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Precision Techniques and Agriculture 4.0 Technologies to Promote Sustainability in the Coffee Sector: State of the Art, Challenges and Future Trends

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ABSTRACT Precision Agriculture (PA) and Agriculture 4.0 (A4.0) have been widely discussed as a medium to address the challenges related to agricultural production. In this research, we present a Systematic Literature Review (SLR) supported by a Bibliometric Performance and Network Analysis (BPNA) of the use of A4.0 technologies and PA techniques in the coffee sector. To perform the SLR, 87 documents published since 2011 were extracted from the Scopus and Web of Science databases and processed through the Preferred Reporting Items for Systematic reviews and Meta-Analyzes (PRISMA) protocol. The BPNA was carried out to identify the strategic themes in the field of study. The results present 23 clusters with different levels of development and maturity. We also discovered and presented the thematic network structure of the most used A4.0 technologies in the coffee sector. Our findings shows that Internet of Things, Machine Learning and geostatistics are the most used technologies in the coffee sector, we also present the main challenges and trends related to technological adoption in coffee systems. We believe that the demonstrated results have the potential to be considered by researchers in future works and decision making related to the field of study.

INDEX TERMS Agriculture 4.0, bibliometric, coffee, digital agriculture, digital transformation, industry 4.0, precision agriculture, strategic intelligence, sustainability.

I. INTRODUCTION

The concept of precision agriculture (PA) emerged in 1980, relating to the use of techniques to deal with field variability [1]. Driven by PA and industry 4.0 (I4.0) concepts, several terms seek to designate the use of emerging technologies in agriculture, such as agriculture 4.0 (A4.0), digital agriculture, smart agriculture and agri-food 4.0, among others [1]–[3]. Discussions about the digital transformation of agriculture represent the transformation of agribusiness

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processes towards automation, flexibility, scalability and increase productivity and quality [4]–[6]. The A4.0 assists farmers in the efficient use of economic, human and technological resources, creating a traceable agriculture to make decisions based on real data and with the least effect on environment [7]. The use of emerging technologies raises the level of understanding of agricultural production, especially about a large number of variables [7].

The challenges in agriculture are mounting and it is estimated that the human population will reach 9 billion people by 2050 [8], increasing by 70% the food demand [9], [10]. To meet the growing demand for food, the water consumption in agriculture should increase by 41% [11], [12], the sector that is already responsible for pollution and consumption of almost 70% of the planet's fresh drinking water [13]. In addition, the world and agriculture face other problems, such as climate change [14] and appropriations of natural resources 30% over nature's ability to regenerate [15]. Despite the evident challenges related to agricultural production, it is estimated that 50% of food is wasted in food production processes, from harvest to final packaging [16], which highlights the need for better agricultural management that can be supported by emerging technologies. In addition one third of the food produced is wasted after being marketed [17], [18]. Therefore, meeting the food demands of the world population will be a major challenge in the coming years [5], [19] and approaches must urgently be developed to tackle these challenges in order to achieve production that meets human needs without damaging the ecosystem.

In this sense, several studies are related to the use of A4.0 technologies, such as sensing and actuation drones to identify and control pests in crops [20], sensors and Internet of Things (IoT) for water management [21], agricultural decision support systems [22], proximal images and machine learning (ML) to identify nutritional deficiencies in crops [23], among others. These technologies assist in data collect, information analysis, diagnostics and formulation of strategies for the agricultural sector [24]. In this research, we review the use of A4.0 technologies and PA techniques in the coffee sector. Coffee is a widely marketed beverage that represents a significant portion of the income of developing countries, generating more than US$ 20 billion annually to producer countries [25]. Around 70% of world coffee is produced in Central America, Southeast Asia and Sub-Saharan Africa, with a number between 25 and 30 million coffee producers in the world [26], and for more than 120 million people worldwide the coffee is the main source of subsistence [27]. The A4.0 in the coffee field represents techniques and technologies that assist farmers in managing singularities of production, such as soil properties, fertilization and harvest to increase the efficiency, productivity and quality of coffee production [13]. In the coffee sector, the application of A4.0 technologies and PA techniques is commonly known as precision coffee growing [28].

However, despite the several advantages of A4.0 and precision techniques, few reviews of the literature have been carried out on PA and A4.0, such as the work of Pusdá-Chulde *et al.* [29] who reviewed heterogeneous architectures for PA, and Klerkx *et al.* [30] who performed the review of social science on digital agriculture. Despite these comprehensive studies, no literature or bibliometric reviews have been carried out to review empirical results and understand the impact of technological adoption as well as the main challenges and trends for the coffee sector. To address this gap in the literature, this work aims to identify the strategic themes related to PA and A4.0 in the coffee sector, the thematic structure of the most used A4.0 technologies and the main challenges and future trends in precision coffee growing. To perform this review, an exhaustive Systematic Literature Review (SLR) supported by a Bibliometric Performance and Network Analysis (BPNA) was carried out. To do this, the Preferred Reporting Items for Systematic reviews and Meta-Analyzes (PRISMA) protocol and the SciMAT software (Science Mapping Analysis Software Tool) developed by Cobo *et al.* [31] were used.

The paper is organized as follows: Section 2 contains the state of the art of coffee production, PA and A4.0. Section 3 presents the research methodology. In section 4, the strategic themes and the thematic structure of the most used A4.0 technologies and PA techniques are presented. Section 5 discuss the emerging technologies in the coffee sector. Section 6 contains the main challenges and future trends, and section 7 presents the conclusion, limitations and suggestions for further research.

II. STATE OF THE ART

A. COFFEE PRODUCTION

There are several challenges related to agriculture in the coming years. For more than 25 million small coffee farmers, challenges such as climate change [32] have a drastic impact on coffee production. Plants and grains are very sensitive to global warming, especially the *Coffea Arabica* [33] which represents around 60-70% of world coffee production [34], [35]. It is estimated that 54% of coffee crops are expected to reach temperatures above 32°C by 2050 [36]. However, varieties such as *Coffea Canephora* (Robusta) must be grown at temperatures between 20-30°C [37]. The coffee yield suffers impacts from climate change mainly on the flowering and fruiting phases, and it causes diseases, reduce the quality and increase production costs [27].

These challenges impact different parts of the world. Brazil, the largest producer and exporter of coffee in the world and the second largest consumer [38], has contrasting cultivation areas, such as mechanized flat regions and mountainous areas, which are difficult to grow. The farmers face challenges related to unshaded areas and limited agroforestry coffee systems, making plantations vulnerable and impacting social and economic environments [39]. Likewise, the coffee production in Vietnam is 90% represented by Robusta Coffee due to the country's soil and climate characteristics, with many challenges related to environmental factors [40].

In Colombia, the third largest coffee producer in the world, the sector is mainly driven by cooperatives and has significant importance for the country's economy. Colombia is one of the countries with the highest sustainable production, seeking sustainable initiatives as a strategy to increase the added value of the product [41]. The specialty coffees, rare and exotic, with high standards of quality and variety, have a higher market value [42], [43]. However, the quality depends on cultivation techniques, genetic traits and technologies used in cultivation and processing.

After crude oil, coffee is the most traded commodity in the world [36]. Coffee is grown on more than 10 million hectares of land worldwide, mainly in tropical and subtropical regions, justifying the largest coffee producers in the world being Brazil (36%), Vietnam (17%) and Colombia (8%) [27], [44] and represents a significant part of the Gross Domestic Product of these countries. Produced in more than 70 countries, the largest amount of coffee is produced in developing countries, and the largest consumption of beverage is in developed countries, whose growing demand has doubled the amount of coffee grown in the last decade [45], [46]. Coffee production also has challenges related to shading, carbon sequestration, pest control, soil properties [34], [47] and rust and plant disease that can reduce productivity by up to 50% [48]. It is also important to mention that coffee agriculture and commercialization are responsible for a large volume of harmful waste that generates major environmental impacts.

B. PRECISION AGRICULTURE

By 2050, the world population is expected to reach 9 billion people, making the need for food to increase by 70% [8]. This increase is expected mainly in developing countries, where agriculture is a key factor for the economy and development. Around 75% of the world's poor live in rural areas and need agriculture to survive, so find ways to increase agricultural productivity are essential to reduce poverty and provide food security [49]. The increasing human population and demand for food create a challenge for sustainability and the future of the planet, and to deal with this challenge, innovative technologies have been used in agricultural scenarios [5].

In this sense, the demands of social development are transforming the primary sector, which is adopting new techniques and technologies that transform agricultural production [50], [51]. The large-scale mechanization has generated several changes in the agricultural sector [52]. The substitution of manual labor for machines increased productivity, allowed the management of larger fields and the use of genetically improved varieties, fertilizers and pesticides, creating economies of scales and uniformity in world production. On the other hand, the mechanization limited the role of the farmer in matters that previously used personal knowledge such as soil characteristics, nutrient demands, climate, weeds and manual practices [53], [54].

In order to balance these facets, the concept of PA emerged in 1980 and represent techniques and technologies that suit the characteristics of the cultivation and environment [55]. The PA offers several sensing techniques to assist in monitoring crops, allowing the processing of large amounts of data on different parameters [5] enabling the management and selective treatment of fields and farms [53]. PA techniques are especially used to measure and control variables such as temperature, water and soil nutrients [5], and to control the proper use of herbicides, fertilizers and other variables related to agricultural production [56].

C. AGRICULTURE 4.0

Although many authors present PA and A4.0 with the same meaning, the concept of A4.0 emerged from the concept of industry 4.0 in 2011 and has greater breadth. A4.0 refers to the technological adoption to create a value chain that integrates the organization, customers and other stakeholders [50]. In this sense, A4.0 refers to the use of information and communication technologies such as Big Data and Analytics and ML to explore the variability of data and use it to deal with changes in the agricultural scenario [57]. A4.0 is directly related to emerging technologies, such as ML algorithms for water management [58] and automation of grain selection [59], complex systems for identifying and monitoring pests and diseases [57], and artificial intelligence for soil analysis [60].

In this frame, agricultural production strategies become more important because the human actions are drastically reducing the planet's biodiversity [61] and the sustainable production is a way to reduce this environmental impact. Food systems and agricultural activities are responsible for around 19-29% of global emissions [62]. In this sense, it is necessary to rethink agriculture in a sustainable way. The A4.0 technologies can provide a range of solutions in this regard, such as data management, automation, traceability, better working conditions and reduction of chemicals [2], reaching economic, social and environmental characteristics of Triple Bottom Line (TBL) [63].

III. RESEARCH METHODOLOGY

To achieve our goal, a SLR supported by the PRISMA protocol, and a BPNA with the support of the SciMAT software was carried out. To guide this review, three research questions (RQ1 - 3) were defined:

RQ1 - What are the strategic themes related to PA and A4.0 in the coffee sector?

RQ2 - What are the most used PA techniques and A4.0 technologies in the coffee sector?

RQ3 - What are the main challenges and future trends related to PA and A4.0 in the coffee sector?

In order to answer these RQ with a wide range of literature, the Scopus and Web of Science (WoS) databases were used, as they are indexed bases with volume and quality of production [64], [65]. Firstly, we select the terms related to PA and A4.0 mentioned in the literature. Then, we insert the term 'coffee' to identify works that discuss the use of PA techniques and A4.0 technologies in the coffee sector. Table 1 present the terms and the search string. For a complete

TABLE 1. Search string.

Terms	Operators	String
agriculture 4.0, digital agriculture, digital farming, smart agriculture, smart farming, precision agriculture, precision farming, agri-food 4.0 [1]–[3]	OR - AND	(("agriculture 4.0" OR "digital agriculture" OR "digital farming" OR "smart agriculture" OR "smart farming" OR "precision agriculture" OR "precision farming" OR "agri-food 4.0") AND ("coffee"))

analysis, we used documents of the type articles, articles in press, reviews and conference papers which contained the search terms present in the title, abstract or keywords. Documents from all languages found (English, Portuguese and Spanish) were considered. We only used documents published from 2011, because the concept of I4.0 started to be widely discussed from this year [66]. The date of the export of the documents was May 18, 2020.

A. SYSTEMATIC LITERATURE REVIEW

To integrate information from different studies and research, the SLR must be clear and precise to articulate information, treat data and identify related topics. In this work, to organize the document selection criteria, we use the PRISMA protocol to ensure the quality and transparency of the review [67], [68]. In this frame, a set of items in protocol were followed to consolidate the research steps, and to identify the knowledge relevant to the field of study [69]. Fig. 1 (below) shows the phases (identification, screening, eligibility and inclusion) and results of the SLR.

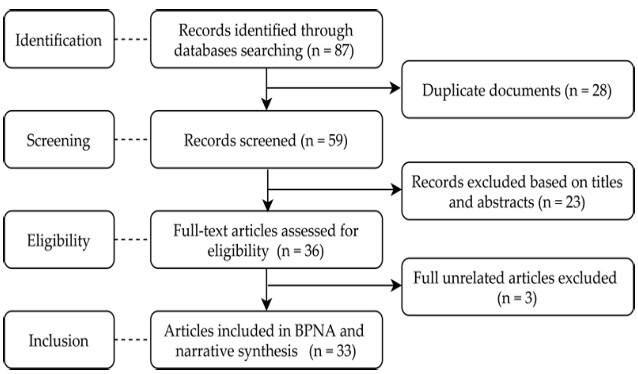


FIGURE 1. The phases of the SLR through PRISMA.

The documents related were extracted from the databases (87 documents) and the duplicated documents (28) were removed, leaving 59 original documents for analysis (Figure 1). We read the title, abstract and keywords of these papers to identify relationships with the field of study, the unrelated articles were disregarded (23). The remaining works were fully read (36), and papers not related to our objective were excluded (3). The selected articles (33) were analyzed by full reading to identify challenges and trends in the coffee sector and included for BPNA analysis to identify the use of technologies and strategic themes of the field of study.

B. BIBLIOMETRIC PERFORMANCE AND NETWORK ANALYSIS

The SciMAT software developed by Cobo *et al.* [31] was used to identify the strategic themes and the thematic structure of the most used PA techniques and A4.0 technologies in the coffee sector. The SciMAT is a free software available that allows a complete bibliometric process, from data processing to analysis of results [70]. In addition, it creates strategic diagrams and intellectual network structures of a field of study [31], [71]–[73].

In the bibliometric process, we only used the documents identified and relevant to the field of study through the PRISMA protocol. In the preprocessing stage, we group keywords with the same meaning, such as 'Internet of Things' and 'IoT', 'smart agriculture' and 'smart agricultures' among others. In addition, misspelled words have been corrected, and meaningless words like 'article' have been removed. Finally, 33 documents and 477 keywords were considered for bibliometric analysis.

To create the diagrams we consider the co-occurrence of keywords and the equivalence index to calculate the similarity between themes [74]. For the creation of clusters and develop the relationships networks, we use the simple center algorithm [75]. In the SciMAT software, we carry out the analysis of the co-occurrence of keywords to identify relationships between units, which represent the nodes of a network [31]. In this set of analyzes, we consider only keywords reported by the authors of the articles, and we do not use frequency reduction or edge value for data or network reduction. In the clustering algorithm stage, we used maximum and minimum network size as 12 and 3 respectively, to identify only the most important themes related to the field of study, in addition the document mappers for co-occurrence networks used was the core mapper [30].

The themes were plotted on two-dimensional diagrams, where the 'x-axis' indicates centrality and the 'y-axis' reflects the cluster density. The diagram is composed of four quadrants according to Fig. 2(a) (below). Q1) Motor themes: highly developed themes; Q2) Basic and transversal themes: despite high centrality, they have low density; Q3) Emerging or declining themes: low development and centrality; and Q4) Highly developed and isolated themes: low centrality, but strong density [31], [72], [73], [76]. The centrality represents

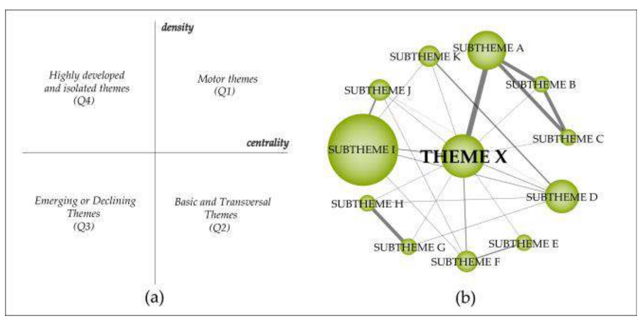
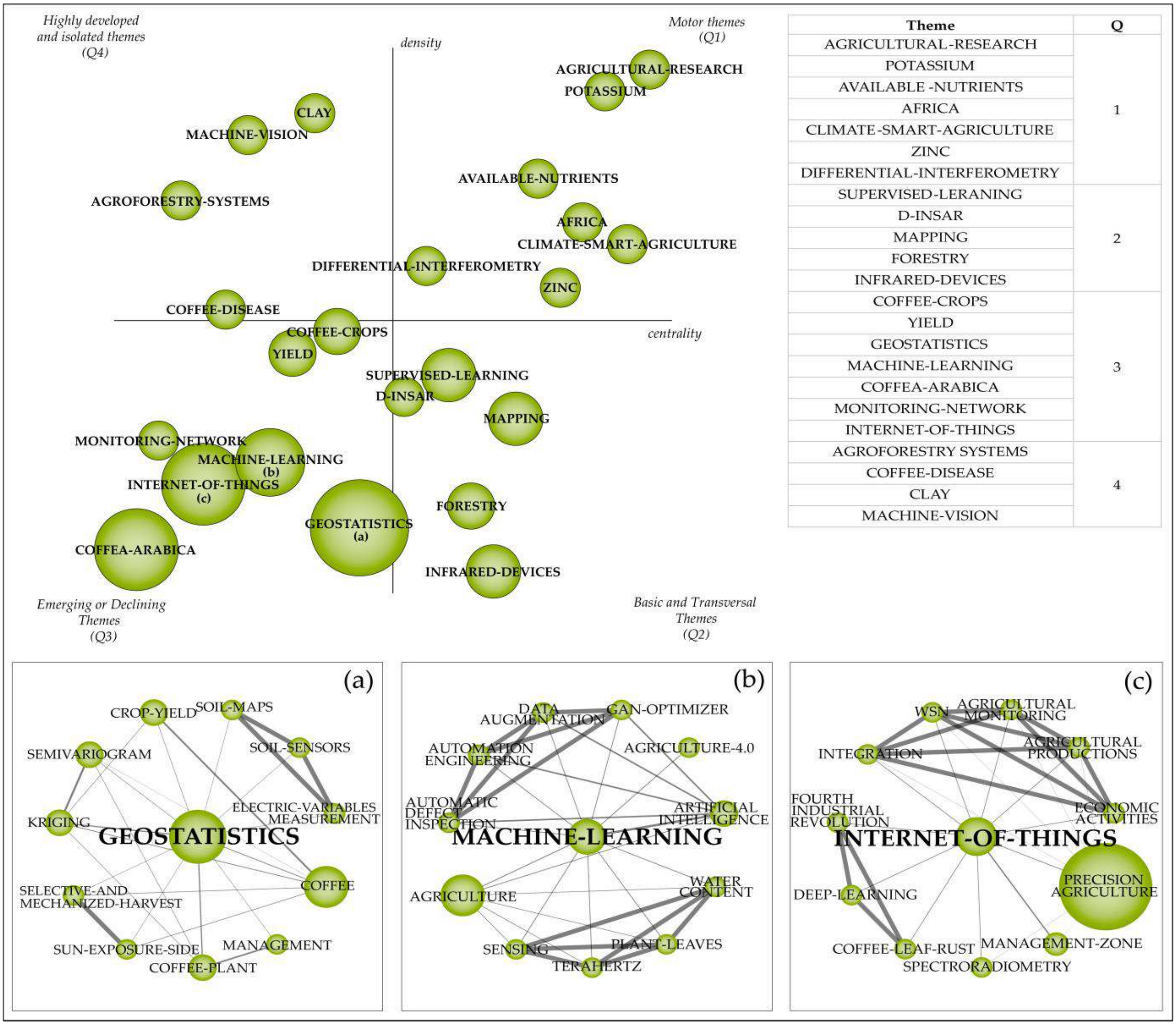


FIGURE 2. (a) Strategic diagram; (b) Thematic network structure.



Theme	Q
AGRICULTURAL-RESEARCH	1
POTASSIUM	
AVAILABLE -NUTRIENTS	
AFRICA	
CLIMATE-SMART-AGRICULTURE	
ZINC	
DIFFERENTIAL-INTERFEROMETRY	
SUPERVISED-LERANING	2
D-INSAR	
MAPPING	
FORESTRY	
INFRARED-DEVICES	
COFFEE-CROPS	3
YIELD	
GEOSTATISTICS	
MACHINE-LEARNING	
COFFEA-ARABICA	
MONITORING-NETWORK	
INTERNET-OF-THINGS	
AGROFORESTRY SYSTEMS	4
COFFEE-DISEASE	
CLAY	
MACHINE-VISION	

FIGURE 3. Strategic themes related to PA and A4.0 in the coffee sector. Centrality represent the importance of the theme for the field of study. Density represents the capacity of the theme to prevail over time. Thematic networks: (a) GEOSTATISTICS. (b) MACHINE-LEARNING. (c) INTERNET-OF-THINGS.

the theme's importance to the field of study, and the density represents the theme's predominance capacity [31]. In this way, it is possible to identify the most important themes over time and the intensity of relationships with other themes [64], [72]. Fig. 2(b) presents an example of thematic network structure.

IV. STRATEGIC THEMES RELATED TO PA AND A4.0 IN THE COFFEE SECTOR

With the support of the SciMAT software, we detected 23 strategic themes related to PA and A4.0 in the coffee sector. 7 clusters are motor themes with high centrality and density, 5 clusters are basic and transversal themes, 7 are emerging or declining themes and 4 clusters are highly developed and isolated. Fig. 3 (below) presents the clusters plotted in four quadrants (Q) of the strategic diagram. The size of the cluster is related to the number of associated documents.

The motor themes (Q1) are mainly composed of clusters that discuss soil attributes such as 'POTASSIUM', 'ZINC' and 'AVAILABLE-NUTRIENTS'. These are motor themes because research on soil quality was the first PA technique used, and also shows that PA techniques are applied longer than A4.0 technologies.

In this quadrant (Q1) (Figure3) the cluster 'CLIMATE-SMART-AGRICULTURE' is very important because it represents the concern of the agricultural sector with approaches to sustainable production [62]. The cluster 'AFRICA' is related to works that mention the importance of coffee production for the African economy [60]. The cluster 'DIFFERENTIAL-INTERFEROMETRY' show the use of radar images for crop growth monitoring [77] as differential synthetic aperture radar interferometry (DInSAR) in Q2.

In addition, it is important to note that the cluster 'AGRICULTURAL-RESEARCH' is the most dense and central, evidencing efforts related to the improvement and transformation of agriculture. Different from the Q1, the basic and transversal themes (Q2) present more topics related to technologies such as 'INFRARED-DEVICES', 'D-INSAR' and 'SUPERVISED-LEARNING'. However, topics related to mapping the spatial distribution of areas ('MAPPING') [78] and forest settlement methods ('FORESTRY') [79] are also discussed.

In Q4 (highly developed and isolated themes), the most important themes are 'CLAY'', 'MACHINE-VISION', 'AGROFORESTRY-SYSTEMS' and 'COFFEE-DISEASE' [57], [79], [80]. Q3 present the clusters 'COFFEE-CROPS', 'YIELD' and 'COFFEA-ARABICA' as efforts related to coffee growing and the *Coffea Arabica* variety. This quadrant presents the largest number of documents related to technologies through the clusters 'GEOSTATISTICS', 'MONITORING-NETWORK', 'MACHINE-LEARNING' and 'INTERNET-OF-THINGS'. These emerging clusters prove the incipient application of technological use in the coffee sector. It also shows that the most important clusters are IoT, ML and geostatistics (Fig. 3).

V. EMERGING TECHNOLOGIES IN THE COFFEE SECTOR

Emerging technologies have been used to drive and develop the agricultural sector [81]. These technologies are used to improve the production quality and data traceability [82], minimize costs and make the activity more efficient and competitive. In addition, it is an effective solution to reduce the environmental impact generated by agriculture [83]. Fig. 3 (above) shows three main emerging techniques and technologies used in the coffee sector (geostatistics, ML and IoT), its thematic structure and its relations with other subthemes. The size of the cluster represents the number of associated documents and the thickness of the lines represents the bond strength between the clusters.

Table 2 (Annex) presents the related works identified through the SLR. The table shows the work, the main technique or technology used and the country where the research was carried out. It is possible to observe that Brazil is the country with the most related work, due to being the largest coffee producer in the world. In addition, the table shows the focus of the work and the application of technologies (ML, IoT and Geostatistics).

A. GEOSTATISTICS

The cluster ''GEOSTATISTICS'' (Fig. 3 (a)) is strongly related to subthemes such as 'SEMIOVARIOGRAM' and 'KRIKING'. It is important to note other subthemes related to this cluster such as 'SOIL-MAPS', 'ELETRIC-VARIABLES-MEASUREMENT', 'SELECT-AND-MECHANIZED-HARVEST', 'SOIL-SENSORS' and 'MANAGEMENT'. The link between these themes highlights efforts related to the management of coffee crops with the support of maps and sensors to analyze variables related to production. These techniques and technologies can be used to increase the knowledge about variables and improve the quality of coffee production, since the quality of beverage is influenced by characteristics such as climate, soil, altitude, cultivation and management. Most works used statistics and geo-statistics to generate and to analyze maps of spatial and temporal variability.

Through PA techniques such as semivariogram and kriging maps, several studies have analyzed the detachment force of green and red fruits in coffee crops [28], [84], [85] Other works explored the level of soil nutrients and its relationship with coffee crop productivity [80], [86]–[90], and the impact of compaction, density and soil penetration resistance (SPR) on plant productivity and development [83], [91]. Other works used sensors and geostatistics to identify the apparent soil electrical conductivity [92], to measure micronutrients and nutritional status of plants [93], and to analyze the soil fertilizer contents [94]. The use of these methods allows spatial analysis with low costs and less uncertainty, mainly for the mapping of soil and plant attributes. It is also a technological option that can be used in different types of plantations, soil and economic realities with reliable and satisfactory results [89].

B. MACHINE LEARNING

The cluster ''MACHINE-LEARNING'' (Fig. 3 (b)) is strongly related to the subthemes 'AUTOMATIC-DEFECT-INSPECTION', 'ARTIFICIAL-INTELLIGENCE' and 'DATA-AUGMENTATION', which highlights the relationships of ML with other technologies for data collection and management, and automation of coffee processes. The use of ML occurs due to its high computational performance that allows to understand the different processes of fields [95]. Several works have implemented A4.0 technologies to improve productivity and sustainability in specific scenarios. Zahid *et al.* [58] propose a non-invasive ML model for water management and generate an accurate estimate of the water content in plants, and Lasso *et al.* [57] reviewed the use of alert systems based on ML to identify pests and diseases.

Other researchers use A4.0 to create a deep-learning-based defective bean inspection model integrated with a Generative-Adversarial Network (GAN) for the selection and separation of defective beans, the model automates the process and reduce the human effort required [59]. Kouadio *et al.* [60] used artificial intelligence (AI) to predict *Coffea Canephora* production based on soil characteristics and properties. The thermography for monitoring stomatal conductance is used in the work of Craparo *et al.* [96] to measure the survival and adaptation capacity of *Coffea Arabica* under different environmental and meteorological changes. The link between these clusters highlights the use of technologies to monitor and collect data and manage different agricultural variables, such as soil, water, climate and pests, among others.

C. INTERNET OF THINGS

The cluster ''INTERNET-OF-THINGS'' (Fig. 3 (c)) shows the concern with the integration of technologies, monitoring and management of networks and processes related to the coffee production. The size of the 'PRECISION-AGRICULTURE' cluster shows the strong relationship between the themes. Other works used ML [97]–[99], IoT and remote sensing [7], [78], [100], [101] to assist in data collection and production management.

In addition, IoT presents relationships with themes such as 'MANAGEMENT-ZONE', 'AGRICULTURAL-MONITORING', 'WIRELESS-SENSOR-NETWORK' and 'DEEP-LEARNING' among others. Valente *et al.* [92] used sensors to measure the variability of the soil electrical conductivity and field properties, and Garcia-Cedeno *et al.* [81] present a proposal of IoT architecture to integrate sensors to monitoring the variables and information of the fields, this integration facilitates the management of the activities and resources. The A4.0 technologies also was used to evaluate the vegetation and soil through hyperspectral and computational processing of images [79], [102] through the use of drones, optical sensors and radars to create maps of crop growth and monitoring the characteristics of the plants [77].

VI. CHALLENGES AND TRENDS FOR THE FUTURE OF THE COFFEE SECTOR

Through the SLR we identify the works related to the use of PA and A4.0 in the coffee sector, and the main challenges and trends related to the field of study. It is possible to observe through the strategic diagram (Figure 3) some of the strategic themes and major concerns of the coffee sector, such as environmental issues and technological integration.

A. MAIN CHALLENGES

Despite the benefits of A4.0, some technologies cannot be adopted by some producers due to their high cost or inadequate field conditions [7], mainly mountainous areas that do not support the use of certain technologies. This highlights the need for studies to adapt and implement emerging technologies in the agribusiness sector. Although the use of big machines in mountainous areas is a challenge, technologies such as sensors can be easier to deploy in these areas and can offer significant support for controlling environment variables. The management of agricultural activities requires a high degree of care in order to not affect the environment. The intensive monoculture, for example, is a harmful activity for the quality of soil, water, air, and human health. In this sense, in-depth studies on coffee production can assist in the identification of best practices in favor of environmental preservation [40], such as climate-smart agriculture and agroforestry systems identified in the strategic diagram (Figure 3). Agrobiodiversity offers paths to environmental resilience and sustainability through mechanisms for production with less risk and mitigation of environmental impacts [103].

For the coming years, it is possible to expect major transformations in the coffee sector, which will impact the social, economic and environmental pillars of sustainability. The concern cannot be only with the level of production and processes, but also aim to improve working conditions, increase quality and develop sustainable agricultural chains between farmers and others involved [81]. Despite being a major challenge, improving productivity and sustainable management will be increasingly necessary. For this, the collection and analysis of large amounts of data on the environment will make an increasing difference in agricultural management. In this sense, data collection and analysis can be supported by technologies emerging from PA and A4.0 such as ML, IoT and geostatistics identified in the strategic diagram (Figure 3). The patterns of food consumption are changing, and meeting these demands requires an increasing number of inputs that can cause a collapse of resources in various sectors, mainly related to water problems, arable land and clean energy. Climate fluctuations also pose risks such as droughts or floods, food shortages and increased social inequalities. Practices related to soil and water management, crop management services, process transformation and crop diversification must be shared and disseminated among farmers in favor of a more sustainable future [62], [104].

Some agricultural practices emit large amounts of greenhouse gases [62], [105]. On the other hand, these emissions harm agricultural production by raising the temperature, affecting the physiology of plants and making them more sensitive to pests and diseases [106]. Climate change may require zoning of coffee crops for more suitable areas, an option may be to cultivate in areas of high altitudes and mild climates [80]. More substantial changes will be a challenge especially for smallholders, who have little access to knowledge networks, little organizational support and financial resources. Smallholder farmers will need collective action schemes that support new policies, incentives, and market formations [107]. One of the main challenges is to convince small producers to use complex technologies that do not offer significant results in a short period of time. The technological implementation and the transformation of management depends on the characteristics of each producer, making it impossible to create a plan of general recommendations.

The challenges related to climate change and difficult technological introduction can reduce agricultural yields and create an operating risk that makes it unsustainable to cover production costs, financially collapsing many producers [93]. In this context, a new way of thinking about agriculture is necessary to seek ways of production that do not harm nature. A4.0 strategies can be a way to world food security, reduce consumption and waste, and ensure a sustainable production with less environmental impact.

B. FUTURE TRENDS

The sensitivity and vulnerability of the agribusiness sector in relation to climate change directly impacts the economy, health and people's level of poverty, and also generates food insecurity and large losses for agriculture [108]. Environmental concerns raise the requirements for sustainable cultivation and processing, reuse and recovery of waste, and ecological solutions for sustainable development [45]. In this sense, financial or technological contributions are important alternatives to help farmers with limited capital obstacles, limited levels of knowledge and skills and environmental changes, factors that affect farmers' income, quality of life and productivity [109]. Following the pace of globalization, the coffee sector needs to integrate the cycle of sustainable development, producing in a way that meets the social, economic and environmental pillars of sustainability through an integrated production [110].

Our results show the works related to sustainability and A4.0 in the coffee sector, as well as the impacts on the environment, economy and society. The coffee sector urgently needs methods and technologies to improve productivity, quality and sustainability [80]. This seems to be happening since our findings (Figure 3) show that emerging technologies and techniques are gaining momentum, however future studies should be conducted in order to mitigate disappearance of such cluster.

In this sense, geospatial analysis can help farmers in the management of crops and resources with less environmental impact [80], [111]. A4.0 is an alternative that propose technologies and strategies that can improve the efficiency, rentability and sustainable development of the agribusiness [84]. Approaches such as climate-smart agriculture (CSA) and sustainable intensification (SI) are alternatives to improve the information flow, risk management and systems integration in the coffee sector. In addition, the knowledge about climate, soil and plant variables such as potassium, zinc, clay and available nutrients (Figure 3) can directly impact the quality of the coffee produced. Therefore, technologies are important allies for collection, analysis and management of production variables.

Exploring the environmental pillar of the strategic diagram, it is possible to see that Agroforestry systems (AS) (Figure 3) is another theme related to promote sustainability in the coffee sector which represents the integration between woody vegetation and crop or animal production to achieve ecological and economic benefits [112], [113]. The climate change is one of the main reasons for research related to shading and agroforestry to protect plantations [96]. AS is a way to transform traditional agriculture towards a sustainable agricultural system capable of conserving biodiversity and nature [113]. AS has been used as solution to improve coffee production and environmental protection. This approach is largely related to data processing, monitoring and manage of data and resources.

To achieve sustainable production, the coffee sector must adopt integrated coffee production programs to monitor diseases, use of pesticides and environmental problems in order to assist in decision making and increase the quality required by the international market [110], [114]. These challenges increase the search for smart ways to manage coffee cultivation and mitigate the effects of climate on production and the effects of production on climate. In this scenario, the technological adoption may be easier to implement than migration of crops to favorable regions and climates or development of more resistant varieties [39].

VII. CONCLUSION

In this study, we revised PA techniques and A4.0 technologies in the coffee sector through an SLR supported by a BNPA. We identified the strategic themes of the field of study and the most used A4.0 technologies. In addition, we presented the main challenges and trends in the field of study.

A. LIMITATIONS

Despite the breadth of this work, its limitations must be mentioned. Although this review used the Scopus and WoS databases, other databases (e.g, Science Direct, Scopus, Google Scholar, etc) can be explored to identify more related documents and their reports of applications, gaps and challenges related to technological adoption in coffee systems. In addition, we present only the thematic network structures of the clusters related to the most used technologies, in this sense, future works could explore the thematic evolution structure of other topics related to the field using SciMAT. Besides, future analysis should be conducted using other bibliometric software such as VOSviewer, Sci2Tool, CiteSpace, etc, in order to compare results with other perspectives.

B. SUGGESTIONS FOR FURTHER RESEARCH

Although researchers have explored issues of implantation of emerging technologies in coffee production, little attention has been directed to best practices for modelling smart processes. The adoption of smart technologies and processes changes the organizational structure and culture, highlighting the need for a structure to model production processes to automate and avoid losses and errors. In this sense, the development of models and systems capable of synthesizing the organizational needs to adapt processes and implement new technologies is a gap and a fundamental pillar to the transformation of traditional farms into smart farms.

The use of technologies in the coffee sector is still incipient, and no work has presented the economic feasibility and operating costs of adopting technology for smart agriculture. This analysis must be done in different scenarios and coffee production systems, based on different technologies and processes. The holistic vision of farmers about the use of PA techniques and A4.0 technologies in the coffee sector has hardly been addressed. Besides that, researchers have not been to establish the technological integration between farmers, intermediaries and customers to improve communication, logistics and waste management, strengthening the social and environmental sustainability. In-depth research on the impact of technologies on crops is also required to determine measures and identify environmental protection actions. Technologies such as ML, IoT, AI, Big Data and analytics, simulation, blockchain, autonomous robots and cloud

TABLE 2. Related works.

Article	Theoretical / Empirical	Focus	Technique / Technology	Country
[85]	Empirical	Analysis of fruit yield and detachment force in coffee planst.	Geostatistics	Brazil
[86]	Empirical	Analysis of the spatial variability of fertilizers.	Geostatistics	Brazil
[115]	Empirical	Analysis of soil chemical properties.	Geostatistics	Brazil
[88]	Empirical	Spatial and temporal variability of soil nutrients.	Geostatistics	Brazil
[100]	Empirical	Analysis of the electrical conductivity of soil.	Sensors	Brazil
[80]	Empirical	Analyze of soil and plants attributes.	Geostatistics	Brazil
[89]	Empirical	Analysis of the spatial relationship between nutrients and soil density.	Geostatistics	Brazil
[83]	Empirical	Analysis of soil attributes (bulk density, clay content and others).	Geostatistics	Brazil
[93]	Empirical	Analysis of the nutritional status of coffee using leaf macro and micronutrient contents.	Geostatistics	Brazil
[101]	Empirical	Analysis of the level of soluble solids and spectral signature of the fruits and correlate this with the global quality of the beverage.	Sensors	Brazil
[92]	Empirical	Analysis of soil properties and apparent electrical conductivity.	Geostatistics / Sensors	Brazil
[84]	Empirical	Measurement of the detachment force of green and ripe fruits.	Geostatistics	Brazil
[94]	Empirical	Spatial distribution of soil chemical attributes	Geostatistics	Brazil
[116]	Empirical	Analysis of the spatial variability of the productivity and nutrients.	Geostatistics	Brazil
[96]	Empirical	Thermography analysis to estimate stomatal conductance of Coffee arabica.	Thermography	South Africa
[99]	Empirical	Aerial images to detection of fruits in coffee crops.	Machine Learning	Brazil
[78]	Empirical	Análise de parâmetros biofísicos e sensoriamento remoto para discriminar plantas saudáveis e infectadas.	Sensor	Brazil
[117]	Empirical	Development of sensor for measuring soil apparent electrical conductivity in mountainous areas and small farms.	Sensor	Brazil
[7]	Empirical	Integration of sensors, cameras and GPS for crop monitoring.	Sensor	Colombia
[28]	Empirical	Spatial distribution of plant attributes such as productivity, maturation index, detachment force and others.	Geostatistics	Brazil
[60]	Empirical	Prediction of robust coffee productivity based on climate and soil characteristics.	Artificial Intelligence	Vietnam
[90]	Empirical	Analysis of soil physical quality for coffee production.	Geostatistics	Brazil
[91]	Empirical	Analysis of critical zones of soil compaction.	Geostatistics	Brazil
[57]	Theoretical	The review on alert systems for diseases and pests for managing smart farms.	Machine learning	-
[59]	Empirical	Deep learning to assist in the identification of defective coffee beans.	Deep learning	Taiwan
[58]	Empirical	Analysis of the water content estimation in plants.	Machine learning	United Kingdom
[118]	Empirical	Multispectral remote sensing to map coffee plant variables.	Remote sensing	Brazil
[81]	Empirical	Proposal for an IoT architecture for the integration of agricultural management systems.	Internet of Things	Ecuador
[102]	Empirical	Use of hyperspectral imaging to predict soil variables.	Hyperspectral image	New Guinea
[79]	Empirical	Evaluation of vegetation through computational image processing.	Image processing	Honduras
[98]	Empirical	Collection and analysis of aerial images for application of machine learning and identification of diseases in coffee crops.	Machine learning	Brazil
[97]	Empirical	Remote sensing and deep learning to identify leaf rust and diseases in coffee crops.	Remote sensing / deep learning	Colombia
[77]	Empirical	Use of drones for crop growth monitoring.	Drones / sensors	Brazil

computing, among others can be used to improve productivity and sustainability of the coffee sector. In summary, the technological adoption is inherent and necessary in the process of globalization and sustainable development, and can be the catalyst to revolutionizing the coffee industry.

ANEXO

See Table 2.

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