Bibliometric analysis of publications discussing the use of the artificial intelligence technique agent-based models in sustainable agriculture

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ABSTRACT

The purpose of this article consists of analyzing publications discussing the use of agent-based artificial intelligence models in sustainable agriculture research. The analysis involved bibliometric indicators and the software with Bibliometrix library. The methodology is descriptive with a quantitative approach. Scientific databases SCOPUS and Web of Science were consulted and the PRISMA methodology was used during the selection process. This led to finding 86 publications that met the inclusion criteria. Amongst the results, United States was listed as the country with thehighest production of scientific material, although France had a higher impact. Additionally, the bibliographical resources that help promote scientific development are open source. It was concluded that the agent-based model has been adopted to simulate different scenarios, which help decision-makers to formulate public policies in favor of sustainable agriculture. This optimizes the use of natural resources and reduces negative consequences for the environment, while also delivering value for the stakeholders of the agricultural system.

1. Introduction

Agriculture is and will remain one of the main pillars of society, since it is an economical sector driven by the imperative need of human survival. Its relevance for nations worldwide, has even led the United Nations (UN) to promote Sustainable Development Goals (SDG) since 2015. Sustainable development is defined as “the development capable of meeting present needs without compromising the capabilities of future generations to meet their own needs” [1]. The 17 Sustainable Development Goals place agriculture at the center of the sustainability pillars: environment, economy, and society [2, 3]. The development goals can be detailed in Table 1.

Out of the 17 SDGs, the second goal focuses on agriculture, aiming for zero-hunger levels worldwide while also being sustainable over time. The nutritional situation worldwide has revealed that 690 million people suffer from hunger and 815 million people are underfed, where most of this population is located in developing countries in Latin America, Africa, and Asia [4]. Hence, strategies to implement food safety play an essential role. Furthermore, agriculture would significantly contribute with the fulfillment of other SDGs. Given that agriculture provides for 40% of jobs worldwide, small farmers provide for 80% of global food supply and, if women had the same access to resources than men, it is estimated that hunger would be reduced by a total of 150 million people [5]. Sustainable agriculture must guarantee global food safety while also promoting healthy ecosystems and supporting sustainable land management, water, and natural resources. This leads to the need for sustainable agriculture, being an important approach agent-based Artificial Intelligence (AI) models and their applications. In this regard, IA can be used for analyzed water, soil, and crop features using big data, image processing, and other techniques. This sets the conceptual footing for the analysis of publications regarding research of applied AI in sustainable agriculture, which is the focus in this article.

Regarding reviews related to sustainable agriculture, the circular and green economy is analyzed in [6] given that this type of economy is noteworthy from the agricultural business, agri-food systems, and supply chains to the realm of academic debate in terms of definition of policies. Such issues include contributing to and addressing social and environmental concerns from the economic development perspective. Additionally, reference [6] also covers a systematic review of the literature and bibliometric analysis from the SCOPUS database taking 1061 indexed documents and dividing them into particular research areas

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like environmental impacts, circular economy, food waste, and green economy. From the observations and tendencies, publication patterns suggest that further research may be based on the first two topics including a multidisciplinary approach to deal with the complex string of food waste and environmental issues.

Other related review is shown in [7] considering the use of technology. In this regard, it can be said that agriculture has evolved through history given its relevance for basic human preservation. Currently, the agricultural sector is adding digital technologies like agriculture 4.0, which involves digital developments from different scenarios like cloud computing, artificial intelligence, internet of things, big data, and advanced robotics centered on agribusiness production chains. The focus in reference [7] is to understand the research themes of agriculture 4.0 employing PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) protocol and the software of VosViewer and Bibliometrix for results recollection. Two key features were found from the above: positive or negative impacts of agriculture 4.0 and developments of agriculture 4.0. As an outcome, it is concluded that digital technologies interaction becomes fundamental for developing automated activities in agriculture.

While reference [6] stresses circular and green economic issues, and reference [7] regards aspects of agriculture 4.0, the approach of this work points AI technique for agent-based models to be employed in a modality of sustainable agricultural activities.

Agent-based models are among the most widely used intelligence techniques since it is noticeably useful for predicting future behaviors between different groups of individuals or agents. For example, a study carried out in 2020 determined that agent-based models were the most used technique to predict future scenarios for possible agricultural public policies [8]. Which helped determine the application of policies on land use [9, 10, 11], climate change [12, 13], negative environmental impact [14, 15] and government subsidies [16, 17].

### 1.1. Article approach and document organization

This article proposes a bibliometric analysis of publications that discuss the use of agent-based models in sustainable agriculture; particularly, how agent-based models have been adopted to simulate different scenarios that help decision-makers to formulate public policies in favor of sustainable agriculture. PRISMA statement was used to select scientific publications. With the selected scientific publications, the bibliometrix data of the publications in .bib or .RIS format were obtained. These bibliometric data were processed through the bibliometrix package of the StudioR software.

The article is organized as follows: In Section 1 is the introduction that helps to contextualize the framework of the study. Section 2 reviews the concepts associated with sustainable agriculture and the evolution of research on this topic in recent years. Then in Section 3, the concepts of agent-based models are reviewed, and the areas of knowledge in which this artificial intelligence tool has been applied. Subsequently, the Methodology is described in Section 4. In Section 5, the results obtained with their respective analysis are presented, through the bibliometric indicators used. Finally, the discussion and conclusions are pointed in Sections 6 and 7.

### 2. Sustainable agriculture

The Food and Agriculture Organization (FAO) of the UN defines sustainable agriculture as the agriculture that “meets the needs of present and future generations in terms of products and services, whilst guaranteeing rentability, safety of the environment and socio-economic equality” [18]. It also sets guidelines to establish and maintain a sustainable agricultural system, which include:

- Sustainable agriculture must guarantee global food safety while also promoting healthy ecosystems and supporting the sustainable management of land, water and natural resources.
- To transition into sustainable food and agriculture globally, it is essential to improve the protection of the environment, the resilience of systems and the efficiency in resources.
- The sustainable agriculture requires a global governance system that promotes food safety in commercial policies and regimes, and reexamines agricultural policies to promote the growth of local and regional agricultural markets [18].

Sustainable agriculture establishment requires considering financial, environmental, social, and economic factors. Therefore, extensive research on the subject has been developed worldwide [2, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33]. Some of these research projects are discussed in this section.

A study in the United States forecasts a global demand of crop production by 2050 by assessing the environmental impact and alternatives to meet such demand [19], leading to an assessment of the viability of sustainable agriculture in current conditions. In Vietnam, a study comprising 93 interviews explored factors that influence the adoption of sustainable agriculture by coffee farmers, given climate change [20]. In Nigeria, factors regarding the adoption of sustainable agriculture practices were studied [21], including banana production crops [22]. A study from Indonesia researched the psychological relationship be-

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**Table 1. Sustainable Development Goals [1].**

| Goal No. | Name |
|----------|------|
| Goal 1   | Put an end to poverty in all its forms worldwide. |
| Goal 2   | Put an end to hunger, achieve food safety and improve nutrition and promote sustainable agriculture. |
| Goal 3   | Guarantee a healthy life and promote welfare of every age group. |
| Goal 4   | Guarantee an inclusive, high-quality and equitable education and promote learning opportunities for all. |
| Goal 5   | Achieve equality of gender and the empowerment of all women and girls. |
| Goal 6   | Guarantee the availability of water resources as well as its sustainable structure and sanitation for everyone. |
| Goal 7   | Guarantee the access to affordable, safe, sustainable and modern energy for everyone. |
| Goal 8   | Promote sustained, inclusive and sustainable economic growth, and productive and decent jobs for everyone. |
| Goal 9   | Build resilient infrastructure, promoting inclusive and sustainable industrialization and innovation. |
| Goal 10  | Reduce inequality within and amongst countries. |
| Goal 11  | Help cities and human settlements become inclusive, safe, resilient and sustainable. |
| Goal 12  | Guarantee sustainable consumption and production modalities. |
| Goal 13  | Adopt urgent measures to fight global warming and its effects, based on the agreements of the UN Framework Convention on Climate Change. |
| Goal 14  | Protect and use sustainable the oceans, seas, and marine resources for sustainable development. |
| Goal 15  | Protect, reestablish and promote sustainable use of terrestrial ecosystems, achieve a sustainable ordination of forests, fight desertification, stop and revert degradation of lands and halt the loss of biologic diversity. |
| Goal 16  | Promote pacific and inclusive societies for sustainable development, facilitate access to justice for everyone and create effective, responsible and inclusive institutions in all levels. |
| Goal 17  | Strengthen the execution levels of sustainable development and revitalize the world alliance. |
tween personal attachment of the production sites and the contribution to sustainable agriculture in rural areas. The attachment had a positive impact on the willingness to keep the lands [23]. In Thailand, authors studied existing agricultural systems given the local economic, social and environmental conditions, delivering a sustainable agricultural system [24]. For instance, a new technology was assessed to plant Dipterocarpus alatus trees. The technology was deemed to be environment-friendly and served to promote sustainable agriculture [25]. In China, a research project described a co-culture of rice and fish which is useful and promotes sustainable agriculture [26]. Researchers from Iran assessed the perception of potato farmers regarding sustainable agricultural practices [27] and present other research projects dwelling on the matter. One of the cases included researchers from USA, UK, Australia, Italy, and Austria and led to the development of a metric-based tool called Sustainable Agriculture Matrix (SAM), which uses historical data on environmental, social and economic indicators [2].

There is a growing interest in the matter. The analysis of scientific production on sustainable agriculture led to finding 9602 publications on the subject in SCOPUS between 2010 and 2021. The worldwide relevance of the subject can be evidenced in terms of the global production per country (Fig. 1) and the collaboration network (Fig. 2).

The top 10 countries in terms of scientific production from first to last are China, USA, India, Italy, UK, Brazil, Germany, France, and Spain. International scientific cooperation plays a key role in driving progress.

3. Agent-based models

Agent-based models are AI computational techniques used to model different interactions within a diverse group of agents in a predetermined setting. Agents are virtual entities that follow a set of rules which represent motivations and behaviors. Agents can affect their environment, so they must be autonomous enough to follow inner motivations and adapt their behaviors according to their own needs. Agents often represent something in real life that can be modeled into their behavior such as people, animals, viruses, plagues, etc. These models are highly used to represent complex systems that cannot be easily predicted or controlled [34].

This technique has been adopted in many knowledge fields. For example, Social Science has used it to simulate urban growth and residential occupancy [35]; to simulate the adoption process of photovoltaic energies within a population [36]; to understand and model innovation practices in the horticultural sector [37]; to analyze the impact of innovation diffusion processes [38]; to assess transportation alternatives in cities [39]; among other articles.

Agent-based modelling has also been applied in Environmental Sciences in tasks such as: analyze water contamination processes caused by mankind [40]; analyze the effects of rural policies for the conservation of rural environments in favor of farmers and tourism [41]; analyze the interaction between weather, soil and plants [42]; predict the adoption of new technologies that reduce CO2 carbon emissions [43]; simulate gradual changes and moving from fossil fuel economies to green
technologies [44]. These are some of the research articles where the technique has been used.

Medicine has also adopted this method to analyze fungi infection in humans and determine possible treatment [45]; compare immunologic systems of humans against a viral infection with other species such as bats [46]; propagate an infectious disease within a city [47]; analyze the effects of vaccination on the spread of COVID-19 [48]; and analyze the effect of a drug on the behavior of cancer cells [49].

Agent-based methods have been used in many fields as the ones previously described and also in Engineering [50, 51, 52, 53, 54], Natural Sciences [55, 56, 57, 58], Economic Sciences [59, 60, 61, 62, 63], and many more. This study will only review the application of agent-based methods in sustainable agriculture.

The search of scientific production discussing agent-based modelling determined that SCOPUS had 14818 articles on this subject between 2010 and 2021. To better understand the use of this tool globally, Fig. 3 presents the disaggregated scientific production per country that has adopted agent-based models.

The top 10 countries in terms of using agent-based models in their scientific research regarding sustainable agriculture are USA, UK, China, Germany, Italy, France, Netherlands, Australia, Spain, and Canada.

4. Methodology

The methodology is descriptive with a quantitative approach [64, 65]. The information was collected from secondary sources. The methodological design can be seen in Fig. 4. The first phase of the study included the review of concepts and state of the art, which comprises sustainable agriculture and agent-based modelling.

The second stage consists of collecting and debugging information, taken from SCOPUS and Web of Science databases. The PRISMA declaration [66, 67] was used as well as the inclusion and exclusion criteria that can be seen in Table 2. Fig. 5 describes the process.

According to the PRISMA statement for data selection, the first stage is the identification of records in the databases. For which the search Equation (1) was proposed, where the symbol * indicates that more characters can be held at this position, and the quotation marks indicate that the structure of the sentence is maintained.

\[ \text{Search items} = \text{“agent-based model*” AND (agricultur* OR agro* OR agraria* OR farm* OR agricol* OR agricol*) AND (sustainable)} \] (1)

The search Equation (1) was applied to the titles, keywords and abstracts of the publications within the databases. Initially, 82 publications were identified in SCOPUS and 82 in WoS. The search was carried out on November 11, 2021 and applied to documents such as scientific articles, review articles, and conference articles. Next, in the selection stage, the records of the consulted databases were unified, and then the duplicated records were eliminated. Afterwards, the title and abstract of the publications were reviewed using the inclusion and exclusion criteria. At the end of the selection stage 117 documents were
chosen. Then, the eligibility stage continued, in this stage the complete documents were reviewed and those that did not correspond to the purpose of the study were excluded. In the eligibility stage, 24 documents were excluded and 93 were selected. In the inclusion stage, a qualitative analysis of the documents is made determining to exclude some when necessary; according to the inclusion and exclusion criteria, only 7 documents were excluded. After finding a total of 86 articles that match the defined criteria, these were analyzed through bibliometric indicators explained in Table 3. These indicators involved the use of Rstudio with the Bibliometrix library.

Social Network Analysis (SNA) was used for collaboration networks. This is a method of structural analysis to describe and measure relationships and information between individuals, this method has been useful in studies on scientific collaboration networks [68, 69, 70, 71]. SNA employs several major indicators like betweenness centrality and closeness centrality. The former measures one node undertaking a “mediation” role in a network. Thus, a mediation node serves as a communication bridge between nodes and the more paths cross through this node within the network, the greater betweenness centrality it will have [72]. Closeness centrality measures the sum of the distances from one node to the other nodes in the network, if the length of node N’s shortest paths with other nodes in the network is small, then node N displays a high closeness centrality [72, 73].

Bibliometric data were analyzed to identify the main characteristics of the research. The results obtained allowed to determine the historical behavior of the publications, primary bibliographic sources, the most relevant authors, countries with the highest scientific production, the most relevant publications, and thematic areas where the topic has been worked on. This way, the result analysis, and the conceptual review were employed to obtain the conclusions.

5. Results

This section details the results obtained when applying bibliometric indicators using Rstudio software Bibliometrix library. The section has the following subsections: yearly scientific production, main bibliographical resources, sources with the most impact, most relevant authors, scientific production per country, collaboration network between countries, most relevant publications, theme-based grouping.

5.1. Yearly scientific production

As seen in Fig. 6, scientific production has increased gradually regarding agent-based modelling applied in sustainable agriculture, es-

Table 3. Bibliometric indicators.

| Bibliometric indicators | Description |
|-------------------------|-------------|
| Yearly scientific production | Shows the number of articles per year within the sampled period. |
| Main bibliographical resources | Presents the most relevant sources, i.e., those with the highest number of articles on the subject. These can be magazines, conference summaries, books, etc. |
| Sources with higher impact | Presents the sources with more impact measured in terms of indexes H and G. H indicates which h publications have been cited at least h times in that source [74]. Index G indicates the most cited articles in the sources when the total number of quotes exceeds G2 [75]. |
| Most relevant authors | Presents the authors with the highest number of articles on the subject and their respective indexes H and G. |
| Scientific production per country | Presents the countries with the highest production base on the subject. The country is determined by the author’s affiliation (organization to which the author belongs to). |
| Collaboration network per country | A collaboration network is used to determine the affiliations of authors registered in the articles. One article may have many authors from different countries. Social Network Analysis (SNA) was used for the analysis. |
| Author Collaboration Network | The network is built by the authors making up the publications and collaborations. Social Network Analysis (SNA) was used for the analysis. |
| Collaboration network per institution | A collaboration network is used to determine the affiliations of authors registered in the articles. Social Network Analysis (SNA) was used for the analysis. |
| Most relevant affiliations | This indicator shows the affiliations (institutions, organizations, universities, etc.) of the authors that chiefly appear in the publications. |
| Theme-based classification | The subjects are grouped according to topics and keywords using the association method [76]. |
especially since 2015 when the Sustainable Development Goals were declared by the UN.

5.2. Main bibliographical resources

Table 4 presents the main bibliographical resources with the highest number of articles involving the use of agent-based modelling in sustainable agriculture research. The 6 main bibliographic sources are presented consisting of 5 journals and the proceedings of a congress.

In Table 4, two sources can be highlighted: the AGRICULTURAL SYSTEMS journal and the JOURNAL OF ENVIRONMENTAL MANAGEMENT, both having 5 articles on the subject. The first is an open access journal from the Elsevier BV editorial group, located in the Q1 index from SJR (Scimago Journal & Country Rank). The articles published in the journal were cited 9.5 times in average each year between 2017 and 2020. Being an open access journal, it has a publication fee of 3710 dollars. The journal publishes scientific findings regarding the different components of the agricultural system and their interaction in the environmental, social and economic settings [77].

The JOURNAL OF ENVIRONMENTAL MANAGEMENT from the Academic Press Inc. editorial is open access and placed in the Q1 index from SJR. The journal publications are cited 9.8 times in average each year between 2017 and 2020. It has an APC (Article Publishing Charge) of 3490 dollars. The journal publishes findings from research involving management of environmental resources and the improvement of environmental quality [78].

Both bibliographical resources are two open access journals ranked in the Q1 index by SJR. This means that the articles published in the journals are likely to have more impact. This is also evidenced by their average yearly citations that surpasses 9 times. The biggest drawback lies in their publication fees which exceed 3000 dollars. This causes that budget estimations must account for publishing costs to ensure that the results obtained can be shared amongst the scientific community and guarantee social appropriation. Publication costs are essential in research projects, especially in developing countries where various institutions carrying out scientific research, such as universities, neither have representative financial resources nor obtain financial support from the government or private companies. Consequently, project developments are carried out with low budgets.

5.3. Sources with the most impact

Table 5 presents the top 5 bibliographical resources in terms of impact. This means that the articles on the subject have had more impact in other research projects. The impact was calculated based on metrics for H and G.

The source with the highest impact in the AGRICULTURAL SYSTEMS journal with H = 3 and G = 4 is also the journal with more articles on the subject. The two following journals with the highest impact are ECOLOGICAL MODELLING and JASSS (JOURNAL OF ARTIFICIAL SOCIETIES AND SOCIAL SIMULATION) journals. Both journals have an index H and G equal to 3.

ECOLOGICAL MODELLING is a journal published by Elsevier. It offers two options for publication. The open access mode requires to pay an APC and the article will be available in the Science Direct database. The subscription mode requires the user to subscribe to the journal and does not factor additional costs for the authors. The journal is ranked in the Q2 index by SJR. The publications of the journal were cited 9.5 times in average every year between 2017 and 2020. The journal publishes the findings of research related with the management of environmental resources and the improvement of environmental quality [79].

The JOURNAL OF ARTIFICIAL SOCIETIES AND SOCIAL SIMULATION stems from Surrey University in England. The journal is open access and is ranked in the Q1 index from SJR. The journal is open

Table 4. Main bibliographical resources.

| Source                                      | # Articles |
|---------------------------------------------|------------|
| AGRICULTURAL SYSTEMS                        | 5          |
| JOURNAL OF ENVIRONMENTAL MANAGEMENT         | 5          |
| ENVIRONMENTAL MODELLING AND SOFTWARE FOR SUPPORTING A SUSTAINABLE FUTURE PROCEEDINGS - 8TH INTERNATIONAL CONGRESS ON ENVIRONMENTAL MODELLING AND SOFTWARE IEMS 2016 | 4          |
| ECOLOGICAL MODELLING                        | 3          |
| JASSS-THE JOURNAL OF ARTIFICIAL SOCIETIES AND SOCIAL SIMULATION | 3          |
| SUSTAINABILITY                              |            |

Table 5. Bibliographical resources with the highest impact.

| Source                                      | Index H | Index G |
|---------------------------------------------|---------|---------|
| AGRICULTURAL SYSTEMS                        | 3       | 4       |
| ECOLOGICAL MODELLING                        | 3       | 3       |
| JASSS-THE JOURNAL OF ARTIFICIAL SOCIETIES AND SOCIAL SIMULATION | 3       | 3       |
| AGRICULTURAL WATER MANAGEMENT               | 2       | 2       |
| ENVIRONMENTAL SCIENCE & POLICY              | 2       | 2       |
access so it charges an APC between 800 and 1300 pounds. It has an interdisciplinary approach and shows the results from social process analyses through computer simulations [80].

The top three journals in terms of impact are either open access only or offer an option for open access. The drawback of being open access is the incurring APC which must be considered in the research budget.

5.4. Most relevant authors

Table 6 presents the most relevant authors, only showcasing those with an H index of at least 2. It was ordered initially taking the H index as the indicator and then it was ordered from the G index. In this way, if there were several authors with the same index H, this group is reordered through the index G. Also, it is explained that the indexes H and G are calculated only from the articles that address the subject matter in this article.

Amongst the main authors in this category is doctor Gert Jan Hofstede from Wageningen University (Netherlands). His research has focused on analyzing the stability, evolution and social shift of different cultural and social waves, via agent-based model simulations. In second place, doctor Jeroen Groot belongs to the Wageningen University with a PhD in agronomy and a Master’s Degree in Sciences of grasslands, animal physiology and tropical animal breeding; his research has focused on agricultural system analysis, planning and model-based landscape design.

Francine Pacilley is currently doing a PhD in IT at the Wageningen University. Her current project is called “Designing disease-resistant cropping landscapes in a changing climate using spatial models of epidemics and socio-institutional dynamics - the case of potato (Solanum tuberosum) and late blight (Phytophthora infestans)”. Lastly, doctor Edith T. Lammerts van Bueren is a professor from the same university. She has 25 years of experience in organic research and management. The main authors in this section all belong to the Wageningen University in Netherlands.

5.5. Scientific production per country

Table 7 shows the scientific production per country, categorized in terms of the number of publications, number of citations and average citations per published article. These indicators help to analyze the production per country from quality and quantity perspectives. The total scientific production that helps to determine which are the leaders in the subject, and the citations and the average of citations helps to determine the degree of scientific acceptance of the publications, which is a quality criterion on the scientific production generated.

The country with the highest number of articles published is the United States. Although this country has published 56 articles on the subject, it has neither the highest number of citations nor the average quotes per article. This means that USA has great interest on the matter. Netherlands is the second country with 32 publications. This country has a total of 60 citations and an average of 6.67 citations per article. This means that the Netherlands has become one of the leading countries on the matter which is consistent with the authors from Wageningen University. France has published 31 articles on the subject, taking the third place, yet it is the top country in terms of citations and average citations received per article. This indicates that France is the main reference point on the use of agent-based models in agricultural research. Lastly, two leading countries can also be mentioned: Germany with 19 publications, 52 citations and 8.67 citations per article, and China with only 14 publications has been cited 51 times and 10.20 times in average. Hence, China has the highest average amongst the listed countries, becoming a global reference point.

On the other hand, it is important to highlight the countries in the top 10 of the production of scientific publications: nine are developed countries and only Iran is a developing country. Additionally, 76% of scientific production is concentrated in the top 10, evidencing the Pareto principle. Therefore, it shows the great scientific gap existing between developed countries and those developing in this subject.

5.6. Collaboration network between countries

Fig. 7 and Table 8 show four clusters. The first cluster is where the United States of America is located along with Italy, Iran, India, Norway, South Africa, Sweden, and Ethiopia. The second cluster includes the United Kingdom, Netherlands, Australia, China, Brazil, and Vietnam. The third cluster includes France, Colombia, Spain, Mexico, Senegal, Burkina Faso, Belgium, Kenya, Ecuador, and Mali. The last cluster is made up of Germany, Canada, Austria, Indonesia, Argentina, Chile, and Hungary.

In the first cluster the USA with the most significant collaboration toward other countries also displaying the highest betweenness in the cluster and in all countries, which explains why this country is the most relevant in the dissemination of scientific knowledge on the subject.

In the second cluster, the country with the highest betweenness is the United Kingdom, which serves as the main bridge of scientific knowledge in the cluster. France in the third cluster is the country with the highest betweenness, for this reason is the main disseminator of scientific knowledge in this cluster, followed by Colombia, Spain, and Mexico. In the last cluster, Germany is the main knowledge disseminating node, followed by Canada.

By looking at the entire network, it is determined that the United States of America, France, the United Kingdom, and Germany are the main bridges of knowledge in the world. These countries significantly promote the global dissemination of scientific knowledge on the use of agent-based applied in sustainable agriculture.

5.7. Author collaboration network

Fig. 8 shows the author collaboration network with 10 different clusters with no communication with each other. The size of the clusters varies between 2 to 4 individuals. This shows that the use of agent-based models applied to sustainable agriculture is an area of research that is still incipient, but with remarkable development potential. This reflection is consistent with what is observed in Fig. 6, corresponding to scientific production in recent years.

5.8. Collaboration network per institutions

Fig. 9 shows the collaboration network by institutions made up of nine clusters. Just like the author collaboration network, there is no communication between the clusters. Therefore, it is established that the use of agent-based models in sustainable agriculture is a topic with great potential for development.

5.9. Most relevant publications

Table 9 lists the articles with more citations on the analyzed subject. Additionally, Table 8 shows the annual average citation of the publications; this indicator is important because it helps determine the
Table 7. Scientific production per country.

| Country | # Articles published | % | Total citations | Average citations per article |
|---------|---------------------|---|-----------------|-----------------------------|
| USA     | 56                  | 19.72% | 64              | 4.92                        |
| NETHERLANDS | 32              | 11.27% | 60              | 6.67                        |
| FRANCE  | 31                  | 10.92% | 97              | 10.78                       |
| UNITED KINGDOM | 24          | 8.45%  | 38              | 7.60                        |
| GERMANY | 19                  | 6.69%  | 52              | 8.67                        |
| CHINA   | 14                  | 4.99%  | 51              | 10.20                       |
| IRAN    | 11                  | 3.87%  | 41              | 8.20                        |
| ITALY   | 11                  | 3.87%  | 7               | 1.75                        |
| AUSTRALIA | 10              | 3.52%  | 10              | 5.00                        |
| JAPAN   | 8                   | 2.82%  | 1               | 1.00                        |

Fig. 7. Scientific collaboration network countries (elaborated using Bibliometrix library from Rstudio).

The importance of the article, normalizing it over time and thus being able to better compare the publications.

The most cited article is “An agent-based-Nash modeling framework for sustainable groundwater management: a case study” with 38 citations in total and 6.33 citations per year in average. The article presents the result of a research project in which an agent-based Nash model was developed to find a sustainable solution for underground water management in Daryan dam (Iran). The authors sought to complete three goals: reduce risk of water deficit, increase equity in water allocation and reduce underground water extraction, whilst considering the need of the three main entities for underground water resources: the farmers, the government, and environmental protection institutes [81].

The second publication with the highest number of citations is an article titled “Effects of land lease policy on changes in land use, mechanization and agricultural pollution” with 30 citations and 6 citations in average per year. This article discusses the research of the changing effects in soil using machinery and agricultural contamination. Hence, the authors proposed an agent-based model with the same decision-making habits as in the real world. The results showed that land leases led to very little increase in agricultural earnings. However, the application of leasing policies for lands increased contamination [9].

In the third place, an article titled “Coupled information diffusion-pest dynamics models predict delayed benefits of farmer cooperation in pest management programs” has been cited 30 times and about 2.72 times per year. The publication exhibits an agent-based model that studies the cooperation process between farmers to share information to control an invading plague. The model was implemented with field data, including learning and control efficiency processes, derived from large-scale polls in the Equatorial Andes. The simulation revealed that diffusion processes are not efficient in the short term for plague control, yet they can be effective in the long term [82].

The following publication, which is the fourth publication with the most bibliography citations, is the article “Modelling carcass disposal practices: implications for the management of an ecological service provided by vultures” has been cited 29 times and about 2.9 times per year. This article analyzes the efficiency in cattle cadaver disposal through
private companies instead of using vultures. The simulation involved an agent-based model [83]. The fifth publication with the highest number of citations is an article titled “An agent-based model of groundwater over-exploitation in the Upper Guadiana, Spain”, cited 28 times with 2.8 citations per year. The research consisted of developing an agent-based model to study the history of irrigation agriculture in the high basin of Guadiana (Spain) to determine the influence of farmers in soils and the excessive use of underground water. A policy is simulated to promote transition from vineyards and cereals to horticulture offering higher income with less water. The results of the model suggest that aversion to risk and de-

Table 8. Scientific collaboration network countries.

| Node   | Cluster | Betweenness | Closeness |
|--------|---------|-------------|-----------|
| USA    | 1       | 1.813155845| 0.016129032|
| Italy  | 1       | 4.311111111| 0.011494253|
| Iran   | 1       | 0           | 0.010989011|
| India  | 1       | 0           | 0.010989011|
| Norway | 1       | 0           | 0.010989011|
| Ethiopia| 1      | 0           | 0.011235955|
| South Africa | 1  | 0           | 0.010989011|
| Sweden | 1       | 0           | 0.010989011|
| United Kingdom | 2  | 113.1718615| 0.01754386|
| Netherlands | 2  | 69.03156566| 0.016129032|
| Australia | 2   | 8.032142857| 0.013333333|
| China  | 2       | 1.211111111| 0.014084507|
| Brazil | 2       | 0           | 0.01369863 |
| Vietnam| 2       | 0           | 0.010989011|
| France | 3       | 124.225     | 0.013333333|
| Colombia| 3     | 46.8        | 0.011764706|
| Spain  | 3       | 45.15       | 0.01369863 |
| Mexico | 3       | 30.64545455| 0.013513514|
| Senegal| 3       | 0           | 0.009615385|
| Burkina Faso | 3  | 0           | 0.01010101|
| Belgium| 3       | 0           | 0.00877193 |
| Kenya  | 3       | 0           | 0.01010101|
| Ecuador| 3       | 0           | 0.009615385|
| Mali   | 3       | 0           | 0.01010101|
| Germany| 4       | 115.3136364 |0.016293443|
| Canada | 4       | 85.07954545| 0.015384615|
| Austria| 4       | 2.572772723| 0.012195122|
| Indonesia| 4    | 2.4642875714|0.012195122|
| Argentina| 4      | 0           | 0.011235955|
| Chile  | 4       | 0           | 0.011235955|
| Hungary| 4       | 0           | 0.013513514|

Fig. 8. Author Collaboration Network (elaborated using Bibliometrix library from Rstudio).

Fig. 9. Collaboration network per institutions (elaborated using Bibliometrix library from Rstudio).

The research determined that the current policy is ineffective in terms of reducing forest transformation and carbon emissions, hence the need to implement support systems for subsistence alternatives and increase prices in agricultural exploitation of forestry and agroforestry products [87].

In ninth place is the article titled “Modelling regional cropping patterns under scenarios of climate and socio-economic change in Hungary” cited 14 times and 3.5 times per year. The study presents the analysis of changes in land usage with 4 possible climatic changes in two regions of Hungary. The simulation determined that the policies need to be specific for each region. In one region, local food safety needs to be promoted, whilst driving the capacity of farmers to adapt to physical limitations. In the other region, farmers need better access to social capital, and environmental conscience needs to be promoted [88].

The last article presented in the tenth position is the one titled “Combining participatory approaches and an agent-based model for better
Table 9. Most relevant publications.

| Article                                                                 | DOI                          | Total citations | Annual average citation |
|------------------------------------------------------------------------|------------------------------|-----------------|-------------------------|
| FARRADI S, 2016, AGRIC WATER MANAGEMENT                                | 10.1016/j.agwat.2016.08.018 | 38              | 6.333                   |
| LI J, 2017, LAND USE POL                                               | 10.1016/j.landusepol.2017.03.008 | 30              | 6.0                     |
| REBAUDDO F, 2011, PLOS COMPUT BIOL                                     | 10.1371/journal.pcbi.1002222 | 30              | 2.727                   |
| DUPONT H, 2012, J APPL ECOL                                           | 10.1111/j.1365-2664.2012.02111.x | 29              | 2.9                     |
| HOLTZ G, 2012, REG ENVIR CHANG                                        | 10.1007/s10113-011-0238-5     | 28              | 2.8                     |
| SHASTRI Y, 2011, BIOENERGY RES                                        | 10.1007/s12155-011-9139-1     | 25              | 2.273                   |
| DELMOTTE S, 2016, AGRIC SYST                                          | 10.1016/j.agyr.2015.12.009     | 22              | 3.667                   |
| SUWARNO A, 2018, MITIG ADAPT STRATEG GLOB CHANG                       | 10.1007/s11027-016-9721-0      | 20              | 5                       |
| LI S, 2018, SCI TOTAL ENVIRON                                         | 10.1016/j.scitotenv.2017.10.038 | 14              | 3.5                     |
| JOFFRE OM, 2015, AGRIC SYST                                           | 10.1016/j.agyr.2015.10.006     | 12              | 1.714                   |

Table 10. Most relevant affiliations.

| Affiliations                                      | Country                | Articles |
|---------------------------------------------------|------------------------|----------|
| Wageningen University and Research                | Netherlands            | 27       |
| Michigan State University                         | United States of America | 12       |
| Leibniz University Hannover                       | Germany                | 5        |
| University of Brescia                             | Italy                  | 5        |
| University of Montpellier                         | Francis                | 5        |
| University of Florida                             | United States of America | 4       |
| University of Göttingen                           | Germany                | 4        |
| University of Southampton                         | United Kingdom         | 4        |
| University of Tabriz                              | Iran                   | 4        |
| Vanderbilt University                             | United States of America | 4       |

Planning shrimp aquaculture" cited 12 times and 1.74 times per year, presents an agent-based model used for the analysis of 4 scenarios of sustainable production and development in the shrimp production process. The research concluded that the M.B.A. tool is very useful as an instrument to exchange knowledge among farmers and decision-makers [89].

As seen in the most cited articles, the agent-based technique is a useful tool to assess future scenarios in which different strategies and guidelines can be assessed to achieve expected goals. Hence, this method can help decision-makers to set agricultural policies to meet specific goals and reduce the uncertainty of policy formulation since this is a complex system comprised of various entities, solutions, issues, and opportunities. This is explained in the trash can model [90], along with the limited rationality of the decision-maker, as stated by Nobel prize winner Helbert Simon in the limited rationality model [91].

The agent-based model has been used mainly to assess scenarios, seeking the optimization of resources (primarily water) to determine the best land usage policy and implement sustainable agriculture in the long term. The next section describes the analysis of certain topics in which the agent-based model has been applied with an association-based grouping of the topics with Rstudio software.

5.10. Most relevant affiliations

Table 10 displays the list of the 10 main organizations that have publications related to the use of agent-based models in sustainable agriculture.

All the organizations that make up the top 10 are universities. The first is the Wageningen University and Research, which appears 27 times in the analyzed publications. This is a public university located in the Netherlands, whose mission is “to explore the potential of nature to improve the quality of life”, for which its research is focused on three lines: food, feed and biobased production; natural resources and living environment; society and well-being [92]. The second in the ranking is the public Michigan State University with 12 appearances in publications. The AgBioResearch Institute, created in 1886 to help farmers also belongs to this university; nevertheless, the institute currently carries out works in the areas of food, health and environment [93].

Then, with five publications appears Leibniz University Hannover in Germany, the University of Brescia in Italy, and the University of Montpellier in France. Finally, there are universities with four publications, which are the University of Florida in the United States of America, the University of Göttingen in Germany, the University of Southampton in the United Kingdom, the University of Tabriz in Iran, and the Vanderbilt University in United States of America.

The most representative affiliations, which have more publications on the use of agent-based models in sustainable agriculture are from the United States and France, demonstrating that these are the leading countries in scientific research on the subject. The above mentions demonstrate the relevance of higher education institutions in scientific development on the subject.

5.11. Theme-based grouping

Fig. 10 and Table 11 show how the topics were grouped using the keywords defined by the authors. Three groups were formed. The three groups can be distinguished in three different colors in Fig. 10 (red, blue, and green). Each group contains the words that were most associated with each other. The association is determined by the group of keywords of each of the analyzed articles.

Table 11 shows the list of words in each group. After Table 11, the thematic focus of each group is presented, explaining what the main objective of each group.

Group 1 (agent-based model, computational methods, autonomous agents, agricultural robots, simulation platform, land usage changes, policy, interested, food supply, crops, economic sciences, environmental impact, populational statistics, water management): The first group refers to the research articles where the agent-based method was used to simulate public policies bearing in mind the interest of stakeholders on
whether to implement agricultural robots [94, 95, 96, 97, 98, 99, 100], the changes in land usage [84, 87, 100, 101, 102], water management [81, 98, 103, 104]; crop behavior [105, 106], food supply chains [94, 101, 107, 108]; and environmental impact [94, 106, 107, 109]. The first group (Fig. 8) has the highest number of words, including projects with simulations of different future scenarios using agent-based models to determine which guidelines are more suitable to formulate public policies that promote sustainable agriculture and contribute with the SDGs defined by the UN [1].

Group 2 (agriculture, decision-making, models, crop system, article, theoretical, agricultural activities, human, theoretical model): This group encompassed research articles where human decision-making models were analyzed [107, 110, 111, 112, 113] to determine agricultural activities [97, 104, 114] and crop systems [107, 109, 110]. The second group of researchers has a more humanistic approach where agent-based models were implemented to model decision-making processes that have an impact in the agricultural system and determine the future behavior regarding current agricultural activities and crop systems in place.

Group 3 (sustainable development, land usage, food safety, climate change, environment policy, environmental economy): The third group is closely related with group 1 as seen in Fig. 8. This group encompassed research articles that contribute to sustainable development, performing simulations using agent-based models to determine land usage [94, 98, 100, 101, 109, 110, 114, 115, 116], considering climate change [95, 101, 109, 110, 117], and environment policies and economies [100, 107, 110, 117, 118, 119, 120], to ensure food safety [101, 107, 110, 116, 120, 121, 122]. In summary, group 3 has a more environmental-focused approach than the other groups favoring finding the best land usage conditions and promoting sustainable development.

As evidenced from the groups derived from keyword association, the agent-based method has been primarily used to simulate agricultural and environmental public policies, and thus, predict future stakeholder behavior under many possible scenarios. This proves the effectiveness of sustainability measures and reduces the uncertainty of decision-making processes, especially in public policy settings. The resulting agricultural public policies can drive productivity and improve the use of environmental resources such as water and land, while cutting the negative effects for the environment, promoting sustainable agriculture and, eventually accomplishing the SDGs set by the UN.

6. Discussion

In order to discuss the subject at hand, three aspects need to be considered: scientific production, the impact of such production, and theme-based analysis.

Scientific production regarding the use of the AI technique of agent-based models in sustainable agriculture was increased since 2015, which marks the declaration of Sustainable Development Goals by the UN [1]. The second goal is directly related to the topic of study since it embodies the following statement: “Putting an end to hunger, achieving food safety whilst improving nutrition and promoting sustainable agriculture” [5, 18]. This requires a balance between economic development, social development and protection of the environment [123, 124, 125, 126]. The inclusion of different perspectives gives a level of complexity to this goal, thereby revealing the need for agent-based models to represent different scenarios and forecast future results. The result would contribute to formulating public policies that promote sustainability and reduce the level of uncertainty of public policy formulation [90, 91, 127, 128]. One of the countries that has led this specific research field is the United States with the highest number of publications and the highest number of collaborations with other countries, thus participating in scientific developments worldwide. Another leading country is the Netherlands, internationally recognized by its strive progress in sustainable development and taking the second place in terms of total publications, which are often cited by other researchers; its relevance stems mostly from the fact that the leading researchers on the matter are Dr. Gert Jan Hofstede and Dr. Jeroen Groot who are professors from Wageningen University. Another example of leading country in this subject is France, having the highest number of citations per article, even though they have less published articles than USA or the Netherlands. France has proved the high quality of its research and received worldwide scientific recognition. Another important aspect is that the United States of America, France, the United Kingdom and Germany are the main bridges of knowledge in the world, which significantly promote the global dissemination of scientific knowledge on this subject, which was demonstrated by making the SNA in which they obtained
the highest betweenness. Finally, it is important to highlight that 76% of the production of scientific publications is concentrated solely in 10 countries, nine developed countries, and only one in the category of a developing country. Remarkably, this proportion shows the large prevailing gap in scientific publications.

The distribution and socialization of knowledge is linked to the information sources with broader coverage and impact, which are Q1-level open access journals. The main journals regarding the implementation of agent-based models in sustainability are “ECOLOGICAL MODELLING” and “JOURNAL OF ENVIRONMENTAL MANAGEMENT”. Both journals have an APC fee between US$ 3400 and US$ 3800. Hence, research projects need to account for these expenses in their budget planning process to ensure the adequate diffusion of knowledge. The articles with the strongest impact are titled “An agent-based-Nash modeling framework for sustainable groundwater management: a case study” and “Effects of land lease policy on changes in land use, mechanization and agricultural pollution”, which sought to determine good practices for the management of natural resources such as water [81] and soils [9] in favor of sustainable agriculture.

Three theme-based strategies were set in place, which are interrelated. The first approach in research projects consisted of assessing scenarios to determine the best public policies that promote sustainable agriculture, giving this approach a socio-political nature. The second approach consisted of assessing scenarios to determine the best agricultural practices that promote development of the agricultural sector, thereby giving a socio-economic nature to this approach. Lastly, the third approach shows different scenarios seeking to determine the optimal usage of natural resources such as water and soil, and ensure the availability of resources over time. Hence, the third approach has an environmental focus in nature. The approaches explored in these research efforts and their perspectives are varied (political, social, economic, environmental) given that sustainable development and sustainable agriculture includes these aspects. The agent-based modelling technique must support the formulation of public policies that contemplate social, economic and environmental aspects, and contribute to the formulation of agricultural policies that promote sustainable development.

Therefore, to achieve success in the implementation of sustainable agriculture that ensures food security, with sustainable and efficient management of natural resources. Which has commercial regimes and agricultural policies that promote local and regional agricultural markets, ensuring profitability [18]. It is necessary to carry out scientific research to analyze all the economic, political, social, and environmental aspects. In order to improve the results and the analysis process of the investigations, computational simulations that show possible future scenarios must be developed and implemented, which will be of great help to researchers and also to decision makers. In this way, it is possible to reduce the degree of inherent uncertainty during the decision-making process [91]. These simulations can be developed with artificial intelligence tools such as agent-based models, among others, which have proven to be highly effective [8, 9, 10, 11, 12, 13, 14, 15, 16, 17].

For all the above, it is suggested that future research in sustainable agriculture using agent-based modeling tools should be developed taking into account the multidimensionality of the system. In such a way, that it is possible to better visualize the possible future scenarios determining the economic, political, social and environmental results in the simulations.

7. Conclusions

The importance of publishing scientific articles in open access journals was evidenced, since it promotes scientific development and technological progress, so that more research and products can be materialized in favor of sustainable agriculture, using agent-based models as a tool.

The leading countries in scientific production regarding the use of agent-based models in sustainable agriculture are the United States of America, the Netherlands, France, UK, Germany and China. The United States is the leading country in terms of scientific production yet France has had a more significant impact on the research than other countries. Furthermore, the importance of international collaborative work was stated for the development of new research projects and scientific products. Also, the United States of America, France, the United Kingdom and Germany are the main bridges of knowledge in the world on this subject.

The agent-based artificial intelligence tool is a very useful instrument to assess future scenarios, where different solution alternatives can be assessed and approximate results that are closer to the expected outcomes. In the case of the analyzed research projects, it can also promote the development of sustainable agriculture.

The agent-based model has proven to become a useful strategy for decision-makers in public policy since it reduces the uncertainty of the decision that needs to be made. The reason behind this is that the tool helps make more rational decisions and reduces the limited rationality discussed by Simon [91]. Hence, the agent-based technique has been widely used to simulate different public policies that drive sustainability in agriculture whilst keeping in mind a better use of natural resources, cutting negative consequences for the environment, and ensuring value generation for stakeholders that intervene in the agricultural system.

Also, the need to carry out future research on sustainable agriculture that develops simulations based on artificial intelligence such as agent-based models in conjunction with others is established. Thus, taking into account the multidimensionality of the system in economic, political, social, and environmental aspects.

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