Cellular agriculture research progress and prospects: Insights from bibliometric analysis

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Abstract

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World agriculture is facing a daunting task to feed the burgeoning population against multiple production and environmental threats. The alarming growth in population vis-à-vis current food production is expected to increase the global food insecurity levels. Inter alia, cellular agriculture – an incipient technology – is being considered as a potential alternative to cater for the growing demand for food and nutrition. The technology aims to develop edible agricultural products including meat with reduced environmental footprint against conventional farm production. In this context, an attempt has been made to review the progress of cellular agriculture research in four decades (1981–2020) through a bibliometric analysis and to suggest a roadmap for future research. The study sourced data from the Web of Science during October 2020. Using keywords, the database showed 212 searches pertaining to cellular agriculture from 135 journals worldwide. Of the journals, seven had at least five published articles and 33 had two articles each. Subsequently, the bibliographic coupling among the identified journals was carried out. It is found that the Journals: Appetite, Meat Science, and Journal of Agricultural and Environmental Ethics had the largest circles corresponding to their respective number of publications coupled with notable linkages with other journals. Also, a detailed analysis was performed on categories, growth trend, keywords, institutions, regions and leading researchers of cellular agriculture. The findings indicate that the Appetite Journal followed by the Journal of Agricultural and Environmental Ethics had published a significant percentage of articles on cellular agriculture, and Environmental Science and Technology was identified as the highly cited journal. The USA, England and the Netherlands were identified as the progressive regions in cellular agriculture research. The bibliometric analysis points to sluggish progress in cellular agriculture research and production despite its potential benefits. Future research should focus on the cost-effectiveness of the technology, consumer willingness to buy, development of food safety protocols on its merit and regional policy governance coupled with popularising its paybacks in the context of ensuring food security.

1. Introduction

Sufficient food availability is a big challenge to the growing population. The issue intensifies with the pressure to reduce the negative environmental effects of conventional agriculture. It seems doubtful that the massive problems ahead will be solved by the current agricultural systems alone (Rischer et al., 2020; Specht et al., 2018). Additionally, the global stress of malnutrition is exacerbated by chronic hunger alongside overweight and obese conditions (FAO et al., 2020). Scientific and agricultural progress allows stability in the food system to be established and therefore the impacts of potential food shortages can be alleviated.

Cellular agriculture, the concept of producing cell-based animal and plant products with little to no animal or plant involvement, is an emerging technology aiming to satisfy the potential demand for food and nutrition while reducing the environmental burden. It is a hotspot of concern for both academic researchers and industry partners to advance a novel food in the future (Specht et al., 2018). Cellular agriculture has many claimed benefits over traditional agriculture in terms of lowering animal suffering and altering the nutrient profile...
of the food (Clayton et al., 2018; Kadim et al., 2015). Moreover, several studies have shown that cellular agriculture has even more positive side effects, ranging from improved climate change to better human health specifically reducing obesity and cardiovascular diseases. Theoretically, it seems that cellular agriculture will be an “environmental panacea”, though it may be intricate to achieve practically unless there is a deep understanding of the technologies involved (Mattick, 2018) and active collaboration to get rid of the challenges including cost, sensory and nutrition profiles (Rubio et al., 2020). After all, cellular agriculture offers an opportunity to reduce the environmental footprint in general and uses less water, land and emits fewer greenhouse gases in particular. The anticipated impacts of cellular agriculture will depend on the source of the main protein (Rubio et al., 2020), how much decarbonisation energy can be produced, and the specific environmental footprints of production that yet needs detail and transparent life cycle analysis (LCA) (Lynch & Pierrehumbert, 2019).

Those benefits, however, do not come up without daring (Mattick et al., 2015a, 2015b). It seems for many to be extremely modern, urbanized, and frankly odd. Tomiyama et al. (2020) and Zhang et al. (2020) discussed the fact that the major concern for researchers developing cell-based goods lies in governing regulation, social ethics, public perception and acceptance, and technological obstacles. The authors, however, agreed that even with these barriers, they are confident that widespread cultivated meats can be embraced amidst these obstacles, even if it needs a change towards broader cultural expectations.

In the milieu, assessing the research activities on cellular agriculture is crucial to identify institutional, national and global contributions in the field, the priority themes discussed by researchers which may set the agenda for future research. Bibliometrics is an effective tool for evaluating the overall trends and evolution of scientific research outputs across countries, institutions, research centres, journals, and, in general, scientists (Cobo et al., 2015). The current study, therefore, used bibliometric analysis to assess the scientific research progress, impacts and future directions of cellular agriculture, which can be useful for researchers and policymakers as a reference in this field. It also provides insights into scientific research and identifies the key scientific actors, contributing to develop alternative approaches, evidence-based descriptions, comparisons, and simulations of research activities in cellular agriculture.

Therefore, this paper aims to perform a detailed bibliometric analysis of scientific production in the field of cellular agriculture during the past four decades. Furthermore, some performance indicators have been used to illustrate certain themes that have gained further attention from the research community.

2. Materials and methods

Data collection for use in this research was done in October 2020 from the Web of Science, University of South Africa Library, South Africa. The keywords used in the research were, “cell-based meat” or “cellular agriculture” or “plant-based meat” or “insect-based meat” or “tissue-engineered meat” or “synthetic meat” or “laboratory-grown meat” or “in vitro meat” or “fake meat” or “factory-grown meat” or “engineered meat” or “cultured meat” or “clean meat” or “cellular meat” or “cell-cultured meat” or “artificial meat”. The search was on a “topic” basis and 212 articles were obtained. All the full records of articles accompanied by their cited references were downloaded and used as the primary source of data for this research. The contents of the full record downloads included the name of the journal, publication date, abstract, source, article title, and authors.

The statistical data on the aspects were analysed in Minitab 17, statistical software and VOSviewer sourced from Leiden University. The interrelationships of citations, countries, and institutions of origin, keywords, and journals were analysed using VOSviewer. The results from the VOSviewer charts were presented in circles and curved lines. In this case, each item whose interrelationship was analysed by the software was indicated using a circle. More important items were labelled using larger circles and different colours were assigned to items of the same cluster or subset resulting from a common feature. The relative positioning of the circles was a default setting of the software to prevent the overlap of labels, which could be confusing to interpret (Van Eck & Waltman, 2010). Curved lines were drawn between each item whose interrelationship was analysed to indicate relationships. The thickness of the line was directly proportional to the strength of the relationship ascertained (Van Eck & Waltman, 2010).

The 212 articles used in this research were not mutually exclusive as the total searched material was 227. The distribution of the document types (number of documents, percentage) was articles (212, 93.4%), proceeding papers (8, 3.5%), early access (6, 2.7%) and retracted publication (1, 0.4%). A comparison of the publication years showed that 2019 had the highest number of articles (49, 23.1%) followed by 2020, 2018, and 2017 at 21.2, 17.0, and 8.5%, respectively.

3. Results and discussion

3.1. Analysis of journals and categories

3.1.1. Journal analysis

Web of Science database search showed 212 searches relating to cellular agriculture for food during the period of review (1981–2020) from 135 journals. Of this total, 7 journals had at least 5 published articles and 33 had two articles each. Table 1 shows the 10 most featured journals. From the analysis, the Journals of Appetite and the Journal of Agricultural Environmental Ethics had the highest number of records contributing to a total of 10.4%. Other journals with a high number of publications include Meat Science, Fleischwirtschaft, and Frontiers in Sustainable Food Systems with 9.4%.

The bibliographic coupling among the identified journals was as shown in Fig. 1. In the mapping analysis using VOSviewer, the minimum number of articles of a source was two. Out of the 212 articles identified, 135 satisfied this condition. A circle represented a journal while a curved line connected a journal to others. The thickness of the line was equivalent to the strength of the interrelationship among journals. Evidently, the Appetite, Meat Science, and Journal of Agricultural and Environmental Ethics had the largest circles correspondent to their number of publications as well as many interrelations with other journals. Seven clusters were identified in the bibliographic coupling of journals and were represented in green, yellow, red, purple, orange, blue and pink colours. The clusters discern searched journals, which are related based on their various research areas and categories.

Table 1

| Rank | Title of Source | Records | Percentage of published records |
|------|----------------|---------|----------------------------------|
| 1    | Appetite       | 11      | 5.2%                             |
| 2    | Journal of Agricultural Environmental Ethics | 11 | 5.2% |
| 3    | Meat Science   | 8       | 3.8%                             |
| 4    | Fleischwirtschaft | 6   | 2.8% |
| 5    | Frontiers in Sustainable Food Systems | 6 | 2.8% |
| 6    | British Food Journal | 5 | 2.4% |
| 7    | Sustainability | 5       | 2.4%                             |
| 8    | Food Quality and Preference | 3 | 1.4% |
| 9    | Foods          | 3       | 1.4%                             |
| 10   | Nutrients      | 3       | 1.4%                             |
3.1.2. Analysis of categories

In this analysis, two types of categories: 1) Web of Science and 2) research area categories were used. The former was based on classifications by the database in the form of sub-fields while research area categories were based on broader and common categories such as social sciences, agriculture, and engineering. The Web of Science categories were 69 in total and out of these 9 had at least 10 publications while 22 had at least 5 publications. The ten highest categories were as shown in Table 2. The total research areas identified were 51 and out of these 10 had at least 10 publications while 18 had at least 5 publications. The top 10 research areas with the highest number of publications were as shown in Table 2.

Considering both the categories, the most prominent areas on cellular agriculture (with comparatively more records) are Food science technology, Environmental sciences, Nutrition dietetics, and Agriculture. In the Web of Science categories, the four fields contributed 66.6% while in research areas, 77% of the total publications. This observation is justifiable from the perceived benefits of the technology in improving food security, dietary and nutritional needs, reducing the carbon footprint and introducing a novel agricultural technology based on biotechnology (Clayton et al., 2018; Mattick, 2018). All the publications involved in this topic, however, spanned over many other fields including behavioural sciences, biotechnology and applied microbiology, history philosophy of science among others. The multidisciplinary nature of cellular agricultural research observed in this context confirmed sentiments by Bordons et al. (2004) who stated that contemporary scientific research has led to overlap and dissolution of disciplines to produce new hybrids of fields and research areas as evident in this study. In the fields, the keywords used in the database search were used either as standalone or jointly to refer to progress in the cellular agricultural evaluations.

3.2. Growth trend analysis

The growth in publications, cited articles, and citations were exponential in the last decade compared to the period between 2000 and 2020. In the last five years, this growth was more pronounced as articles published were 73.6% of the total publications searched while total citing articles and total citations excluding self-citations were 76.7 and 68.9%, respectively (Table 3). The growth in publication and research in this field is associated with the global concerns on sustainable and healthy food production in an era of increasing population and climate change challenges (Jönsson et al., 2019; Sexton et al., 2019; Rischer et al., 2020). From these concerns, the need for

![Fig. 1. Bibliographic coupling of identified journals.](image-url)

### Table 2

| Rank | Web of Science categories | Records | % | Rank | Research Areas | Records | % |
|------|---------------------------|---------|---|------|---------------|---------|---|
| 1    | Food science technology   | 64      | 30.2 | 1    | Food science technology | 64 | 30.2 |
| 2    | Environmental sciences    | 33      | 15.6 | 2    | Agriculture     | 37 | 17.5 |
| 3    | Nutrition dietetics       | 26      | 12.3 | 3    | Environmental sciences ecology | 36 | 17.0 |
| 4    | History philosophy of science | 24 | 11.3 | 4    | Nutrition dietetics | 26 | 12.3 |
| 5    | Agriculture multidisciplinary | 18 | 8.5  | 5    | History philosophy of science | 24 | 11.3 |
| 6    | Ethics                    | 17      | 8.0  | 6    | Social sciences other topics | 20 | 9.4 |
| 7    | Biotechnology applied microbiology | 14 | 6.6  | 7    | Biotechnology applied microbiology | 14 | 6.6 |
| 8    | Environmental studies     | 14      | 6.6  | 8    | Engineering     | 14 | 6.6 |
| 9    | Behavioural sciences      | 12      | 5.7  | 9    | Science technology other topics | 14 | 6.6 |
| 10   | Agricultural dairy animals science | 9 | 4.2  | 10   | Behavioural sciences | 12 | 5.7 |
alternative sources of proteins from conventional farming to prevent malnourishment and lifestyle-based diseases such as obesity is predominant (Ben-Arye & Shulamit, 2019; Boler et al., 2020; Faustman et al., 2020).

The title of the article, research area, author and journal of publication, and region or region of origin for the top 10 publications are detailed in Table 4. From the analyses, the article detailing the environmental effects of tissue-engineered meat using the life cycle assessment (LCA) method by Tuomisto and de Mattos (2011) was the most cited with 181 citations in total. This trend pointed to the use of the method, LCA in several pieces of research as highlighted by Izuchukwu et al. (2020) in a bibliometric analysis on eco-efficiency research where the method was a frequently used keyword. Research by D’Odorico et al. (2014) that discusses about the biotechnological

| Year | Publications | % | Citation Report | Total Citing articles | % | Total citing articles without self-citations | % |
|------|--------------|---|-----------------|----------------------|---|---------------------------------------------|---|
| 2020 | 45           | 21.2 | 1016           | 403                  | 24.3 | 364                                         | 21.9 |
| 2019 | 49           | 23.1 | 729            | 405                  | 24.4 | 365                                         | 22.0 |
| 2018 | 36           | 17.0 | 394            | 231                  | 13.9 | 204                                         | 12.3 |
| 2017 | 18           | 8.5  | 225            | 134                  | 8.1  | 119                                         | 7.2  |
| 2016 | 8            | 3.8  | 151            | 99                   | 6.0  | 92                                          | 5.5  |
| 2015 | 13           | 6.1  | 182            | 98                   | 5.9  | 88                                          | 5.3  |
| 2014 | 11           | 5.2  | 82             | 60                   | 3.6  | 53                                          | 3.2  |
| 2013 | 7            | 3.3  | 67             | 39                   | 2.3  | 32                                          | 1.9  |
| 2012 | 3            | 1.4  | 49             | 37                   | 2.2  | 36                                          | 2.2  |
| 2011 | 2            | 0.9  | 28             | 26                   | 1.6  | 25                                          | 1.5  |
| 2010 | 4            | 1.9  | 37             | 33                   | 2.0  | 32                                          | 1.9  |
| 2009 | 3            | 1.4  | 20             | 14                   | 0.8  | 14                                          | 0.8  |
| 2008 | 1            | 0.5  | 23             | 19                   | 1.1  | 18                                          | 1.1  |
| 2005 | 1            | 0.5  | 19             | 18                   | 1.1  | 18                                          | 1.1  |
| 2002 | 1            | 0.5  | 14             | 13                   | 0.8  | 13                                          | 0.8  |
| 2001 | 1            | 0.5  | 11             | 10                   | 0.6  | 10                                          | 0.6  |
| 1998 | 1            | 0.5  | 16             | 13                   | 0.8  | 12                                          | 0.7  |
| 1997 | 2            | 0.9  | 18             | 18                   | 1.1  | 18                                          | 1.1  |
| 1995 | 1            | 0.5  | 14             | 13                   | 0.8  | 12                                          | 0.7  |
| 1994 | 2            | 0.9  | 9              | 8                    | 0.5  | 7                                           | 0.4  |
| 1991 | 1            | 0.5  | 4              | 3                    | 0.2  | 2                                           | 0.1  |
| 1986 | 1            | 0.5  | 2              | 2                    | 0.1  | 2                                           | 0.1  |
| 1985 | 1            | 0.5  | 0              | 0                    | 0    | 0                                           | 0    |

Table 3
Trends in growth of publications, citing articles and citations excluding self-citations.

Table 4
Various aspects of the top 10 most cited articles including their title, author, year of publication, journal of publication, institution, research area and frequency of citation.
advances towards in-vitro meat production in efforts to feed humanity was the second-best cited with 117 citations. Bax et al.’s (2012) study on cooking temperature as a factor influencing in vitro meat digestion was the third-best cited article with 115 citations. Evidently, the second and third most cited articles show that cellular technology is growing interest among researchers who are seeking to explore, optimize and understand it better owing to its potential to transform the food insecure world today and in future (Mattick et al., 2015a, 2015b; Tomiyama et al., 2020).

Other highly cited articles are in the fields of history and philosophy of science, environmental sciences, agriculture, food science and technology as well as nutrition and dietetics. In the last two decades, extensive studies have been done in these fields about cellular agriculture owing to the relationship between high demand for healthy and adequate food, environmental concerns on conventional food farming systems and global warming, and the ethics of alternative cellular agriculture production systems (Lynch & Pierrehumbert, 2019; Bryant et al., 2019).

3.3. Keyword analysis

Pre-existent studies have used keywords to classify recent trends and issues (Zhang et al., 2017). In this study, 1139 keywords resulted from the VOSviewer analysis while the author keywords were 614. Using the all keywords option and a threshold of three, 150 keywords were found to meet the threshold and the strength of the links between their co-occurrence was as shown in Fig. 2. The keywords with considerably high total link strength based on their circles and curved lines were used in this analysis. Clusters in the map analysis were divided into five and differentiated by colours red, yellow, green, blue, and purple. The red colour consisted of words related to cultured meat and its production protocols including cell cultures, skeletal muscle, growth culture, and tissue engineering among others. Cultured meat focuses on the production of meat using laboratory protocols to serve as an alternative to conventional meat (Ben-Arye & Shulamit, 2019). The yellow cluster focused on keywords related to the ethics of cellular agriculture. The words included animal welfare, technology, in-vitro meat, veganism, and animal rights among others. This category of words is a result of the existing debate on the correctness, safety and practicality of cellular agricultural processes as noted by Schaefer and Savulescu (2014) and Eibl et al. (2021).

On one hand, research on cellular agriculture is realistic and exciting owing to its potential to solve food insecurities and alleviate climate change effects (Clayton et al., 2018). On the other hand, there has been detraction in the technology with concerns on 1) its ability

![Fig. 2. Keyword analysis of cellular agricultural research.](https://ssrn.com/abstract=3887301)
to encourage cannibalism, 2) compromised happiness to animals and 3) its associated disrespect to animals and/or nature (Eibl et al., 2021).

The green cluster was associated with the potential of cellular agriculture as a healthy food source and a solution to environmental challenges. It consisted of words such as food security, sustainability, land use, insects, climate, greenhouse gas emissions, and mitigation among others. Cellular agriculture and the in vitro production of meat have been extolled for their capacity to enhance food security, environmental conservation, and overall sustainable development (Verbeke et al., 2018; Lindgren et al., 2018; Rischer et al., 2020). The blue and purple clusters were closely associated and consisted of words on the consumption trends, risks, and consumer acceptance aspects of in vitro meat. Some of the words with strong linkages in these clusters included attitudes; health, consumers, consumption, future, and acceptance just to mention a few. The keywords pointed to the uncertainty in cellular agriculture for large-scale food production and the likelihood to be accepted and preferred compared to conventional meat as Eibl et al. (2021) highlighted. Studies have highlighted the possibility of consumer reservations towards consuming cultured meat, issues which are recognised by advocates of the technology (Bryant & Barnett, 2018; Bryant & Dillard, 2019; Zhang et al., 2020).

### 3.4. Institutional and regional analysis

#### 3.4.1. Institutional analysis

From the Web of Science database, 305 organizations were involved in publishing cellular agriculture research, and out of these 8 had at least 5 publications. The top ten most productive institutions were as shown in Table 5. Wageningen University and Research of the Netherlands involved in training and research on commercial, social and scientific challenges in natural resources and life sciences had the highest publications at 4.7% of the total searches. The University of Oxford, based in England and the French National Institute for Agriculture, Food and Environment (INRAE) were second and third best publishers with 9 and 8 publications, respectively. Other top publishers included the University of Bath, United Kingdom, ETH Zurich of Switzerland, and the Clermont Auvergne University of France. The institutions came from developed countries and this coincided with previous bibliometric analyses by Wang et al. (2018) on climate change and Izuchukwu et al. (2020) on eco-efficiency towards sustainable development. In these countries, technology application is advanced and the financial capacity to explore biotechnological technologies such as cellular agriculture is readily available compared to poor developing countries of Africa and Asia.

Using the minimum number of documents from each institution as 2, more than 50 institutions met this VOSviewer threshold and their bibliographic coupling was as shown in Fig. 3. From the map analyses, institutions represented with the same color are likely to have jointly published articles of similar research areas. A circle represented a particular organization while the curved line was a link from one institution to the other. The strength of the line was represented by the thickness of the line. In this case, the circles of Wageningen University and Research among other top 10 institutions listed in Table 5 were the most conspicuous. This observation was associated with the high number of publications affiliated with the institutions.

#### 3.4.2. Region analysis

The top 10 most active countries in the research on cellular agriculture were as shown in Table 5. From the Web of Science database, 45 countries were involved in publications on cell-based meat production, and out of these, the USA, England, and the Netherlands were the most active with 25.5, 17.4, and 11.8% of all publications in respective order. Publications of the top ten countries summed up to 93.3% of all the records. These countries were mainly developed where awareness of sustainable food production and environmental conservation is high in an era of reducing finite resources and climate change (Izuchukwu et al. (2020) and Wang et al. (2018) observed in two different bibliometric analyses using the VOSviewer software. Similar research in developing countries may be limited due to low human and technological capacity as well as financial resources constraint to conduct cellular agricultural research as Zhong et al. (2016) highlighted in a bibliometric analysis on the accounting of natural resources.

Fig. 4 shows the bibliographic coupling of the 45 publishing countries. From the map analysis in VOSviewer, 27 countries met the set minimum threshold, which was 2 publications. In the map analysis, a circle corresponded to a country while the curved lines interlinked them. Thick lines represented strong linkages while analogous colours corresponded to inter-country collaborations in various researches of a common research area within the cellular agriculture technology. The USA was the most conspicuous in reference to interlinkage strength and number of publications represented by blue lines and circles, respectively.

#### 3.5. Author analysis

The top 20 productive authors were as shown in Table 6. The frequency of recorded articles corresponds to the extent of the given topic (in this case cellular agriculture) and the academic dominance of the author (Wang et al 2018). From the Web of Science database, 607 authors were affiliated with cellular agriculture-based researches and only 4 of them had at least 5 publications. This shows that the cellular agriculture topic is relatively new. It also corresponds to the sluggish growth of research on this subject, which could be associated with the reservations in the technology with regards to its safety, ability to produce in large scale at low cost and inability of developing countries to uptake the technology due to financial and human capacity constraints (Eibl et al., 2021).

Mark Post, a vascular physiology professor of the Maastricht University of the Netherlands had the highest number of publications at 2.8% of the total. He has researched the processes of meat culturing, factors to consider, attitudes and uncertainties of the technology as...
Fig. 3. Bibliographic coupling on institutions involved in cellular agricultural research.

Fig. 4. Bibliographic coupling of countries involved in cellular agricultural research.
well as its viability (Post et al., 2020; Rolland et al., 2020; Bodiou et al., 2020). Michael Siegrist, a professor at the ETH Zurich, Switzerland was the second most productive author with 5 publications. His research interests focus on consumer acceptance and the ethics around cell-based meat and cellular agricultural products (Michel et al., 2021; Siegrist & Hartmann, 2020; Siegrist et al., 2018). Neil Stephens of the Brunel University of London was the third best author with five publications. His works revolve around the hopes, concerns, and challenges in tissue engineering technology to improve cultured meat production (Stephens et al., 2018a; Stephens et al., 2018b; Stephens et al., 2019).

Fig. 5 shows the associations of author citations. From the VOSviewer software, the minimum citations were taken as 5, and out of the total 6718 authors, 262 met this threshold. Circles represented authors while their interrelationships were shown using curved links whose strength was signified by their size. A thick size corresponded to strong interlinkage. Authors that shared an analogous colour had the same citation according to Ertz and Leblanc-Proulx (2018). Evidently, many authors are trying to collaborate in optimizing cellular agriculture technology. Such collaborations amongst and between authors result in growth and development in the topic since concerns, challenges, reservations and grey areas are clarified (Wang et al., 2018).

4. Future directions for cellular agriculture research

Improvements and changes in food production are the need of the hour owing to the exponentially growing population. Cellular agriculture and cultured meat are promising technologies that could resolve the food security problems to a certain extent. However, the acceptance of the end products of cellular agriculture is still moderate (Weinrich et al., 2020). The neophobia associated with cellular products needs to be addressed. The acceptance of the end products from cellular agriculture has increased drastically after awareness and knowledge about it was provided (Zhang et al., 2017). The personal health benefits and the environmental sustainability associated with these products are yet to be popularised. Though cellular agricultural products are associated with positive impacts on various areas like glo-

Table 6
Top authors on cellular agriculture from the Web of Science database.

| Rank | Authors      | Records | Rank | Authors      | Records |
|------|--------------|---------|------|--------------|---------|
| 1    | Post MJ      | 6       | 11   | Driessen C   | 3       |
| 2    | Siegrist M   | 5       | 12   | Hartmann C   | 3       |
| 3    | Stephens N   | 5       | 13   | Heinz V      | 3       |
| 4    | Hocquette JF | 4       | 14   | Jeong J      | 3       |
| 5    | Verbeke W    | 4       | 15   | Jonsson E    | 3       |
| 6    | Acevedo CA   | 3       | 16   | Mancini MC   | 3       |
| 7    | Antonioli F  | 3       | 17   | Mantick CS   | 3       |
| 8    | Banks CJ     | 3       | 18   | Smetana S    | 3       |
| 9    | Borja R      | 3       | 19   | Wang ZJ      | 3       |
| 10   | Bryant CJ    | 3       | 20   | Woll S       | 3       |
bal food security, sustainability, environmental improvements, they should not be considered as a definite solution to these problems. Cellular food processing in small quantities is achieved at present but the challenge of large-scale and cost-efficient production is less determinate (Stephens et al., 2018b). Another challenge is the price competition and taste difference of the products when compared to their real counterparts. The day when cellular agricultural production leaves a significant mark on the global climate and food security improvement is still far.

As observed from the bibliometric analysis carried out in this study, research in cellular agriculture is still in its infancy. The potential of this area is huge and there are vital aspects of cellular agriculture that need to be analysed and developed. The efficiency in production, acceptance, and viability are the core areas to be focussed on. In evaluating the current state-of-art, some key aspects that should be addressed by future research are as follows:

- How can the production process be made more efficient to make cellular products more cost-effective compared to conventional meat?
- What is the consumer acceptance level of cellular products among different age groups and geographical areas and how it can be improved?
- What are the food safety challenges that can arise due to bacterial growth in the bioreactors during the cellular agriculture production process?
- How can the texture, chewiness, and taste of meat analogues be enhanced so that the pessimism towards these products is alleviated?
- What policies and governmental interventions are to be taken to develop cellular agriculture especially in developing countries?

5. Conclusions

This bibliometric analysis provides insights and perspectives on cellular agriculture research during the past four decades. The analysis shows that the Appetite journal followed by the Journal of Agricultural Environmental Ethics recorded the most significant percentage of articles while Environmental Science and Technology is a highly cited journal on cellular agriculture. Most cellular agriculture research areas published in the Web of Science are categorized under Food science and technology. Although official research on cellular agriculture was recorded in 1985, there is a rise in research progress in the past half-decade. The USA, England, and the Netherlands were identified as the major contributors and play leading roles in cellular agriculture research production. There are significant research outputs within the top institutions involved in cellular agriculture. The study indicates that there is room for intensive research in aspects of cellular agriculture considering its potential to ensure food security. Research teams should be collaborative and interdisciplinary, including members of various institutions, departments, and levels of experience. Such advances will ensure conducted research encompasses all versatile aspects of the cellular agriculture. From the techno-economic perspectives, challenges to do with cost, process, and flavour and texture optimization need to be addressed in accordance with regulatory frameworks. Consequently, there should be a great interest in more research on bottlenecks, deployment, and potential benefits of cellular agriculture technology.

CRediT authorship contribution statement

Joan Nyika: Conceptualization, Formal analysis, Visualization, Software, Writing - original draft, Supervision, Writing - review & editing. Joby Mackoil: Formal analysis, Writing - original draft, Writing - review & editing. Endashaw Workie: Formal analysis, Writing - original draft. Chaitanya Adhav: Writing - original draft. Sendhil Rama das: Formal analysis, Writing - original draft, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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