Shaping the Future of Cold Chain 4.0 Through the Lenses of Digital Transition and Sustainability

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Abstract— **The digitisation of supply chain management lies at the crux of modern industry and similar trends are noticeable in the cold chain (CC) under the cold chain 4.0 (CC 4.0) concept. However, the extant research lacks a systematic summary of existing findings on CC 4.0. Therefore, this study provides a bibliometric and network analysis of 618 high-quality CC 4.0 publications extracted from the Web of Science (WoS). The study uses performance assessment and science mapping to investigate the impact of digital and sustainable technologies in the CC domain. Four main research streams and 19 research propositions are identified to provide an informative overview of the most recent developments in the emerging and growing domain of CC 4.0 and the interface between information systems and operations management. The study further identifies the critical role and impacts of digital-sustainable transformation and presents an agenda for future research focusing on critical theoretical and managerial areas that remain understudied.**

Index Terms— **Cold supply chain management; digital transformation; Industry 4.0; logistics; perishable products; pharmaceutical cold chain; sustainability management**

I. Introduction

THE cold chain (CC) has significantly contributed to curbing perishable product waste [1][2], but numerous challenges threaten its overall sustainable performance. These include high energy consumption, carbon emissions, contamination, product deterioration due to temperature mismanagement, high costs, ineffective collaboration and coordination between partners, lack of real-time data sharing, labelling, packaging, and traceability errors [3]. Additionally, CC accounts for 30% of the global energy consumption [4] and 1% of global greenhouse gas emissions [5].

To this end, Industry 4.0 could offer promising solutions as it integrates networking, computation, and physical processes, while including a wide array of technologies, such as blockchain, cloud computing, mobile devices, radio-frequency identification (RFID), Internet of Things (IoT), robotics, big data, cyber security, machine learning, augmented reality, artificial intelligence (AI), smart sensors, and additive manufacturing [6][7][8][9]. The term Logistics 4.0 has been coined to refer to 'the specific applications of Industry 4.0 in the era of logistics and was created as an integral part of the Industry 4.0 concept' [10]. In the CC area, this technological shift could improve traceability capabilities, temperature management, and thus sustainability through value chain optimisation, cost reduction, energy saving, resource conservation, and health risk reduction [11][12].

The promising features of cold chain 4.0 (CC 4.0) make this research area burgeoning. Theories and practices about CC 4.0 have enhanced the overall understanding of the research field. Systematic reviews and empirical and conceptual studies have also been conducted. For instance, Ding [13] studied the barriers to sustainability of CC and how Industry 4.0 could be implemented in the sustainable CC context. Furthermore, Badia-Melis et al. [14] demonstrated the advantages and disadvantages of CC 4.0 for traceability purposes. Some researchers have investigated the role of smart packaging [15] and RFID [16][17][18][19]. Some scholars have developed traceability models using RFID and IoT sensor technology [20], or RFID and the Electronic Product Code (EPC) Network [21][22][23], while others have reviewed the opportunities and challenges of integrating sensing data into decision support systems [24] and electronic data interchange (EDI) [25]. Bottani et al. [26] evaluated the environmental sustainability of RFID technology using a life cycle assessment methodology.

Despite the promising developments in CC 4.0, the research area lacks a holistic summary of its advancements and trends. Previous studies have advanced CC 4.0 knowledge by mobilising various disciplines, viewpoints, and research patterns. Nevertheless, the extant literature is not adequately theorised and the diversity of the methods used remains unclear. Currently, no study has combined both qualitative and quantitative approaches to link the influential contributions of CC 4.0. In addition, the CC 4.0 scholarship is fragmented into several sub-disciplines, leading to the absence of a coherent perspective of the domain. This is challenging because it

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hinders multiple stakeholders from thoroughly appraising the complex CC 4.0 domain, identifying suitable solutions for significant problems, and finding relevant theoretical and applied solutions.

With the exponential growth of the literature, bibliometric and network analyses have emerged as valuable alternatives to systematic literature reviews for evaluating the current status and identifying emerging and established research areas [2][27]. Moreover, such analyses inform stakeholders about the state of a research field in terms of journals, authors, countries, relevant topics, and research areas. In addition, such analyses yield clusters of influential authors and publications to comprehend the dynamics of a specific research stream and its corresponding knowledge base [28]. Finally, past research has highlighted the importance of mapping and organising prior research on a rapidly developing research domain to understand its trends and implications for scholars and practitioners. Both bibliometrics and network analysis may contribute to this objective in CC 4.0. Hence, this study intends to fill the research gaps mentioned above, specifically those related to the absence of a broad outline of CC 4.0, by employing a robust analytical approach and providing thematic quantitative and qualitative insights of CC 4.0 research through bibliometrics and network analysis.

Accordingly, the study contributes significantly to the current knowledge on CC 4.0 because it: (1) provides a structured summary of CC 4.0 research; (2) highlights temporal trends in publications, most active and influential papers, journals, research institutions, countries, most prolific and cited authors, and most commonly used terms; (3) uncovers the research scopes, methodologies, and empirical concerns covered by extant research; (4) discovers impacts, explores themes and topics, and develops fundamental relationships between them through citation information; and (5) underlines key outcomes from past research to pinpoint new research opportunities and propose an agenda for future research. While conventional reviews are based on 50–150 articles, this study extends beyond by using the Web of Science Core Collection.

II. Methodology

A. Bibliometrics and Co-citation Analysis

Bibliometrics is a set of mathematical and statistical methods employed to critically study and assess the evolution of past studies in a specific research domain [29]. This methodology is instrumental in examining a research topic's structure, characteristics, and patterns [30]. Additionally, it outlines future research avenues and guides scholars in bridging the existing research gaps. The methodology draws on a rich corpus of tools and perspectives from library and information sciences to assess past research developments on a given topic and across various disciplines [31]. We employed the widely recommended research methods for bibliometric and network-based review research as defined by Merigó et al. [31] and Shashi et al. [2]. Bibliometrics mainly includes a performance assessment and science-mapping approach.

The performance assessment approach grasps the dynamic characteristics of past publications, namely year-wise research progress; the geographical distribution of research; top publishing and citing journals, institutions, and countries; leading prolific and impactful scholars; and the most frequent keywords in the research field. Furthermore, it counts the citations of specific articles to highlight their comparative role in the growth of the research field. Moreover, the science-mapping approach includes co-citation analysis to explore hidden research patterns. Co-citation analysis may illustrate the similarity of content and therefore assist in uncovering clusters of research areas and scholars and how and to what extent they may be related to each other [2], thus facilitating the proposition of a theory-based agenda for future research [3].

B. Material Collection and Selection

In this study, the Web of Science (WoS) repository was used to extract high-quality bibliographic records on CC 4.0. WoS is primarily a quality-oriented repository, followed by Scopus and Google Scholar [32]. It comprises extensive coverage of citations and bibliographic records from various research disciplines. WoS consists of multidisciplinary citation information from approximately 80,000 books, 18,000 high-impact journals, 180,000 conference proceedings, and more than one billion cited references. The comparative advantage of WoS over other datasets is greater consistency and standardisation in recording publications [33]. Although Scopus and Google Scholar include more publication outlets than WoS, they are less influential [34].

Additionally, the publication outlets in the Thomson Reuters WoS have impact factor values in the Journal Citation Reports (JCR). Furthermore, researchers (e.g. [2]) have claimed that employing a single database avoids the homogenisation bias of using different databases for bibliometric studies. Finally, this study performs a co-citation analysis by utilising the reference lists of sample articles to identify other relevant scholar communities and literature that might have been overlooked in conventional literature reviews [2]. Consequently, we also identified, studied, and reviewed additional articles not included in WoS, but available in different databases (e.g. Scopus, K-Hub, EBSCO, and ProQuest). We relied primarily on WoS and extended our search to other databases based on this premise.

A string of keywords and boolean operators ('Industr* 4.0' OR 'Smart' OR 'Integrated industr*' OR 'Connected industry' OR 'Industrial internet' OR 'Internet plus' OR 'Internet of things' OR 'IoT' OR 'Internet of Services' OR 'Cyber-physical system' OR 'RFID' OR 'Senso*' OR 'Machine-to-machine communication' OR 'Mensch-Maschine-Interaktion' OR 'Big data' OR 'Radio-frequency identification' OR 'Cyber-physical system*' OR 'Cognitive computing' OR 'Radio Frequency Identification' OR 'Cloud computing' OR 'Advance analytics' OR 'Artificial intelligence') AND ('perishable' OR 'cold' OR 'refrigerated' OR 'fresh' OR 'frozen ' OR 'temperature') AND ('supply chain*' OR 'logistics') was used to retrieve records from the WoS database, searching these keywords in the title, abstract, or keywords. The asterisk indicates plural terms or values for any number of characters. We restricted our literature search to 1991–2020. The rationale is that WoS yielded no publication on the CC 4.0 domain before 1991 [35]. Subsequently, we considered only papers written in English and peer-reviewed full-length articles and reviews, excluding other types of articles (e.g. early access, book chapters, editorial notes, conference proceedings, books, technical notes, professional reports, and articles). Consequently, we selected 627 sample articles in August 2020. Further, we manually checked the sample and retracted nine articles as they were found irrelevant. Meanwhile, articles from England, Scotland, Wales, and Northern Ireland were reclassified under the United Kingdom (UK). The final sample selected for further analysis comprised 618 articles published by 2,028 authors affiliated with 671 institutions in 63 countries and published in 438 sources, citing 14,895 references.

Fig. 1 shows the methodological classification of the 618 sample articles. There were 230 experiments, 165 literature reviews, 77 conceptual studies, 44 mathematical modelling studies, 32 survey-based studies, 32 case studies, 26 mixed-methodology approaches, and 12 interview-based studies.

III. Performance assessment

Since the beginning of the 21st century, the academic productivity of global CC 4.0 research has grown significantly. Fig. 2 presents the extent of literature published on CC 4.0 between 1991 and August 2020. The analysis of the sample indicated a growing research interest, especially in the last eight years, since 2014. The most fruitful year was 2017 with 84 topical articles. The growth in the number of publications occurred in three stages. The first stage spanned from 1991 to 2006, when topical research was burgeoning. During these 16 years, 28 articles were published, representing only 4.50% of the total sample.

However, no papers were published between 1992 and 1996. In the second stage, during 2007–2014, the research grew moderately. Consequently, 180 articles were published, representing 29.12% of the total sample. Lastly, a sharp increase in academic interest was observed during the third stage, ranging from 2015 to August 2020, with 410 articles (66.34%) being published.

This exponential growth suggests that the causes and consequences of massive perishable product waste have become a rising topic of interest, explored from multiple disciplines and perspectives, especially emphasising how technology (4.0) can solve this issue. Based on the preliminary results, it is expected that this research area will continue to attract unabated growth in the following years, as it is yet to penetrate the maturity stage.

A. Influential regions, authors, and institutions

Analysing authors' countries and regions of origin can provide insights into the growth of research centres, research groups, and schools of thought. Countries or regions affected by or reliant on CC 4.0 may be particularly interested in studies at the regional or national levels. In addition, institutions and individual authors publishing on this topic play a role in developing connections between research interests and disciplines. Thus, CC 4.0 is a cross-disciplinary subject, and in the following sections, we investigate which disciplines have contributed the most to its recent growth.

1) Performance of countries and regions

From a geographic perspective, it can be found that 618 articles on CC 4.0 originate from 63 countries, belonging to four () continents. There was a greater geographic breadth of scientific publications, as the 20 most productive countries were responsible for 88.18% of the world's total literature. China's contribution (154 articles) outperforms that of other countries, followed by the United States (77 articles). China's first place can be related to the series of food and drug adulteration incidents (i.e. making something inferior in quality by adding another substance) that occurred in China, prompting the Chinese government and industries to focus on CC digitisation [36]. Recently, 52 traceability system regulations and laws have been introduced in China [37]. While China and India are the world's most populated countries and the safety of perishable products is of utmost importance, there is a vast difference in research focus. China accounts for 24.91% of the total CC 4.0 research, while India's contribution is 3.55%. This may be due to India's persistent challenges in modern technology adoption compared with China [38]. The United States published half the volume of papers published by China but has emerged as the most impactful, with 857 citations. Similarly, Italy published approximately four times fewer papers than China, but its impact (788 citations) was higher than that of China (749 citations).

2) Performance of authors

An Academic scholars' publication quantity indicates their strength and effectiveness in their research work. Thus, a scholar's total number of articles is considered one of the key performance indicators for mapping the scholar's influence in the domain [39]. A total of 2,028 scholars have published 618 articles. Of these 2028 scholars, 89.54% have authored/co-authored one article on the topic. This indicates that CC 4.0 is an area of expertise for a few scholars. Y.P. Tsang from Hong Kong Polytechnic University (Hong Kong) has the most significant number of articles (six), followed by Reiner Jedermann (University of Bremen), and Ricardo Badia-Melis (Universidad Politécnica de Madrid).

Concerning the impact of 3 prolific authors, Reiner Jedermann's CC 4.0 work has attained prominent citations (199 citations), followed by Ricardo Badia-Melis (181 citations), and Luis Ruiz-Garcia (142 citations). In addition, these three authors attained the highest average number of citations per article. Based on these results, it can be concluded that these authors have contributed significantly to the development of the CC 4.0 domain.

3) Performance of institutions

Articles published by authors affiliated with different institutions worldwide were analysed to identify the most influential institutions in the CC 4.0 field. In total, authors from 671 institutions have published articles in the sample. Among them, 84.14% of the institutions published only a single article. The top 15 institutions accounted for 126 articles (20.38% of the total sample). China Agricultural University appeared to dominate the CC 4.0 domain. In this line, it produced the highest number (28) of published articles, followed by Hong Kong Polytechnic University (Hong Kong) and the University of Bremen (Germany), both having published 10 articles each.

Subsequently, we analysed institutions that enjoyed the highest impact by citations. Consistently, China Agricultural University emerged as the most impactful institution with 308 citations, followed by Wageningen University and Research Center (Netherlands) and the University of Sheffield (United Kingdom) with 283 and 271 citations, respectively. For average citations per article, the University of Sheffield is the most impactful with 135.5 average citations per article, followed by EmpowerTech Inc. (United States), RFID European Lab (France), and Technical University of Munich (Germany) with 49.00, 47.50, and 42.25 average citations per article, respectively.

B. Performance of journals

We further analysed the leading journals that published research on CC 4.0. A total of 618 articles appeared from 438 different sources, indicating an average of 1.41 articles per journal. Most journals are engineering- or technology-based research journals. Fifteen journals published 119 sample articles representing 19.25% of the overall published literature. The journal *Trends in Food Science & Technology* paid early attention to this field. *Computers and Electronics in Agriculture* (15 articles) published the most articles, followed by *Food Control* (14 articles), and achieved continuous progress in recent years. Similarly, *Sensors*, *Journal of Food Engineering*, *International Journal of Production Economics*, and *Applied Sciences* are other leading journals with 10, 9, 8, and 8 articles, respectively. The year-wise publication growth pattern highlights that these journals started paying attention to CC 4.0 in 2007.

Next, we summarise the most impactful journals in terms of average citations and total citations per article to evaluate their influence. We considered only journals with at least two published articles for this ranking. For authors, this analysis highlights that leading journals in terms of the number of articles published are not necessarily the most impactful ones. In addition, articles published in these 438 journals were cited 4,124 times. This high number hints at the multidisciplinary nature of safety culture research and the wide variety of research themes. Regarding citations, *Food Control* is the most impactful journal with 363 citations, followed by *Renewable & Sustainable Energy Reviews* (272 citations), *Philosophical Transactions of the Royal Society A-Mathematical Physical and Engineering Sciences* (218 citations), *Journal of Food Engineering* (191 citations), *and Computers and Electronics in Agriculture* (181 citations). Concerning the average citations per article, *Renewable & Sustainable Energy Reviews* is the most impactful journal with 136.00 average citations per article, followed by *European Journal of Operational Research (*43.50 citations per article), *Food and Bioprocess Technology* (38.00 citations per article), *and Philosophical Transactions of the Royal Society A-Mathematical Physical and Engineering Sciences* (36.33 citations per article). This analysis shows that this field is a multidisciplinary research area distributed across various journals and covers diverse research domains. However, journals publishing CC 4.0 literature relate primarily to engineering, computer sciences, agricultural, and biological sciences.

C. Citations performance of articles

It is generally assumed that citations show an article's influence and impact and, hence, its quality. Therefore, the higher the citations of an article, the greater its impact and contribution towards developing the body of knowledge [2]. In this context, evaluation of citation performance of articles enables identifying the most impactful articles that have contributed the most to field enrichment. In total, 618 sample articles were cited 4,124 times. The 30 most-cited CC 4.0 articles have been cited 1,771 times, representing 42.94% of all citations. The article entitled '*Recycling of WEEEs: An economic assessment of present and future e-waste streams*' [40] appeared to be the most impactful, with 261 citations in WoS. Interestingly, among these 30 top-cited articles, none was published before 2012. This means that CC 4.0 papers published in the last eight years are more impactful than articles published before 2012. Furthermore, the results reveal that at least two researchers co-authored all of the most cited articles. The higher numbers of co-authored articles indicate a stronger association between scholars within similar fields and more significant opportunities for future collaboration.

D. Keywords analysis

Keyword analysis was performed to explore the prevalent themes in the CC 4.0 literature. This study reveals important research subfields and identifies trending topics in scientific research. This assessment further establishes inferences regarding research priorities. A pool of 2,303 keywords was identified in the sample. This larger pool was substantially reduced by establishing an occurrence frequency threshold at a minimum of 5. In total, 106 keywords were identified. We classified the keywords into two themes: general and technology based. A panel of five leading CC researchers and five CC managers was appointed for this classification. A list of keywords was given to the panel and it was requested to classify the highly-cited keywords. The panel evaluated the scope of each keyword and classified them into two groups: general and technology based. Table 1 lists the 10 most frequently cited keywords for both themes. Notably, the cumulative occurrence frequency of general keywords (568) was relatively higher than that of technology-based keywords (343).

IV. Science Mapping

Next, science mapping was performed. It demonstrates the intellectual connections within the changing landscape of the scientific knowledge system. This mapping depends on graph theory to explore the data structure [41]. In the academic literature, different approaches are available to develop intellectual connections. For instance, it is possible to draw the network structures of authors, journals, countries, institutions, and articles. However, researchers have advocated co-citations of article references and authors as the most imperative structures [42]. Co-citation measures the correlation between two articles that address similar subject areas [42]. It facilitates the exploration of existing research topics discussed in previous years and enables future research avenues. Co-citation visualisation can help to understand tie strength within the entire network and how a specific citation is positioned within the field [43]. The network comprises edges and nodes. Each node represents an article. The thickness of the edge between the two nodes represents their co-citation frequency. Thicker edges indicate a higher co-citation frequency for any pair of articles. Node size represents the total number of citations received by the article.

This study performed a co-citation analysis of references and authors. We employed VOSviewer, a text-mining tool based on the VOS algorithm, which visually depicts similarities between given objects (i.e. citations) [44]. VOSviewer aims 'to provide a low-dimensional visualisation in which objects are located so that the distance between any pair of objects reflects their similarity as accurately as possible' [44]. The distance between two nodes indicates their relatedness [28]. Furthermore, we thoroughly analysed the co-cited articles and authors.

A. Co-cited authors and co-citation analysis

This section presents the most co-cited authors from a sample of 618 articles. In this line, 11,324 cited authors were identified. To improve the network presentation, we lowered the number of authors by applying a minimum of 15 citations. This resulted in the identification of 53 most co-cited authors. Subsequently, as group authors, we performed network analysis according to similar research interests [2]. Fig. 3 shows the three clusters, and Table 2 provides detailed information. The results confirmed 'Jedermann R and 'Ruiz-Garcia I' (108 co-citations) as the most co-cited authors, followed by 'Jedermann R' and 'Gurbbstrom, RW' (88 co-citations); 'Jedermann R' and 'Defraeye T' (76 co-citations); and 'Jedermann R' and 'Badia-Melis R' (69 co-citations). Fig. 3 shows three clusters of three different colours. Each node refers to an author and the node size represents the number of citations. The edge thickness between the two nodes reflects their degree of sharing similar characteristics. There were a few leading CC 4.0 authors within each retrieved cluster. These authors are responsible for the substantial development of CC 4.0.

For instance, in Cluster 1 (red), Abad specialises in RFID smart tags for traceability and CC monitoring. Atzori advances knowledge about the use of IoT. Aung is another impactful author who has contributed significantly to developing a deep understanding of effective temperature management through an accurate traceability system to reduce unsafe product production and distribution. Regattieri's work highlights the legal and regulatory standpoints of traceability and a system of closed-loop traceability that supports decisions pertaining to CC logistics. Badia-Melis's research summarises a few imperative topics, such as advanced trends in CC monitoring, the dynamic behaviour of CC 4.0 technologies and their effect on temperature management, and how CC 4.0 systems can win customers' confidence by providing clear-cut information about product quality and safety. Costa's work revolves around barriers and opportunities for the broader adoption of RFID. Kang specialises in RFID sensor-tag-based CC simulation models. Ruiz-Garcia investigated technologies for perishable products supply chain (SC), while Verdouw explored virtual SCs through IoT for reliable information systems. Finally, Xiao's contribution is toward enhancing the traceability and transparency of CC logistics through wireless sensor networks (WSN).

Within Cluster 2 (green), Akyildiz's research revolves around the WSN for transmitting sensor data. Giannakourou's work focuses on shelf-life extension and improvement, and the application of shelf-life decision support systems. Both Heising and Yam's contributions clarify opportunities for intelligent packaging to enhance product quality. Kerry extended the literature on new packaging technologies, materials, and formats, and the processing of raw products to curb waste rates. Further, other researchers specialise in challenges and perspectives on advanced processing, distribution, and storage technologies and the application of time-temperature integrators to monitor product quality (e.g. Koutsoumanis and Rabb). Kumar's research focused on third-party logistics selection for CC management. Kuswandi's work covered nanotechnology and sensor trends in product packaging. Labuza's contribution highlights incorrect handling, improper storage, and transport conditions under the CC. The contributions of Tsironi and Taoukis correspond to CC database development and its application, training for shelf-life testing, validation of time-temperature labels, and quality/safety assurance systems.

The impactful authors in Cluster 3 (blue) are Jedermann, who specialises in intelligent food logistics, and Nunes, who specialises in improving logistics quality. Kader's research summarises CC policies, product presentation, quality, and smart packaging. Defraeye specialises in CC performance measurement and virtual CC to assess cooling heterogeneity, package designs, and trade-offs between maintaining product quality and minimising environmental impact. Hertog's expertise is in shelf-life modelling for predicting product quality and atmosphere packaging. Grubbstrom's contribution to inventory management. Dabbene highlighted traceability issues in CC, traceability methods, and optimisation of CC in uncertain environments. Research in this cluster further addresses perishable product waste at different SC levels and related causes (e.g. Gustavsson and FAO).

B. Co-citations analysis of co-cited articles

In the 618-article sample, 14,895 citations were identified. Choosing a proper threshold level is always challenging because a low value will result in a highly crowded network visualisation, whereas a high number could lead to superficial results. Articles with at least nine citations were selected, resulting in the 62 most co-cited articles. Further, co-citation analysis was applied, and Fig. 3 shows the corresponding co-citation network. Fig. 4 further presents the network of the most co-cited CC 4.0 articles, and the associated in-depth details are provided in Table 3. Fig. 4 highlights the four clusters with diverse colours: red, green, blue, and yellow. In addition, it shows how the most commonly cited articles are linked within a similar cluster. The node size indicates the citation frequency of an article. Consequently, the structure facilitates underlining the core articles within each cluster, which further assists in defining the cluster features.

Cluster 1 (red) specialises in temperature monitoring using Industry 4.0. Amador et al. [45] examined the utilisation of RFID in mapping temperature through a comparative analysis of RFID temperature-tag performance with traditional temperature-mapping techniques and their use in CC. Aung and Chang [47] analysed methods to determine an optimal temperature range for multi-commodity cold storage and found WSN to be superior to traditional methods. Badia-Melis et al. [48] investigated the dynamic behaviour of RFID and WSN while describing how they affect the temperature measurements.

Badia-Melis et al. [49] supported the role of WSN and RFID in recording product-specific history (e.g. the location and presence of certain gases, temperature, and humidity) and providing product location, which strengthens the chain of information. Research under this cluster also introduced 2G-RFID-Sys, a system that combines IoT technology with RFID sensor tags to evaluate the temperature in an intelligent CC [50]. Similarly, researchers have developed CC predictor software for effective CC improvement and management [51]. Furthermore, Gubbi et al. [52] proposed a cloud-centric vision for IoT implementation worldwide. Hong et al. [53] explored the financial viability of business models by applying RFID technology to a CC traceability system. Kang et al. [54] designed an RFID sensor tag-based CC simulation model. Kim et al. [55] introduced the idea of quality measurement entitled '*Freshness Gauge*' and developed an algorithm to set the optimal temperature and humidity by highlighting product quality changes. Kuo and Chen [56] presented a CC logistics service framework that considers advancements in multiple temperature joint distribution systems. Qi et al. [57] illustrated a WSN-based CC as a decision support system for shelf-life prediction in a CC management framework. Ruiz-Garcia et al. [58][59] studied the ability of WSN to evaluate the transport conditions and cold storage. Thakur and Forås [60] reviewed the process of an online system based on the EPCIS to evaluate the time temperature and record traceability. Verdouw et al. [61] examined the virtual SC concept from the viewpoint of IoT and introduced an architecture to implement enabling information systems. Wang et al. [62] drew on a ZigBee-standard WSN to develop a real-time CC-monitoring system. Xiao et al. [63] used a WSN integrated with compressed sending to establish a temperature monitoring system for chilled and frozen aquatic products. The objective of this technological arrangement is to improve the efficiency of the temperature-monitoring system.

Cluster 2 (green) focuses on product quality and shelf life prediction. Grunow and Piramuthu [64] studied product-level information generated through RFID from retailer, distributor, and consumer perspectives, emphasising the remaining shelf life and expiry date. In addition, this study focuses on RFID investment decisions. Gustavsson et al. [65] stress that investments are required in the infrastructure, transportation, and packaging industries. Heising et al. [66] reviewed the opportunities for intelligent packaging to map the quality of perishable packed items. In this cluster, research has also emphasised shelf-life modelling for predicting quality changes and remaining shelf life to implement the first-expired-first-out CC approach for warehouse management [67]. Research has also highlighted the unavoidable role of intelligent food logistics. In this context, miniaturised RFID temperature loggers can be employed to examine the extent of local deviations, capture temperature gradients, and predict the number of sensors required for reliable mapping inside trucks or containers [68][69]. Meanwhile, Jedermann et al. [70] looked for a potential solution to technical challenges that still hamper the realistic implementation of WSNs in transport supervision. Laguerre et al. [71] presented a combined deterministic and stochastic model to measure the early product characteristics and operating conditions. Lang et al. [72] discussed a cognitive system based on an intelligent container to record quality losses due to temperature, control sensor density, and identify malfunctioning sensors. Furthermore, a structured model to detect optimal managerial practices to minimise CC logistics costs was proposed by Montanari [73]. Nunes et al. [74] claimed that shelf-life forecasting should not rely on individual quality factors. The quality characteristics that limit shelf life may vary depending on the temperature history. In the context of international transport, Rodríguez-Bermejo et al. [76] conducted a thermal study of a container to determine its temperature distribution. Rong et al. [77] developed a mixed-integer linear programming model in which they integrated product quality and cost parameters to design and operate CC distribution systems. Ruiz-Garcia et al. [78] reviewed WSN benchmarks and wireless communication technologies in the agri-food sector. Finally, Wang and Li [79] proposed a dynamic product quality assessment framework for CC to reduce product spoilage and improve retailer profits.

The intelligent packaging theme in cluster 3 (blue) was the most prevalent. Yam et al. [95] and Vanderroost et al. [94] defined intelligent packaging based on the packaging functions. Furthermore, they reviewed the current developments in intelligent packaging devices (e.g. RFID tags, barcode labels, gas indicators, biosensors, and time-temperature indicators). Taoukis and Labuza [93] studied the most important types of commercial time-temperature indicators. Papetti et al. [92] integrated an electronic tracking system with a non-destructive quality analysis system. Pacquit et al. [91] designed a colorimetric dye-based indicator to efficiently capture the increase in volatile amines as a fish-spoilage indicator. Bibi et al. [81] claimed that RFID tags provide wireless systems for evaluating food packages through tag reads, fostering traceability, while offering instantaneous information about stock rotation and tracking. Costa et al. [82] discussed the opportunities and drawbacks of broader RFID adoption. Similarly, Ghaani et al. [84] described both the technical and commercial implementation of intelligent packaging, and pointed out the aspects restricting the full harnessing of intelligent packaging in the food industry. Kumar et al. [89] defined the key concepts and terms, working principles, and components associated with the RFID system in CC. They discussed various challenges related to its implementation (e.g. reading accuracy, security concerns, recycling issues, reading range, cost, non-uniform standards, and privacy). Kerry et al. [87] examined the potential of RFID, sensor technologies, and indicators (e.g. time–temperature, freshness, and integrity indicators) to be used in CC products, and underlined the benefits of packaging technologies that are active and intelligent.

Cluster 4 (yellow) focused on real-time traceability. Abad et al. [97] built and validated RFID smart tags for monitoring and real-time traceability of CC applications. Aung and Chang [99] provided detailed information on traceability from the viewpoint of product safety and quality. Angeles [98] discussed RFID technologies and their application in SC, and underlined implementation issues. Wang et al. [108] developed an online decision support system and real-time monitoring to enhance the reliability of CC delivery systems. Storøy et al. [107] developed a '*TraceFood*' model, which suggests common principles for the unique identification of perishable items, good traceability practices, standards for the electronic exchange of traceability information, and the interrelationship between data elements. Ruiz-Garcia and Lunadei [106] highlighted the significant challenges in RFID applications, such as extreme temperatures, dirt, harsh environments, the need for longer reading ranges, heterogeneous standards, and vast data volumes. Regattieri et al. [105] studied the regulatory and legal perspectives of the traceability of perishable products and designed a model to identify fundamental functionalities and mainstays. Kelepouris et al. [104] shed light on the significant requirements for traceability, and how RFID technology can meet these requirements. Feng et al. [103] demonstrated the CC's information acquisition, transformation, and transmission process. Bosona and Gebresenbet [102] identified and provided a definition of motivating forces, obstacles in designing and executing traceability systems, advantages, novel traceability technologies, improvements, and performance of food traceability systems. Researchers have provided a novel conceptual definition of traceability system as a crucial logistics element. They concluded that deep knowledge of fundamental processes from legal, technological, and social issues is crucial for developing efficient and complete CC traceability systems. Barge et al. [101] verified the effect of tag type and shape, required antenna orientation and polarisation, power, fixing method, and ripening duration on reading traceability reliability and performance. Finally, Badia-Melis et al. [100] clarified the role of advanced traceability systems at different stages of CC. They claimed that offering detailed information about product quality and safety throughout the CC could also win customers' confidence.

1) Findings and future research avenues

The four clusters derived from the article co-citation analysis have been investigated in detail in Table 4. This table presents the current research themes and suggests an agenda for future research related to each theme. When treated separately, the clusters interacted meaningfully with each other. Specifically, particular technologies and their broader infrastructures (Cluster 1) improve product quality and shelf-life prediction (Cluster 2). These two themes enabled the third and fourth themes. Based on technologies and architecture complemented with proper statistical analysis and modelling - which takes the form of Big Data [109] increasingly- it is possible to implement 'smart packaging' and 'real-time traceability.' The latter two offer valuable opportunities for future applications and research on sustainability and commercialisation, as explained subsequently.

Studies in cluster 1 focused on WSN and RFID as two key technologies that provide better temperature monitoring capabilities than traditional temperature mapping techniques [45][110]. While past research has focused on documenting and improving the application of these technologies to CC, future research should emphasise solving persisting technical hurdles, especially regarding WSN. These include, but are not limited to, increasing the autonomy of WSN (e.g. harsh environment, self-healing, and self-organisation) and the scalability of interconnected WSN (e.g. interconnecting thousands of nodes), operation at low bandwidth, and self-configuration. Regarding RFID, while its performance is comparable and often superior to that of other technologies for mapping temperatures, it still suffers from higher costs [53][84][111].

In line with Hong et al. [53], more research should investigate the routes for financially viable RFID integration within CC traceability systems. The differentiated performance and possible costs of various RFID tags, such as active tags, passive functional tags, passive identity cards, and semi-passive tags [111], could also be explored to improve technical capacity and financial viability. Additionally, similar to many other technologies, WSN and RFID require large quantities of energy to function correctly. With regards to WSN, energy conservation remains a crucial issue. Simultaneously, for RFID, battery technology embedded in specific tags, such as semi-passive and active tags, needs to be improved for further energy efficiency and environmentally neutral battery disposal. These research areas would further establish the much-needed connection between CC 4.0 and the sustainability nexus in operations management to meet product quality, safety, and customer expectations, as suggested by Ivanov et al. [112]. Therefore, the following research propositions (RP) are presented:

RP1: Improving the technical capacities of WSN in terms of (a) autonomy, (2) scalability, (c) low-bandwidth operating mode, and (d) self-configured mode.

RP2: Improving the financially viable application of various types of RFID in traceability systems.

RP3: Exploring additional methods to improve the energy efficiency of WSN and RFID for environmentally neutral impacts.

a) Leveraging on the growing ubiquity of cloud computing and blockchain technology to improve technologies and technological architectures underpinning temperature monitoring

An additional axis researched in cluster 1 refers to the technical architecture and infrastructure for temperature monitoring. This has been widely addressed in the operations literature, which investigated the measures, analytics, and management of time-temperature conditions [113]. While past research in operations and other disciplines has provided valuable insights into the architecture, decision support systems, algorithms, and processes needed to better integrate WSN and RFID technologies in broader networks, integration remains limited. Current challenges pertain to deploying more deeply non-centralised distributed architectures (including IoT architectures). WSN rely on communication architectures that perform data transmission, whereas another type of architecture called 'middleware' refers to deployment issues and application development. There is a need to incorporate other new technologies to strengthen architectures for higher accuracy and access to improve both layers for optimal communication performance from an industry 4.0 perspective. Cloud-centric frameworks have been suggested as a valuable solution [52]. However, research in this area is limited. Therefore, there is a need for refinements of pioneering works in cloud-centric or cloud computing-based CC, such as Gubbi et al. [52], Singh et al. [114], Alfian et al. [115], and Prashar et al. [116], to truly achieve a whole structure akin to the 'Internet of perishable logistics' proposed by Pal and Kant [117]. More specifically, for CC operations management, this would reveal a CC logistics system based on cloud computing, as Li et al. [118] advocated in the early 2010s. In addition, blockchain technology can significantly contribute to this objective. As a 'decentralized and secure database of transactions based on decentralized nodes' [119, p. 86], it would significantly develop such distributed architectures to map temperature while allowing a host of other CC applications in a 4.0 perspective.

RFID networks rely on a multiplicity of protocols that may create undue complexity and errors in mapping temperatures and food products, with the risk of being hacked. Protocols need to be more secure, lightweight, and simplified while remaining efficient to integrate systems better. In this regard, novel perspectives have emerged recently, such as 'hash-based RFID mutual authentication protocol for context-aware management' [120, p. 1]. Other examples include secure and ultra-lightweight protocols like SECLAP [121] or double PUF-based RFID protocol [122]. Furthermore, the connection with blockchain technology can further be made about protocols because several authors have proposed authentication RFID protocols for blockchain SC [123], as well as (symmetric) cryptography [124] to provide improved, secure, and more straightforward protocols. Although more complex, such mechanisms also integrate well within IoT-based multimedia systems, typical in CC 4.0.

However, research in this area remains scarce, especially given the promising opportunities in these technologies to build complex industrial systems and applications to better monitor temperature and food items. This lack further hinders the development of operations management, as it impedes efficient OM and IS interfaces [125]. Hence:

RP4: Advancing the application of cloud-centric and blockchain-enabled architectures and frameworks for temperature monitoring.

RP5: Leveraging the potentialities of cryptography, hashing, and other technologies to develop more secure, ultra-weight, and more straightforward RFID protocols for temperature mapping in a CC 4.0 context.

b) Harnessing the power of systemic integration and prescriptive analytics in more managerially-sound approaches while improving chain-wide participation in CC 4.0

An essential part of the research in cluster 2 revolves around using statistical tools and methods to predict product quality and shelf life. These tools and methods have been used in the operations management literature (e.g., [126]). However, past research has frequently emphasised the need to integrate these piecemeal techniques into broader systems that can be used for faster decision-making purposes (e.g. [53], [73]). This impetus refers to the need to adopt a more managerial perspective to assist managers in dealing with product quality and freshness more effectively. This would mean transitioning from a descriptive and predictive analytic framework to a more prescriptive one [127], developing valuable algorithms and techniques that predict shelf-life and quality, and inform, recommend, suggest, and assist managers in making decisions. This refers to third-order logistics in monitored CC [67]. The most promising methods to explore and apply in this regard include optimisation, simulation, and heuristics-based decision-modeling techniques [127]. Specifically, they need to be attached to the broader monitoring and tracking architectures typically discussed in the previous subsection to enable sophisticated information-fed decision support systems in operations management and logistics.

RP6: Developing prediction tools that blend broader decision support systems and managerial dashboards to provide a managerial and strategic perspective.

RP7: Transitioning from descriptive and predictive decision-making tools to predictive tools that assist managers in their decision-making processes.

Research in cluster 2 also paved the way for intelligent food logistics with the goal of increasing product quality, which is tantamount to operations management goals [128], because such RFID- and WSN-underpinned systems allow for efficient product and information travel that remain highly contingent upon synchronicity across production, storage, and distribution [67][129]. Thus, this issue requires collaboration between partners; there is a need for standardised formats, languages, protocols, structures, levels of technological adoption, and information beyond operations to enable intelligent logistics. While research in Cluster 2 has significantly advanced the technical means to efficient data and product exchange, much more needs to be done to develop a chain-wide propensity to participate and to contribute to systems that allow high volume, high velocity, wide variety, and high veracity information to be shared across CC members.

RP8: Developing an understanding of the determinants, best practices, and critical indicators of CC partners' willingness to participate in inter-company relations and data exchange for intelligent cold food logistics.

Research in cluster 3 centres on intelligent packaging from two different perspectives. The first approach approaches smart technologies from a technological perspective, while the second delves deeper into the broader ramifications of intelligent packaging: social, financial, or economic. Regarding the first perspective, despite cumulative growth in smart packaging performance, there is still ample room for improvement. In food supply chains (SC), packaging often carries multiple pieces of information, including physical and chemical parameters, error prevention alerts, nutritional values, and diet specificities. Innovative packaging should integrate these functions more effectively to foster smart food SC [15]. For example, biotechnology and biosensors may provide accurate information about glucose, ampers, acids, and fat for sustainable food engineering [130]. In addition, there remains a discrepancy between the results obtained for smart packaging performance in testing or laboratory conditions and those obtained in real CC systems (e.g. the difference in quantities of food packed, pH level, and presence of allergens) [84]. Future research should reduce this gap by increasing performance in real environments.

RP9: Improving the capacity to display multiple information types (i.e. multifunctionality) of intelligent packaging.

RP10: Minimising the technical deficiencies of smart packaging in actual CC conditions.

c) Improving cost-efficiency of intelligent devices and communicating about the features of smart packaging to nurture consumer and public trust

The nomological framework of smart packaging refers to its causes, benefits, barriers, impacts, good practices, and other antecedents or consequences of smart packaging. Worthwhile developments have been made, which contributed substantially to the theory of the field. However, additional research areas remain to be explored. First, smart packaging relies on barcode labels, time-temperature indicators, gas indicators, biosensors, holograms, micro-tags, tear labels, tapes, thermochromic inks, and RFID tags [94][131]. However, some technologies, particularly RFID, are expensive. The cost of intelligent devices is approximately 50–100% of the entire cost of the final package. By contrast, the cost of most food product packages should not exceed 10% of the total package cost [84]. The need to lower the RFID costs expressed in relation to Cluster 1 can be extended to include all intelligent devices for packaging. Alternatively, the cost premium should be justified in light of the superior benefits to the producer, carrier, retailer, or consumer. It is important to target customers because they also need to be educated about intelligent packaging and its features, benefits, and limitations to make informed purchase decisions. If consumers perceive little benefit in smart packaging, they will most likely avoid it and prefer traditional formats. Given the enormous investments needed for smart packaging, ensuring consumer and market acceptance is crucial for financial viability. Apart from consumers, the public and society generally need to trust smart packages. Enacting trust is a complex process because it entails a broad array of measures, such as complying with regulations, eradicating device-food contamination possibilities, or reducing effects on humans and the environment [84][31]. Future studies should therefore explore the acceptability of smart packaging at an individual level using conventional models, such as the technology acceptance model) or UTAUT2 (unified theory of acceptance and use of technology), but also at the macro level using Rogers' [132] diffusion of innovation theory, among many other frameworks.

RP11: Improving the cost efficiency of intelligent devices included in smart packaging.

RP12: Educating consumers about the specificities of smart packaging and assessing their acceptance and potential use of intelligent packaging.

RP13: Developing strategies and approaches to cultivate public and consumer trust in smart packaging.

d) Leverage technology for traceability and sustainability while ensuring consumer and social acceptance

Research in Cluster 4 refers to the paradox between improving real-time traceability capabilities on the one hand while addressing societal concerns and concerns concerning these pervasive technologies on the other. From a technical and performance perspective, continuous efforts should be devoted to improving traceability in CC. In addition, blockchain and algorithm-driven food traceability solutions should be researched more extensively (e.g. [133], mainly because they improve the operation of the SC [134] and, subsequently, inventory management [135]. There is also a strong need to incorporate these tools into a broader decision-support framework for food traceability. Nevertheless, this remains challenging because of the variety of foods accounting for food CC complexity [37]. Consequently, future research should explore new avenues to integrate various tools, food products, and CC stages into a comprehensive traceability framework.

RP14: Leveraging distributed and algorithm-driven food traceability solutions.

RP15: Developing comprehensive frameworks for food traceability.

Addressing traceability issues from a technical viewpoint may reassure consumers at the point of purchase. Consumers are increasingly concerned about food connections and transparency, that is, their origin, production methods, and nutritional value [3]. Traceability could be leveraged to provide them with much needed information about the production, processing, and distribution processes of food items. Although SC traceability has become crucial in operations and SC management, several gaps remain [134][136]. Future research could investigate how consumers are aware of, accept, and process information originating from traceability systems and possibly interact with intelligent packaging (e.g., via QR codes). While traceability and intelligent packaging may contribute to sustainability through augmented traceability, it remains questionable whether intelligent systems used to enable traceability are sustainable and contribute to the overarching concept of sustainable packaging. Future research should investigate the possibility of applying product lifetime extension strategies, including reusing, redistributing, repairing, recovering, renting, and improving product design [137] for longer-lasting intelligent devices. This is particularly important for sensors and tags because of their high volume and ubiquity in CC 4.0. Research should also investigate consumers' role and capacity to contribute to extension strategies for sustainable packaging.

RP16: Exploring consumers' awareness, acceptance, preference, usage, and willingness to pay more for traceable food items.

RP17: Applying product lifetime extension strategies (e.g. reuse, improved product design, recycling, repair, recovery, renting, and redistribution) to intelligent devices used within CC 4.0.

RP18: Investigating consumers' roles, resources, motivation, and capacities to contribute to lifetime extension strategies applied to intelligent devices for sustainable packaging.

Intelligent devices remain controversial from a social and regulatory perspective, while contributing to consumer welfare and meeting sustainable objectives. The key topic in operations and SC management research and interests lies in traceability in production and consumption processes [134][135][136] . However, various challenges have emerged with increasingly ubiquitous, precise, and perceivably invasive technologies, such as blockchain, to ensure smooth operations and SC traceability [134]. Individuals may feel that they have lost their privacy, whereas regulatory frameworks evolve to adjust to these growing challenges. Consequently, regarding the second axis, future research could provide additional knowledge on how society is receptive to intelligent systems for tracing food items.

RP19: Surveying public opinion about the traceability of food items through CC 4.0 from production to consumption.

V. Discussion and Implications

The CC 4.0 has attracted considerable attention among scholars [47][66][69][97][99][116][117][138][139][140](. However, an integrated examination of the research trends and advances in this area is still lacking. Previous studies, such as Shashi et al. [2][3] provided a structured literature review and a bibliometric/network analysis of food CC management. However, these studies did not specifically investigate the connection between food CC and Industry 4.0, and were limited to food CC, while CC is much broader, including pharmaceuticals/drugs. Sharma et al.'s [8] systematic literature review on machine learning applications for sustainable agriculture SC performance comes closer to integrating CC and Industry 4.0, but focuses exclusively on the ML subset of Industry 4.0, although the latter has a much broader scope (e.g. RFID, IoT sensor technology, blockchain technology, mobile devices, and cloud computing). Such reviews lack comprehensive coverage of the literature connecting CC to those diversified technologies (such literature would typically include, for example, [6], [7], [8], [9]). In addition, similar to Shashi et al. [2][3], Sharma et al.'s [8] study focused on the agricultural sector. Therefore, the current study differs markedly from past research in that it takes a broader perspective to investigate the embedding of CC – in general – into Industry 4.0, defined as an overarching concept that includes a great diversity of technologies.

The study also differs from past research (e.g., [3], [8]) by recoursing bibliometric and network analyses instead of systematic or structured literature reviews, as bibliometrics and network analyses have been proven to offer more valuable alternatives to evaluate the current status and identify both emerging and established research areas [2][27][141]. This is particularly noticeable in CC 4.0 research area. None of the review-based contributions have comprehensively summarised this field. The major drawback of employing traditional methodologies (e.g. systematic or structured literature reviews) for conducting review studies is the dependence on tendentious shortlisting of a few articles, which may result in bias and flaws in the findings owing to incomplete analysis of vital aspects [142]. However, bibliometric and network analyses overcome the different biases caused by traditional methodologies. Moreover, it fully covers the literature set and can quantitatively explore intellectual structures, research hotspots, and provide new insights into specific scientific fields [142]. Accordingly, this study provides a comprehensive overview of the latest evolutions in applying Industry 4.0, technologies to CC processes, by summarising 618 research articles.

This study explores the evolution of new technologies such as IoT, RFID, sensors, blockchain, and so on in the CC context, while presenting major technology enablers and defining IoT in SC management. The study further provides a bibliometric analysis conducted on a representative sample of the CC 4.0 literature using the performance assessment and science mapping approaches. This allowed us to analyse the development of the CC 4.0 research field across countries, journals, and authors and obtain compelling insights into the conceptual and content roots of the field. As a result, four main research streams were identified, and 19 research propositions that future researchers can address contribute to the theory by delineating the key research themes emerging from the literature on CC 4.0. Thus, this review provides an informative overview of the most recent developments that have taken place in this emerging and growing area of CC 4.0, which is of interest to both researchers and practitioners.

This review revealed an emerging trend in the scientific community that refers to integrating new technologies into CC to address important objectives and achieve superior sustainability and productivity performance. Preliminary applications and implementations of emerging technologies of the Fourth Industrial Revolution have been discussed in different contexts, such as temperature monitoring and real-time track-and-trace activities, showing a positive impact on their purposes. These results highlight new challenges in managing CC issues. The analysis has shown that these technologies significantly reduce uncertainties because they provide precise data in real time, whereas tools providing such real-time information offer new opportunities for organisations to react quickly in the face of changing conditions in SC. Consequently, more efficient and effective CC management may reduce energy consumption, leading to more sustainable CC.

In this vein, future policymakers should focus their attention on the application and scalability of Industry 4.0, in real-world cases, to improve the management of SC from three sustainability perspectives–economic, environmental, and social–in an integrated view. It is recommended that additional real-world applications and practically oriented research incorporate different Industry 4.0 technologies into SC and manufacturing systems. These technologies produce a large amount of data, and special attention should be paid to the identification of formal methods and strategies to extract and formalise knowledge created by the integration of the different technologies and investigate how they differentiate from the existing solutions and impact the challenges of increasing resilience, flexibility, sustainability, agility, and efficiency along with the whole SC from the manufacturers to the final customers. In this sense, an investigation of the SC scenario, where disruptions frequently and significantly affect perishable products and CC resilience, can be an interesting future research avenue for identifying policy implications.

Furthermore, the study offers additional evidence on different areas and methods of Industry 4.0, executions in CC, and possible outcomes, improving managers' awareness and understanding before executing it as a strategic intervention. More specifically, managers can obtain detailed insights on diverse aspects such as CC monitoring and modulating systems; legal, regulatory, technological, and social considerations of traceability; CC predictor software for optimised CC management; active and intelligent packaging technologies; technical and commercial implementation of intelligent packaging; electronic fresh food spoilage indicators; benefits of advanced traceability systems for consumers; CC shelf-life decision support system for CC management; and RFID for traceability and stock rotation. Reviews published in the past have not simultaneously covered these wider CC 4.0 perspectives. A deep understanding of the areas mentioned above would assist managers in the conceptualisation of effective CC 4.0 strategies, and their execution will offer numerous benefits in terms of solid CC relationships, information sharing, limited wastage, customer satisfaction, and business growth. As the business environment is characterised by increasing competitiveness, deregulation, and constantly evolving customer demand, the traditional approaches, even in primary sectors, may no longer allow CC companies to remain profitable, and technological innovations can solve such a complex environment. Therefore, managers need new ways to stay ahead of competition, which can be achieved by fully exploiting the potential of Industry 4.0. Likewise, CC managers should collaborate with prominent research institutions in emerging Industry 4.0, areas that need solutions. Future research should focus on promoting and fostering technological innovation processes involving all CC partners working jointly for common objectives using integrated technologies that can increase their performance more significantly than if they have done it alone. In the CC context, real-time monitoring and continuous observation may result in a significant and continuous improvement in the supply system performance. This goal can be achieved when companies achieve a high level of coordination and integration between upstream and downstream actors. Close strategic relationships with suppliers and customers enable firms to learn and adapt to the external environment and improve their ability to face SC disruptions. Thus, CC integration and coordination can be enhanced by Industry 4.0 technologies.

This study can motivate and guide researchers in investigating unexplored research areas. For instance, prioritising the development of technical capacities of WSN, but also financially viable and energy-efficient applications of RFID, technological protocols, strategically oriented decision support systems, data analytics, integrating product lifetime extension strategies, and multi-functionality in intelligent packaging. Furthermore, governmental bodies may benefit from the results of this study by identifying the most promising technologies which have already shown successful implementation. This would guide governmental programs in devising strategic objectives and policies for companies. Similarly, the government should make financial levels available for companies' projects in all sectors.

VI. Conclusion and Limitations of the Study

This study offers a detailed investigation of CC 4.0 research published over the last three decades by (1) assessing the development of the area over the period; (2) identifying and underlining the major CC 4.0 research trends and themes; and (3) providing possible avenues for future research by classifying the literature into clusters, identifying the discrepancies and limitations, and developing the research propositions under each cluster. A bibliometric and network analysis approach was applied to 618 articles retrieved from the WoS database, representing the period between 1991 and August 2020. In addition, we examined a list of productive and influential countries, sources, research institutions, authors, and their collaborations.

From the study findings, it was noticed that the most productive and influential works are from China, the USA, and Italy. The literature began growing in 2015, and a steady increase in the total number of articles was observed until 2020. Therefore, scholars intending to pursue research in this area should consider the identified core sources and articles for their reference. The outcomes open out four critical clusters of CC 4.0 research comprising Industry 4.0, technologies for temperature monitoring, quality and shelf-life prediction, intelligent packaging, real-time traceability, and related challenges. On the other hand, each cluster was divided into the sub-research-themes such as WSN and RFID technologies for monitoring temperature, technological architecture and infrastructure for temperature monitoring, statistical tools for product quality and shelf-life prediction, intelligent food logistics for longer-lasting product quality, new technologies, and applications of smart packaging, the nomological framework of intelligent packaging, real-time traceability capabilities, and societal and commercial implications of real-time traceability and related research. They were thoroughly investigated and associated research avenues were developed accordingly. Accordingly, 19 research propositions were proposed, inviting future researchers to answer them as research questions.

This study has some limitations. Although we analysed an appropriate number of articles extracted from the reputed WoS database, the integration of other databases could have resulted in additional relevant articles. Therefore, future studies should use these databases. Moreover, our literature search was limited to SC and logistics. Therefore, future studies can incorporate broader perspectives by adding keywords from operations management to provide a comprehensive overview. In addition, the development of lean, agile, and resilient CC capacities is growing, and their conceptualisation and empirical testing could significantly contribute to the development of state-of-the-art.

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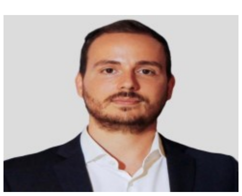

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TABLES

TABLE I
THE 10 MOST FREQUENTLY CITED GENERAL AND TECHNOLOGY-BASED KEYWORDS

General keywords				Technology-based keywords			
Keywords	**Frequency**	**Keywords**	**Frequency**	**Keyword**	**Frequency**	**Keyword**	**Frequency**
Cold chain(s)	89	Temperature	57	Radio frequency identification (RFID)	88	Big data	24
Quality	73	System	47	Internet of Things (IoT)	64	Temperature sensor	23
Traceability	63	Management	45	Wireless sensor network (WSN)	53	Cloud computing	17
Supply chain	58	Shelf life	42	Internet	27	Industry 4.0	13
Food safety	57	Storage	37	Technology	26	Intelligent packaging	8

TABLE II
CLUSTERING OF THE MOST CITED AUTHORS

Cluster 1 (689)		Cluster 2 (309)	
Abad, E. (53)	Ngai, E.W.T. (18)	Akyildiz, I.F. (17)	Kuswandi, B. (18)
Atzori, I. (20)	Qi, I. (31)	Dalgaard P. (16)	Labuza, T.P. (21)
Aung, M.M. (43)	Regattieri, A. (26)	Giannakourou, M.C. (19)	Pal, A. (17)
Badia-Melis, R. (50)	Ruiz-Garcia, I. (78)	Gram, I. (17)	Potyrailo, R.A. (21)
Barge, P. (15)	Thakur, M. (21)	Heising, J.K. (19)	Raab, V. (16)
Bosona, T.(17)	Trebar, M. (19)	Kerry, J.P. (18)	Taoukis, P.S. (32)
Chen, Y.Y. (15)	Verdouw, C.N. (31)	Koutsoumanis, K. (27)	Tsironi, T. (19)
Costa, C. (25)	Wang, J.Y. (15)	Kumar, P. (15)	Yam, K.L. (17)
Finkenzeller, K. (18)	Wang, I.X. (19)	**Cluster 3 (388)**	
Kang, Y.S. (21)	Wang, X. (21)	Dabbene, F. (22)	Jedermann, R. (120)
Kelepouris, T. (16)	Xiao, X.Q. (39)	Defraeye, T. (22)	Kader, A.A. (33)
Mainetti, I. (19)	Zhang, J. (23)	FAO (20)	Moureh, J. (17)
Mejjaouli, S. (16)	Zhang, Y.F. (20)	Grubbstrom, R.W. (22)	Nunes, M.C.N. (63)
		Gustavsson, J. (27)	Zou, Z. (17)
		Hertog, M.L.A.T.M. (25)	

The number of citations is presented between brackets next to the name of the cluster number.

TABLE III
CLUSTERING RESULTING IN THE MOST CITED REFERENCES

Cluster 1: Industry 4.0 technologies for temperature monitoring (240 Citations)		Cluster 2: Quality and shelf-life prediction (219 Citations)	
• Amador et al. [45] (12) • Atzori et al. [46] (20) • Aung and Chang [47] (19) • Badia-Melis et al. [48] (9) • Badia-Melis et al. [49] (10) • Chen et al. [50] (15) • Gogou et al. [51] (11) • Gubbi et al. [52] (12) • Hong et al. [53] (12)	• Kang et al. [54] (10) • Kim et al. [55] (9) • Kuo and Chen [56] (10) • Qi et al. [57] (22) • Ruiz-Garcia et al. [58] (17) • Thakur and Forås [60] (9) • Verdouw et al. [61] (12) • Wang et al. [62] (15) • Xiao et al. [63] (16)	• Grunow and Piramuthu [64] (14) • Gustavsson et al. [65] (14) • Heising et al. [66] (11) • Hertog et al. [67] (14) • Jedermann et al. [68] (23) • Jedermann et al. [69] (29) • Laguerre et al. [71] (10) • Lang et al. [72] (10)	• Montanari [73] (12) • Nunes et al. [74] (13) • Parfitt et al. [75] (14) • Rodríguez-Bermejo et al. [76] (9) • Rong et al. [77] (11) • Ruiz-Garcia et al. [78] (16) • Wang and Li [79] (10) • Zou et al. [80] (9)
Current research in cluster 1		**Current research in cluster 2**	

WSN and RFID technologies for monitoring temperature	• RFID for mapping temperature (vs traditional temperature mapping techniques) • Optimal temperature range for multiple commodities • WSN and RFID for temperature measurements • WSN and RFID for product-specific history recording • CC predictor software for optimized CC management • IoT technology-RFID embeddedness for temperature evaluation in smart CC • Financial viability of RFID application	***Statistical tools for product quality and shelf-life prediction***	• Intelligent packaging for shelf-life modelling in warehouse management • Deterministic and stochastic modelling of early product characteristics and operating conditions • Modelling optimal managerial practices to curb CC costs • Mixed-integer linear programming modelling for improved CC distribution systems
Technological architecture and infrastructure for temperature monitoring	• Cloud-centric vision for IoT implementation • RFID-based CC simulation modelling • Algorithm-based temperature and humidity management for freshness • IoT architecture for enabling information systems • CC shelf-life decision support system for CC management • WSN for cold storage and transport conditions • CC monitoring and modulating systems	***Intelligent food logistics for longer-lasting product quality***	• RFID-based estimation of the expiry date and remaining shelf-life • WSN for communications in the agri-food sector • Dynamic product quality assessment framework for CC
Cluster 3: Intelligent packaging 16 (189 Citations)		**Cluster 4: Real-time traceability and related challenges (204 Citations)**	
• Bibi et al. [81] (11) • Costa et al. [82] (18) • Finkenzeller [83] (9) • Ghaani et al. [84] (9) • Giannakourou et al. [85] (9) • Jedermann et al. [86] (13) • Kerry et al. [87] (16) • Koutsoumanis et al. [88] (13)	• Kumar et al. [89] (12) • Kuswandi et al. [90] (9) • Pacquit et al. [91] (10) • Papetti et al. [92] (9) • Taoukis and Labuza [93] (15) • Vanderroost et al. [94] (11) • Yam et al. [95] (13) • Zhang et al. [96] (12)	• Abad et al. [97] (49) • Angeles [98] (9) • Aung et al. [99] (21) • Badia-Melis et al. [100] (9) • Barge et al. [101] (11) • Bosona and Gebresenbet [102] (16)	• Feng et al. [103] (9) • Kelepouris et al. [104] (14) • Regattieri et al. [105] (23) • Ruiz-Garcia and Lunadei [106] (18) • Storøy et al. [107] (9) • Wang et al. [108] (16)
Current research in cluster 3		**Current research in cluster 4**	
New technologies and applications of smart packaging	• Developments in smart packaging devices • Commercial time-temperature indicators • Electronic-tracing systems • Electronic fresh food spoilage indicators • RFID for traceability and stock rotation	***Real-time traceability capabilities***	• RFID smart tags for real-time traceability and monitoring • Tech-enabled traceability for product safety and quality • Issues related to RFID technologies implementation in the supply chain • Real-time monitoring and decision support systems for CC delivery • Standards, principles, and good practices for traceability information • RFID applications in extreme environments
Nomological framework of intelligent packaging	• Technical and commercial implementation of intelligent packaging • Concepts, terms, components, and principles of RFID systems for packaging • Active and intelligent packaging technologies	***Societal and commercial implications of real-time traceability***	• Legal and regulatory considerations on perishable products' traceability • Information acquisition, transformation, and transmission process • Legal, technological and social considerations underpinning efficient CC traceability systems • Benefits of advanced traceability systems for consumers

TABLE IV

THE PROPOSED CLUSTER CLASSIFICATION WITH CURRENT AND FUTURE RESEARCH PER CLUSTER

Cluster number and cluster label	Current research	Future research suggestions
Cluster 1		
Technology for temperature monitoring	WSN and RFID technologies for monitoring temperature	• Prioritize the development of technical capacities of WSN • Financially viable application of RFID in traceability systems • Energy-efficient applications of WSN and RFID
	Technological architecture and infrastructure for temperature monitoring	• Distributed architectures underpinning WSN and RFID applications without centralized control and goal-setting processes • Improve protocols about RFID and WSN
Cluster 2		
Product quality and self-life prediction	Statistical tools for product quality and shelf-life prediction	• Embedding tools in broader strategically oriented decision support systems • Integrating prescriptive data analytics
	Intelligent food logistics for longer-lasting product quality	• Chain-wide propensity to contribute to information-sharing systems
Cluster 3		
Smart packaging	New technologies and applications of smart packaging	• Multi-functionality in smart packaging • Improvements in the technological prowess of intelligent packaging
	Nomological framework of intelligent packaging	• Financial considerations surrounding intelligent packaging • Educating consumers about intelligent systems • Nurture public and social confidence in the security of intelligent packaging
Cluster 4		
Real-time traceability	Real-time traceability capabilities	• Distributed and algorithm-driven food traceability solutions in the CC • Development of comprehensive frameworks for food traceability
	Commercial sustainability and societal implications of real-time traceability	• Consumers' awareness, acceptance, preferences, usage, and willingness to pay a premium for traceable food • Application of product lifetime extension strategies to intelligent devices within CC 4.0 • Role of consumers in product lifetimes extension strategies • Gauge public opinion regarding food traceability from production to consumption

FIGURES

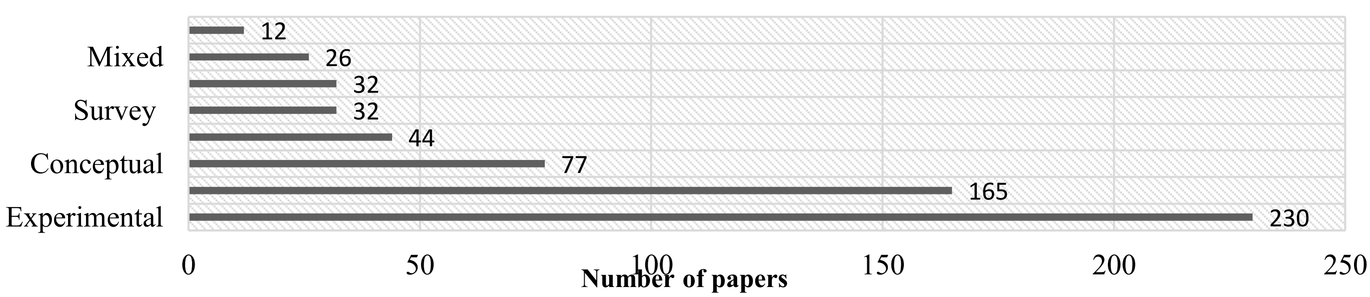

Fig. 1. Distribution of articles based on the methodology.

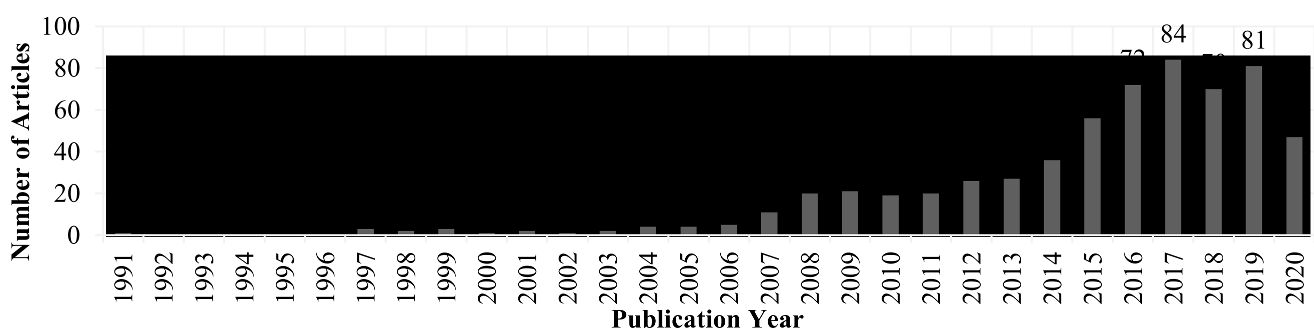

Fig. 2. Year-wise growth pattern of CC 4.0 research.

Cluster 1
1. RFID-centric traceability and CC monitoring (e.g., E. Abad)
2. CC 4.0 systems (e.g., R. Badia-Melis)
3. IoT-based virtual supply chains (e.g., C.N. Verdouw)
4. Technology for perishables (e.g., I. Ruiz-Garcia)

Cluster 2
1. Wireless sensor network for data transmission (e.g.,I.F.Akyildiz)
2. Shelf-life decision support systems (e.g., M.C. Giannakourou)
3. Intelligent packaging for product quality (e.g., J.K. Heising)
4. New packaging technologies (e.g., J.P. Kerry)
5. Nanotechnology and sensor trends for product quality (e.g., B. Kuswandi)
6. CC database development and modelling (e.g., PS. Taoukis)

Cluster 3
1. Intelligent food logistics (e.g., R. Jedermann)
2. Smart packaging, product and quality (e.g., A.A. Kader)
3. Virtual CC methods (e.g., T. Defraeye)
4. Shelf life modelling (e.g., M.L.A.T.M. Hertog)

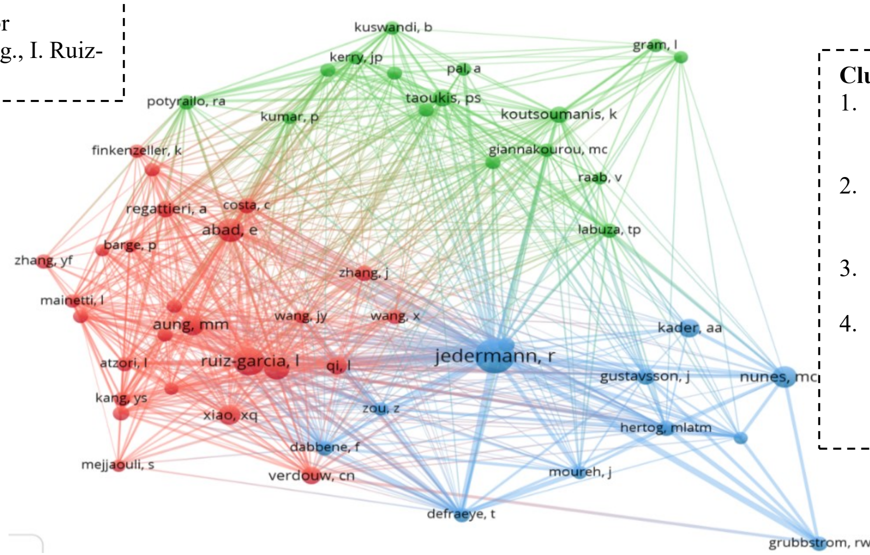

Fig. 3. The co-citation network of the most co-cited authors.

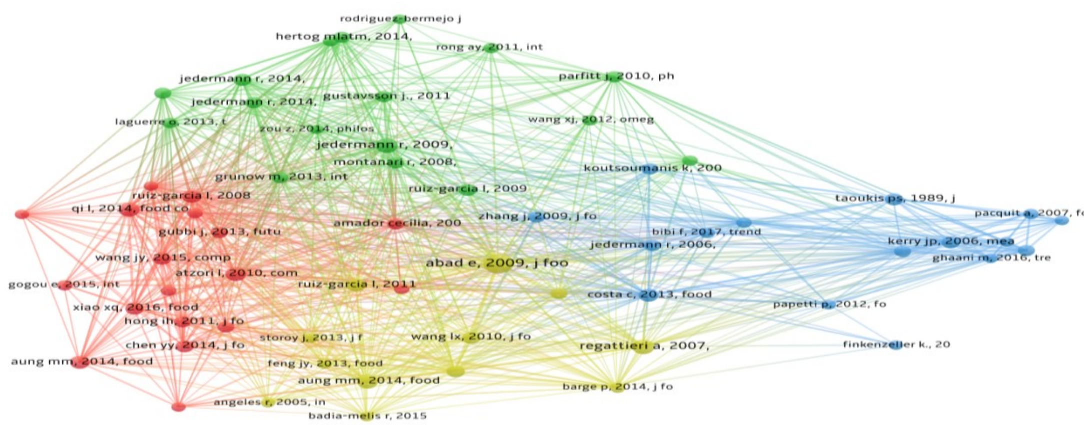

Fig. 4. Co-citation network of most co-cited articles.