORE**	**2**
CANADA	**5**	**THAILAND**	**2**
INDIA	**5**	**TURKEY**	**2**
MALAYSIA	**5**	**UK**	**2**

Source: created by the authors.

A country's scientific output (**Table 2**) shows the contributions of various countries to the agrivoltaic area. In terms of the geographical distribution of scientific research works, approximately 14.2% of publications are produced in the USA, which is not surprising since the USA is a leading country in renewable energy consumption [8]. In addition, US researchers are studying the potential of co-locating photovoltaic energy production with pasture production, cattle, lamb or sheep, crops, grazing behavior, soil rehabilitation and other ecosystem services [9][10][11][12]. A US study showed that the development of solar energy applications in agriculture function is important to multi-level and multi-sectoral policy integration [13]. China ranks second in the number of publications, with the continuous growth of China's demand for clean energy, such as solar power generation. Its high-level population demands a large amount of food, as well as the gradual improvement of the corresponding photovoltaic industry policy and photovoltaic industry service system; photovoltaic industry projects in various regions continue to be launched. The photovoltaic industry presents a thriving scene [14][15][16], which is reflected in the outstanding work related to photovoltaic agriculture. On the side of agrivoltaic system, in European countries, a few agrivoltaic system projects have also been implemented in Europe in recent years. France was the first country to implement the AV financial support scheme in September 2017. Between 2017 and 2019, 15 MW of AV capacity was auctioned, and Germany is also one of the countries considering AV implementation. A German study constructed a comparative scenario of the cost structure, including CAPEX and OPEX of the AV system and GM-PV system. The actual CAPEX (including commissioning) in Germany regarding AV was higher by 73% compared to the normal PV installations. In contrast to the higher CAPEX, the OPEX of AV systems was lower than normal PV installations; the difference was 13%, according to German experiences [4]. AV implementation also depends on the legislation of the country and geographical area, as well as on agrivoltaic objectives and crop selection.

Table 3 lists the most influential articles in the journal. Top 10 articles cited during the study period of 11—(2011–2022), including authors' initials, publication year, publication sources (journal), titles, digital object identifier (DOI), total citation and yearly citation. The analysis of the references cited is carried out in two stages. In **Table 3**, researchers show the article with the most citations and the average number of citations per year to give a meaningful assessment of the impact of this article on the research community. The research articles listed from the dataset using co-citation analysis have been cited in other pairs of articles in the sample, giving an idea of the contribution of major citations that have influenced the development of the field in recent years. It has been proven that citations are increasing year by year. This is probably due to the large interest in research in this field. Notably, old papers were favored because the longer time allows them to accumulate more citations compared to recently published research work. Dupraz et al.(2020) [17] from INRA, UMR System, France, ranked at one. The article has 256 citations and 21.33 total citations per year. This paper becomes the most prolific and dominant paper in the field of agrivoltaic systems. Therefore, the total citation per year was also taken into account when assessing the new trends in this field. However, due to its significant contribution to the current discussion on the social, economic, and policy aspects of APV, Schindele et al.'s (2020) [4] paper titled "Implementation of agrophotovoltaics technoeconomic analysis of the price performance ratio and its policy implications" published in 2020 received an average of 25.67 citations each year.

Table 3. Most cited articles.

Paper	Titles	DOI	TC	TC Per Year
DUPRAZ C, 2011, [17], RENEW ENERGY	**Combining solar photovoltaic panels and food crops for optimizing land use towards new agrivoltaic schemes**	**10.1016/j.renene.2011.03.005**	**256**	**21.33**
MARROU H, 2013, [18], EUR J AGRON-a	**Productivity and radiation use efficiency of lettuces grown in the partial shade of photovoltaic panels**	**10.1016/j.eja.2012.08.003**	**143**	**14.30**
MARROU H, 2013, [19], AGRIC FOR METEROL	**Microclimate under agrivoltaic systems is crop growth rate affected in the partial shade of solar panels**	**10.1016/j.agrformet.2013.04.012**	**135**	**13.50**
AMADUCCI S, 2018, [20], APPL ENERGY	**Agrivoltaic systems to optimize land use for electric energy production**	**10.1016/j.apenergy.2018.03.081**	**117**	**23.40**
ADEH EH, 2018, [9], PLOS ONE	**Remarkable agrivoltaic influence on soil moisture micrometeorology and wateruse efficiency**	**10.1371/journal.pone.0203256**	**86**	**17.20**
MARROU H, 2013, [21], EUR J AGRON	**How does a shelter of solar panels influence water flows in a soilcrop system**	**10.1016/j.eja.2013.05.004**	**80**	**8.00**
SCHINDELE S, 2020, [4], APPL ENERGY	**Implementation of agrophotovoltaics technoeconomic analysis of the priceperformance ratio and its policy implications**	**10.1016/j.apenergy.2020.114737**	**77**	**25.67**
VALLE B, 2017, [22], APPL ENERGY	**Increasing the total productivity of a land by combining mobile photovoltaic panels and food crops**	**10.1016/j.apenergy.2017.09.113**	**75**	**12.50**
ADEH EH, 2019, [23], SCI REP	**Solar PV power potential is greatest over croplands**	**10.1038/s41598-019-47803-3**	**75**	**18.75**
MALU PR, 2017, [24], SUSTAINABLE ENERGY TECHNOL ASSESS	**Agrivoltaic potential on grape farms in India**	**10.1016/j.seta.2017.08.004**	**71**	**11.83**

TC: Total Citations. Source: created by the authors.

The above table provides information at two levels, both in absolute and relative terms. Consequently, researchers have two metrics: total citation (TC) and total citation per year (TC per year). The most cited references in absolute terms are:

- Dupraz et al. (2011) [17], with 256 citations. The top-cited paper by Dupraz et al. [17] first proposed to designate the combination of solar panels and food crops in the same field as an agrovoltaic system. The researchers contrasted the relatively low intrinsic efficiency of the photosynthetic process (around 3%) with the average yield of commercially available monocrystalline photovoltaic (PV) solar cells (~15%) and estimated global land productivity increases of 35% and 73% for two different system designs. From an economic point of view, the authors predicted the land equivalent ratio (LER) of agrivoltaic systems, and the results were impressive. A value of 1.7 LER would mean the following, related to the productivity of land: a 100-ha farm would produce as much green energy and crops altogether as a 170-ha farm, when it is used independently for photovoltaic energy production and food crops.

- Marrou et al. (2013) [18] (with 143 citations) and Marrou et al. (2013) [19] (with 135 citations). Among the plant species studied, short-cycle crops such as various lettuce [18] and cucumber [19] appear, as well as long-cycle crops such as durum wheat [19].

- In relative terms (weighted citation of an article by the number of years), TC per year, the top three articles, with an average of over 20 citations, are:

- Among the publications, only the techno-economic side was researched by Schindele et al.(2020) [4], comparing the additional investment cost of agrivoltaic system and ground-mounted photovoltaic (PV-GM) system and both systems considered a reference to a land plot of two hectares. The total investment cost of AV amounts €1,343,846, and for PV-GM, €1,031,042. Cost factors that include PV models, installation, site preparation, and soil protection have relatively higher investment cost for AVSs. This is a very important study because APV represents a major source of economic analysis within agrivoltaic systems.

- Amaducci et al. (2018) [20] discovered that the productivity of land using agrivoltaic system can be doubled with APV over the separate production of maize and GM-PV modules. However, radiation available to the crop during APV is reduced by about 15–40%. These light conditions correspond to moderate shading which means that the amount of radiation available under an APV array depends more on the density of the panels than on the panel mobility. Authors found that growing corn under agrivoltaic systems in non-irrigated conditions can decrease soil evaporation, reduce crop losses in dry years and increase the average yield.

- Dupraz et al. (2011) [17] has an index of Total Citation per Year of around 21.33%.

4. Keywords Dynamics

Figure 2 presents the co-occurrence assessment and connection of keywords plus, which reflects the high frequency of matching keywords in research articles and conference papers; more than half of the author's keywords were mirrored in the keywords plus sets. Keywords plus covers most of the author's keywords, so researchers choose keyword plus methods.

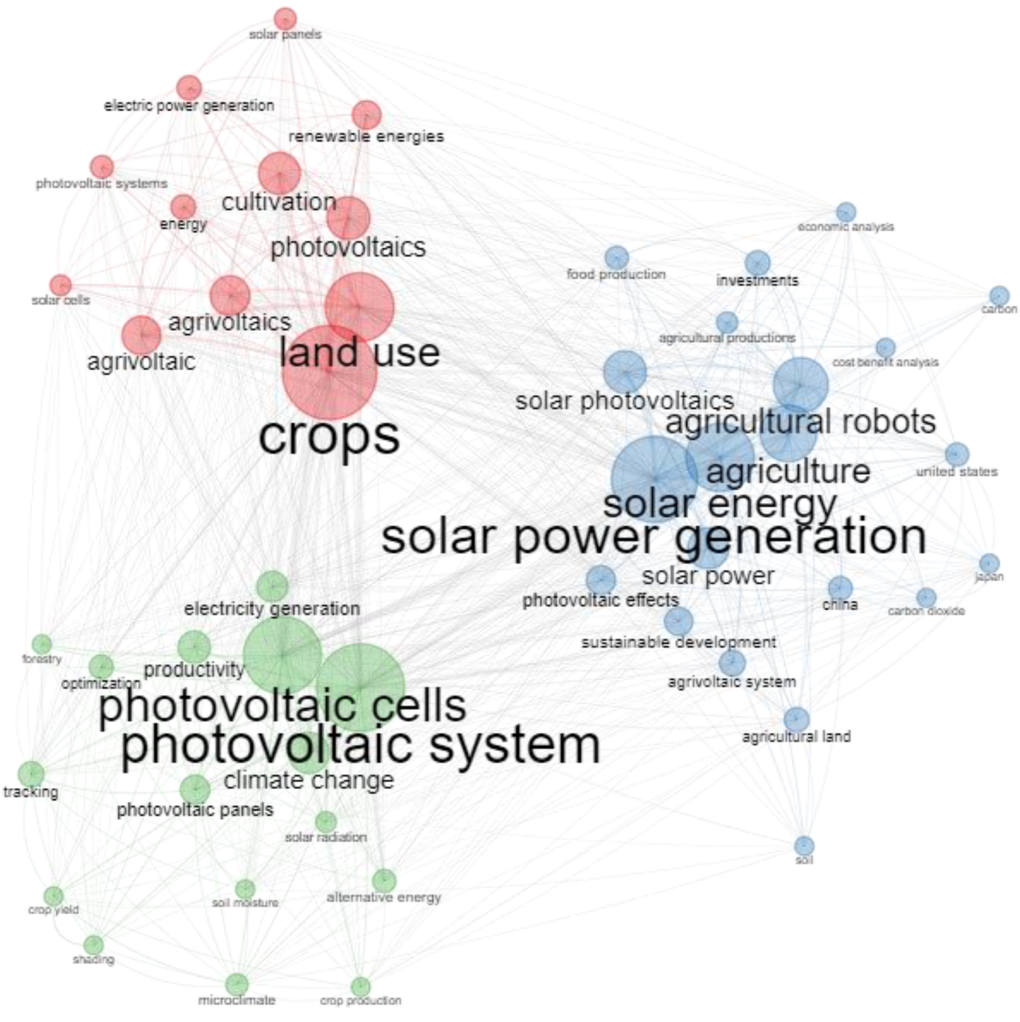

Figure 2. Keyword co-occurrence network. Source: created by the authors.

Authors' keywords co-occurrence is following analysis prepared by Rstudio Biblioshiny, which was a way to comprehensively understand the leading keywords for agrivoltaic systems in agriculture activities, greenhouse and open fields. The size of the circle reflects the frequency of occurrence of the term, i.e., the larger its area, the more often this word or phrase occurs in the general list of an author's keywords. The distance between terms is a measure of their connection: a smaller distance represents a stronger connection. In contrast, the connection itself is determined by the frequency of the terms' joint occurrence. Colors, as already mentioned, are used to indicate clusters.

The concept map shows that the terms form a complex network in which three thematic clusters can be distinguished. The first (marked in red) is related to the crops of land use in the context of studying solar power generation, as well as the cultivation of crops in a typical agrivoltaic system. The second cluster (light blue) is closely related to the first and focuses on the concept of studying various types of fields, such as agricultural robots and carbon dioxide. At the same time, investment and economic analysis, cost-benefit analysis and agricultural land are studied separately. The third cluster (light green color) is associated with the study of photovoltaic systems with tracking systems placed crops in a microclimate where strips of shading are in any plant position several times a day.

5. Thematic Analysis and Evolution

Researchers focus on the conceptual structure of AV's publications. This type of analysis helps to understand the topics and define the most important and recent ones. Identifying the conceptual structure could also be useful for studying the research topic's evolution over time [25].

The basic idea is that terms (keywords, terms extracted from titles or abstracts) which appear together in a document can be represented as a term's co-occurrence network. researchers started from a co-occurrence matrix in which each cell outside the principal diagonal contains the similarity of two terms expressed as equivalence [26]. The co-occurrence matrices can be seen as adjacency matrices and graphically visualized as undirected weighted networks. On each subperiod co-occurrence matrix, researchers performed a community detection based on the simple center algorithm [27]. This analysis allows finding subgroups of strongly linked terms, where each subgroup corresponds to a center of interest or a given research theme/topic of the analyzed collection. Once the analysis is carried out, it is possible to plot the results in a so-called strategic or thematic diagram [28]. The graphical representation allows defining four typologies of themes [29], depending on the quadrant in which they are plotted:

- Themes in the upper-right quadrant are known as the motor themes, characterized by high centrality and high density, meaning that they are developed and important for the research field;
- Themes in the lower-right quadrant are known as basic and transversal themes, characterized by high centrality and low density, meaning that these themes are important for a domain, and they concern general topics transversal to the different research areas of the field;
- Themes in the lower-left quadrant are known as emerging or declining themes, with low centrality and low density, meaning that they are weakly developed and marginal;
- Themes in the upper-left quadrant are known as the highly developed and isolated themes, with well-developed internal links (high density) but unimportant external links (low centrality), meaning that they are of limited importance for the field.

Figure 3 shows that five main topics emerged. The upper-right quadrant shows the motor themes. They are characterized by both high centrality and density. Among the motor themes that are the more developed in the literature, the main concern is crops. Highlighting how researchers have focused on this topic in the last few years is extremely important for structuring the field of study. The lower-right quadrant shows the themes that are basic and transversal. These themes concern general topics transversal to the different research areas of the field. In this area, 'solar power generation' appeared as a general theme and also included different applicative domains of the topic. In the lower-left quadrant are the emerging or declining themes. The theme of 'agriculture' emerges. In particular, 'agriculture' is a new topic in the field of agrivoltaics, where agriculture activities are emerging to explore new approaches related to agrivoltaic systems in agriculture production and green electricity on the same land and at the same period. The 'solar energy' and 'climate change' are in the upper-left quadrant as niche themes of the topic, with high density but low centrality, have a higher frequency, indicating that these research themes are considered very specialized in agrovoltaic research work.

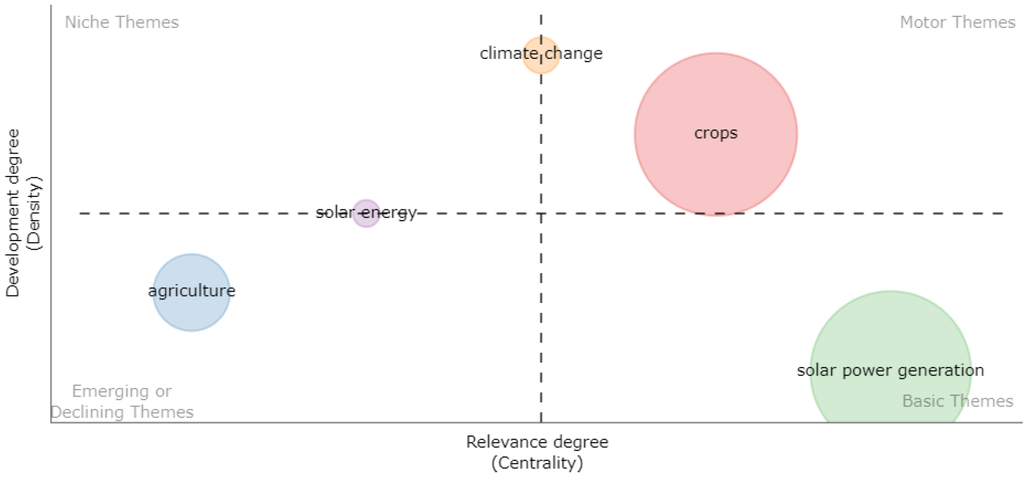

Figure 3. Thematic map. Source: created by the authors.

Figure 4 shows a co-word analysis, which aims to map the conceptual structure of a framework using the word co-occurrences in a bibliographic collection. The analysis was performed using Multiple Correspondence Analysis (MCA) as a dimensionality reduction technique. The conceptual structure includes natural language processing (NLP) routines to extract terms from titles and abstracts. It compresses extensive data with multiple variables into a low-dimensional space to form an intuitive two-dimensional graph that uses plane distance to reflect the similarity between the keywords. Keywords approaching the centre point indicate that they have received close attention over the years. The results are interpreted based on the relative positions of the points and their distribution along the dimensions; as words are more similar in distribution, the closer they are represented on the map. The red cluster is the most significant and consists of 42 keywords that focus on the documents related to 'agrivoltaic system', 'agrophotovoltaic', 'sustainable agriculture', 'energy' and 'photovoltaic panels'. The blue cluster of 5 keywords comprises papers regarding 'shading', 'organic agriculture', 'land productivity' and 'crop yield'. The green cluster consists of 5 keywords, focusing on the articles related to 'shade', 'lettuce', 'cucumber' and 'evapotranspiration'.

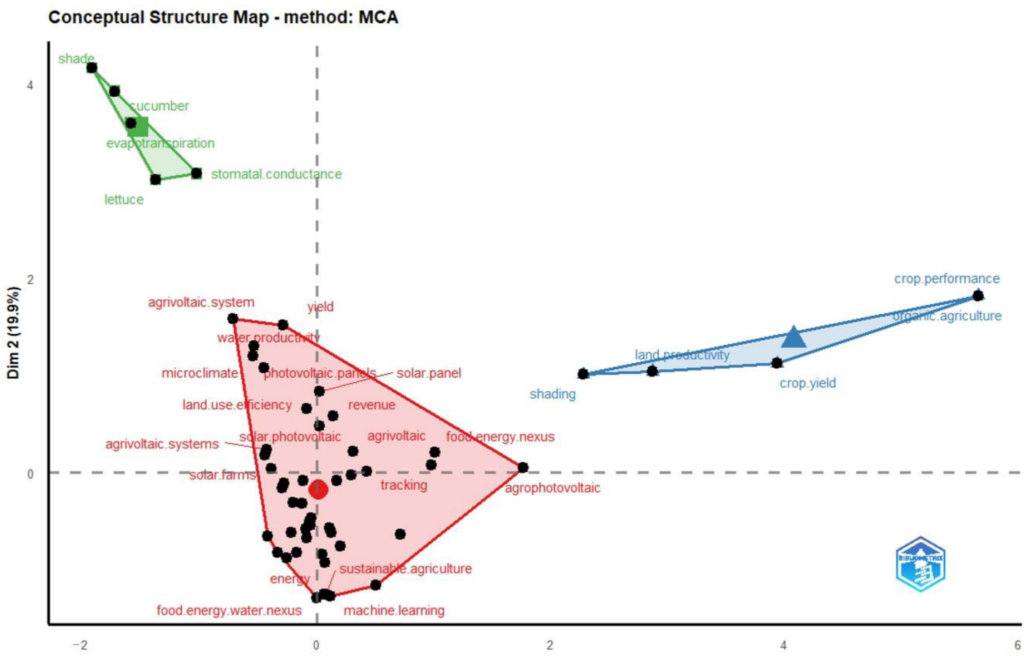

Figure 4. Multiple Correspondence Analysis of high-frequency keywords. Source: created by the authors.

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