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Review Article

A decade of eco-friendly active and intelligent food packaging research: A quantitative review

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ABSTRACT

The thrust for active and intelligent food packaging systems utilizing sustainable biopolymer resources has gained significant momentum in recent years as the global food industry seeks innovative solutions to enhance product freshness and safety while reducing environmental impact. Active packaging aims to extend the shelf life of packaged foods through the incorporation of substances. Intelligent packaging, on the other hand, is intended to offer up-to-date data on the quality, freshness, or safety of packaged foods by integrating various indicators into the packaging film that displays variations in storage conditions, gas levels, pH, and other factors. The present quantitative review is targeted to investigate quantitatively the research activity in the biodegradable multifunctional packaging utilizing the Web of Science database data. The top ten authors, countries, and journals associated with the present topic have been analyzed using the Bibliometrix-Biblioshiny package of R. This software package also utilizes the thematic evolution in terms of trend topic analysis. In addition, the VOS viewer software package has been used to predict inter-country collaboration, as well as, collaboration between authors. This software package also predicts co-occurrences and the evolution of keywords. Such an extensive computational approach thus expected to predict the grey areas in eco-friendly active and smart food packaging research both in terms of synthesis and properties.

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INTRODUCTION

Packaging is an inevitable part of the modern food industry as it plays important role in maintaining food freshness, food safety and extending the shelf life of the food [1-4]. As per the Food and Agriculture Organization, about 1.3 billion tons of food materials are wasted globally in a year, which accounts for one-third of the worldwide production of food [5]. This deterioration is caused by several detrimental factors, such as, mechanical deterioration, environmental factors, oxidation, growth of unwanted microbes, difficulty in transportation etc. [6, 7] Packaging protects food from external factors by providing a boundary between food and the environment and thus facilitates food containment, preservation, and protection. Traditional food packaging materials utilizes synthetic polymers, such as, polystyrene (PS), polyethylene (PE), polypropylene (PP), polyvinylchloride (PVC), ethylene vinyl alcohol (EVA), polyethylene terephthalate (PET) [8-10]. For instance, the packaging of meat nowadays is done by utilizing low-density polyethylene (LDPE), high-density polyethylene (HDPE), polypropylene (PP), polyesters, polystyrene, and polyamide [11]. In addition, LDPE, LLDPE (linear low-density polyethylene) or their blend (LDPE-LLDPE) is generally utilized in packaging milk and other dairy products such as curd, butter milk etc. [12] These synthetic polymers are very much attractive from a consumer viewpoint, owing to its good processibility, mechanical robustness, optical clarity, and barrier properties

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[13]. It has raised the demand of such synthetic polymers in the last few decades reaching 320 million global productions in the current years [13, 14]. However, the unlimited use of these synthetic plastics have threated lives on earth associated with the persistency of the plastics in the environment for years and contamination of soils and water with the micro-plastics or nano- plastics generated from these materials [13, 14]. Additionally, significant research focus has been put by the worldwide research communities towards the development of new packaging materials utilizing renewable resources as an alternative to the conventional non-renewable petroleum based synthetic polymers [15, 16].

Biopolymers, such as, proteins, polysaccharides, and lipids from different biological resources are well established renewable raw materials owing to their high abundance in nature, non-toxicity and inherent biodegradability. Machado et al. [17] defined biodegradable polymers as materials that can degrade and allow anaerobic digestion forming carbon dioxide, methane, and water in an open atmosphere in the presence of microorganisms. To get rid of environmental issues the use of biodegradable polymers should be maximized in the packaging era for the sustainable development of the environment. The most widely investigated bio-polymeric materials for polysaccharide-based films are starch, cellulose and their derivatives, chitosan and starch, while casein, whey, and gelatin are the protein based matrix materials. There are several literatures considering protein gelatin derived from skin and bones of animals [18, 19]. However, these protein and polysaccharide based materials suffer from inherent brittleness and extreme mechanical weakness limiting their utilization in commercial packaging. This problem can be partially solved by crosslinking the biopolymer matrix using citric acid [20] gluteraldehyde [21], ascorbic acid [22] etc. Enhancing the chemical and structural properties of biopolymers can also be achieved by incorporating reinforcing agents, which make them suitable for commercial applications. In recent years, there has been a growing interest in utilizing nanotechnology in packaging [23]. Nanofillers are employed to improve the properties of polymeric materials in composites for specific applications [24].

Nowadays, consumers have become health conscious and thus ready to bear extra pennies to have healthier, fresh food [25, 26]. This necessitates the development of new generation active and smart food packaging systems which not only ensure the preservation of the food for a longer time by shielding or controlled release, but also display the spoiling of food by visual change [27]. As a consequence, the food packaging sector witnessed a paradigm shift towards the development of biodegradable, non-toxic, safe biopolymer based active, smart films [28]. Active packaging enhances the shelf life of the food by interacting with the packaged food [29]. The packaging materials help to retain the quality of food by releasing preservative substances or absorbing undesirable substances coming out of the packaged food. The active ingredient in the packaging may exist in the form of sachet and labels, coatings or may be in the matrix phase of the packaging [30]. The active packaging can either be absorbers of oxygen, ethylene, and moisture or emitters of carbon dioxide, antimicrobial agents, antioxidants, preservatives, and flavors [31]. On the contrary, intelligent packaging enables consumer real–time evaluation of the quality and freshness of the packaged food [1, 32, 33]. The indicator present in the packaging material ensure the food quality from visual color change during storage [34, 35]. During microbial growth in the packaged food, the metabolite of microbes and indicator reacts, resulting chromatic changes of the indicator through change in pH. The indicator present in the packaging thus results in visual change originating from the change in pH with the growth of microorganisms in the packaged food. Thus, the consumer can detect the food freshness and quality status from the color of indicator in the packaging film [33]. Numerous synthetic dyes, such as, bromocresol green, bromocresol purple, xylenol, chlorophenol, cresol red have been used by different scientific communities to serve the purpose [36, 37]. However, the toxicity, even carcinogenicity, associated to these dyes has limited their application in food packaging owing to the sustainability of the life and the environment [38, 39]. Renewable and nontoxic natural pigments can preserve food safety and fulfill consumer expectation hygienic safe food. Natural pigments, such as, anthocyanin [40, 41], curcumin [42, 43], alizarin [44], betalain [45], shikoin [46], green tea extract [47], chlorophyll [48], carotenoids [33], tannins [49] etc. have proved themselves as efficient indicator in the pH responsive films. These natural indicators, being incorporated during the fabrication of biopolymer films, restrict the microbial growth in the packaged food, leading to good antibacterial activity [50]. Additionally, the interaction of the packaged food with the natural pigments present in the packaging material can inhibit oxidation of the oxygen-sensitive food by scavenging free radicals, leading to impressive antioxidant activity, enhancing the stability of the food and favoring its preservation for a longer period [51].

In the era of eco-friendly packaging systems, significant research focus has been put in the development of active packaging, which by virtue of its release into the food restricts the spoilage of food items packed and smart or intelligent packaging, which can detect the spoilage of food by the visual alternation of color. Several active or smart ingredients are strategically introduced into the biodegradable packaging systems for specific purposes. In the present investigation, bibliometric parameters, viz. the year-wise growth, country-wise distribution, journal wise distribution in the biodegradable active and smart packaging research have been discussed thoroughly. The collaboration between authors, as well as, countries can also be found in the present manuscript. The evolution of keywords and their inter-links are very much important to find the eligible materials for active and intelligent food packaging systems. Thus, this bibliometric study is expected to be helpful to new researchers in selecting processes and materials for biodegradable next generation packaging systems.

METHODOLOGY

Publication Data Retrieval

This review considers the data published on biodegradable smart or active packaging materials utilizing a unique search string related to the present topic in the Web of Science (WoS) database, presently maintained by Clarivate Analytics (previously by Thomson Reuters). This database extensively covers the present research field and has proved itself to be a widely accepted tool for systematic bibliometric investigations. The search string in the present bibliometric investigations was "TS=(((biodegrad* OR sustain* OR (eco friend*)) AND packag* AND (smart OR active OR intelligen*))" in the 'Advance search' of WoS database limiting the period of analysis to 01-01-2014 to 31-12-2023 i.e., last ten years. A total number of 1891 publications were resulted on limiting our study only to the articles. All the articles thus obtained were manually scrutinized to verify their acceptability in the present study. After meticulous analysis, 1399 number of articles displayed their suitability in the present consideration. The present review article is confined into these 1399 articles.

Bibliometric Parameters Analysis

Here, the Bibiometrix-Biblishiny package of R was utilized for analyzing different bibliometric parameters associated with the quantitative analysis in the said topic [52]. The year-wise growth of publication along with mean total citations per article (MTCPA), and mean total citations per year (MTCPY) have been plotted in the same plot to explore the year wise growth of publications with related citation parameters. The most involved authors worldwide were analyzed along with average citations per publication (ACPP), and h-index to explore the most active author in the said research avenue. The most productive countries around the globe and related citation parameter were also investigated. The year wise growth of top five countries in the present topic was also evaluated. This software package was also utilized to predict the most related keywords in terms of a number of mention in the articles under consideration. The growth of the top ten most significant keywords was also analyzed. This software package also facilitates to analyze the number of articles, ACPP, and h-index of articles published in different journals. The Biblioshiny package was also utilized for trend topic analysis.

Analysis of Collaborative Networks Between Countries, Authors

The interconnecting networks between different countries, as well as, authors were studied in terms of bibliometric parameters, such as, co-authorship, and utilizing VOS viewer, a java based software tool for creating network clusters. This tool has proved itself very promising for overall analysis of the entire subject area and cluster analysis [53]. This software package utilizes bibliometric data from Scopus or Web of Science database. Here, the Web of Science database has been utilized for the present investigation.

Analysis of Interconnection between Journals

The interconnections between journals were studied in terms of citations utilizing the same VOS viewer software package. In this analysis, the optimizations of the related parameters are required. In the present study, the number of publications, as well as, citations was optimized at 20 to have visually detectable connections between the journals.

Analysis of Co-Occurrence of Keywords

The correlation between different keywords mentioned in different publications considered during this period can also be predicted by utilizing this VOS viewer. This software package also enables visualization of the co-occurrence of keywords. During this analysis the minimum number of occurrences of keywords was optimized at 100, as it resulted in visually fair networks.

RESULTS

Analysis of the Key Bibliometric Parameters

The key bibliometric parameters related to biodegradable smart and active packaging have been summarized in Table 1. The present systematic review considers the 1399 articles published during the last decade, i.e. 2014-2023 from the Web of Science database after manual investigation. The articles has been found to be published in 242 sources, which includes both journals and books with an annual growth of 9.11 %, suggesting the present research field to be flourishing in the last decade. Moreover, the articles received an appreciably good number of average citations 24.51. It is worth mentioning that, the complete collection of the publications has generated 2173 keywords in keywords plus, while 3121 keywords in the author's keywords. Moreover, all the publications are co-authored by 5148 authors worldwide, of which 16 documents are single authored. The co-authorship per document 5.2 and international co-authorship to be 28.68 %

WOS Categories

Fig 1 depicts the top ten most relevant categories in which the articles on the present topics were published in our considered time frame. As evident from the figure, the highest numbers of articles on biodegradable multifunctional packaging belongs to "Food Science and Technology" followed by "Polymer Science", "Chemistry Applied", "Biochemistry Molecular Biology" and "Materials Science Multidiscipline". Thus, the present bibliometric analysis data suggests the close interrelation of the present field with food science, polymer science, applied chemistry, biochemistry, and materials science discipline. The abovementioned wings has been analyzed to produce highest number of articles on biodegradable multifunctional packaging in the last decade.

Table 1. Summary of the key bibliometric data associated with biodegradable smart and active packaging research in the last decade

Description	Results
MAIN INFORMATION ABOUT DATA	
Timespan	2014:2024
Sources (Journals, Books, etc)	242
Documents	1399
Annual Growth Rate %	9.11
Document Average Age	3.15
Average citations per doc	24.51
References	48635
DOCUMENT CONTENTS	
Keywords Plus (ID)	2173
Author's Keywords (DE)	3121
AUTHORS	
Authors	5148
Authors of single-authored docs	13
AUTHORS COLLABORATION	
Single-authored docs	16
Co-Authors per Doc	5.2
International co-authorships %	28.68
DOCUMENT TYPES	
article	742
article; early access	635
article; proceedings paper	22

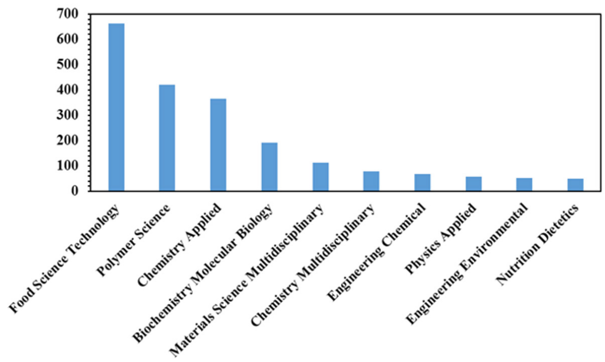

Figure 1. Top ten WOS categories publishing articles on biodegradable multifunctional packaging

Year-wise Growth of Publication and Citation Parameters

Fig 2 depicts the year wise growth of publications, as well as, mean total citations per year (MTCPY) and mean total citations per author (MTCPA) during the last ten years (2014-2023). As evident from the data plot, the biodegradable active or smart packaging research is found to be on the inclining trend, proving itself as a field of growing interest for the worldwide scientific community. It is worthy to mention that, the first five years of research produced 236 numbers of articles, while the last five years of research produced 1163 articles in the field under consideration. Moreover, the citation parameters (MTCPA, MTCPY) can be found in an appreciably good value in the given data plot.

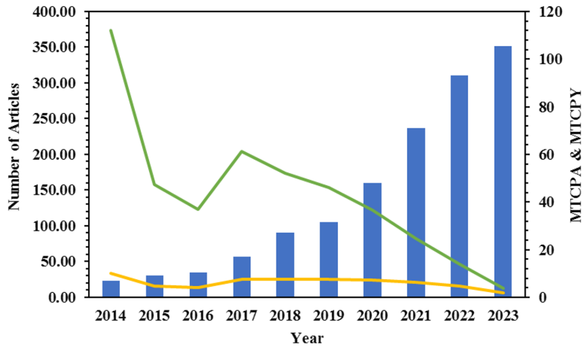

Figure 2. Year wise growth of number of publications, mean total citations per article (MTCPA) and mean total citations per year (MTCPY) in the period 2014-2023

Most Productive Countries and Their Citation Impact

Fig 3A depicts the total number of publications (as bar), as well as, average citations per publications (ACPP). China, Brazil, Iran, India, and Spain are found to publish in high frequency in the said field. However, the articles published by Portugal, USA, Spain, Iran, and Thailand received the most ACPP i.e. average citations per publication, an important parameter to reveal good acceptability of the article towards the worldwide scientific community. Good ACPP is directly related to the quality of investigation. The countries with fairly good ACPP reflect their quality, as well as, acceptability of their investigation towards the scientists involving in biodegradable packaging research around the globe.

The most relevant countries (top ten) by corresponding author publishing articles on biodegradable multifunctional food packaging during the period under consideration has been plotted in Fig 3B. The publication by each country includes both the single country publication (SCP) and multiple country publication (MCP). As can be seen, China published the highest number of publications in terms of affiliation of the corresponding author, followed by Brazil, Iran, India, and Spain. It is worthy to note that, the MCP of China is significantly greater than that of Brazil, signifying greater inter-country coauthored articles. Moreover, the inter-country collaborating articles were found to be significantly high in the articles originated from Spain. However, to obtain the inter-country collaboration extent more sophisticated analysis will be required.

Fig 3C represents the growth of the biodegradable multifunctional food packaging research done by the most active five countries in the last ten years. According to the Web of Science database, these five countries include Brazil, China, India, Iran, and Spain. It is well evident from the data plot that the said field flourished more specifically after 2018, i.e. in the 5-6 years. Although, all five countries are found to give almost linear stagnant numbers in the first five years, Brazil is found to lead the field during the early period of research in biodegradable multifunctional food packaging research. It is very interesting to find that, China led the area after 2022 followed by Brazil and Iran. Very surprisingly, the articles published by India increased significantly in the recent year, although the number of articles published by India was below the rest four countries in the entire period under consideration. The acceptability of the present field in recent years is well evident from this outcome.

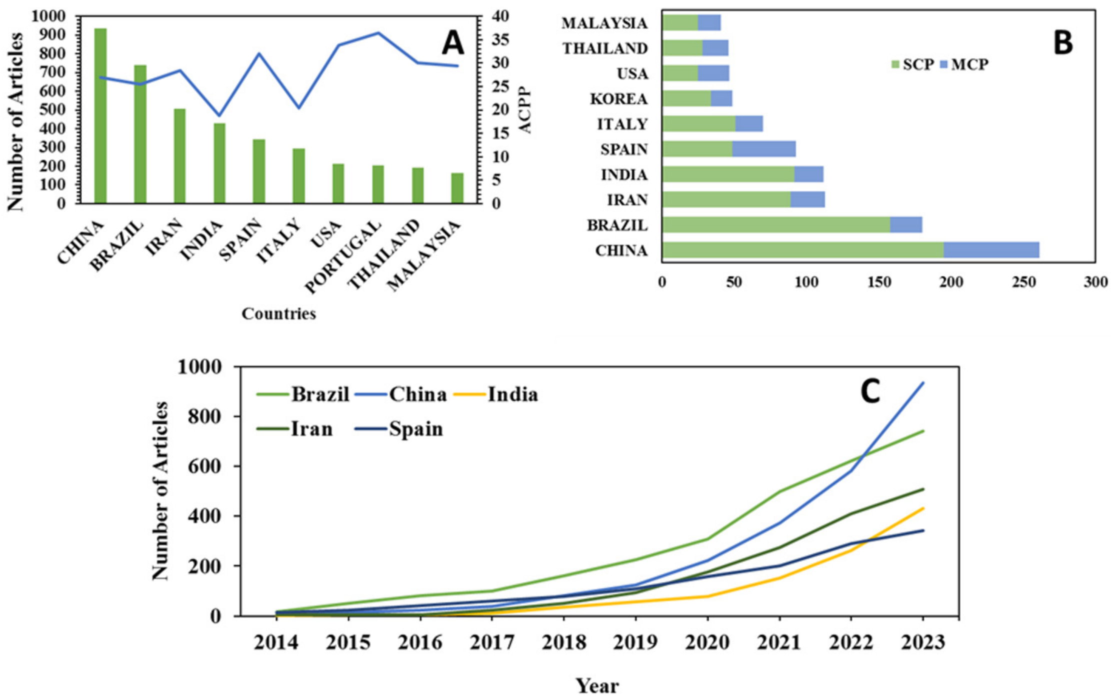

Figure 3. (A) Country wise distribution of number of publications, average citation per publication (ACPP) (B) Most relevant countries by corresponding author doing research on biodegradable smart or active packaging (C) Growth of biodegradable active or smart packaging research executed by top five countries in the period 2014-2023.

Most Active Authors: Number of Publications and Citation Parameters

Fig 4 depicts the top ten most relevant authors in terms of number of publications, ACPP, and h-index. As can be seen, Wang Y (29) published the highest number of articles on the said topic followed by Liu Y (21), Wang X (16), Li J (15), and Song KB (14). In terms of h-index Liu Y, Wang Y, Li X and Song KB have the highest h-index on the articles published on biodegradable smart or active packaging during the ten years. It is noteworthy that, the ACPP of the articles published by Flores SH is highest, followed by Haas Costa TM, Raos AO, and Mcclements DJ.

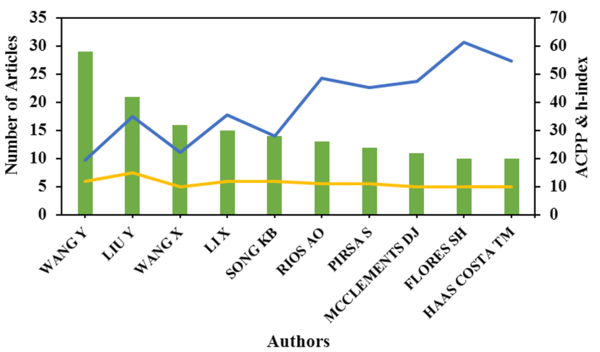

Figure 4. Number of articles, ACPP, and h-index of most active authors (top ten) publishing articles on biodegradable multifunctional food packaging in the period 2014-2023

Most Frequent Journals and Citation Parameters

The distribution of articles in different journals, ACPP, and h-index has been summarized in Fig 5. As can be found, the highest number of articles was published in the esteemed journal International journal of biological macromolecules (135). Food packaging and shelf life, a very good journal of international repute, published appreciably good number of articles (122) in the field under consideration. This trend was followed by highly reputed journals like, Food hydrocolloids (70), Polymers (62), LWT-Food Science and Technology (40), Carbohydrate polymers (40) etc. It is worthy to mention that, the citation related parameters, such as, ACPP, h-index was found to be highest in Food hydrocolloids.

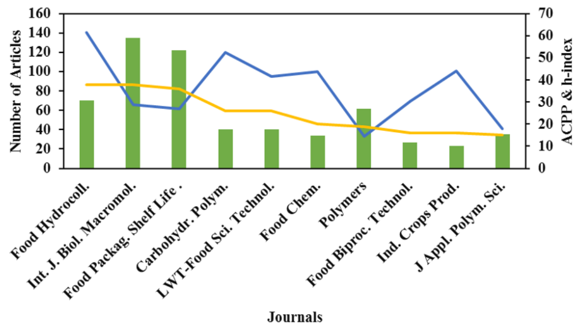

Figure 5. Total number of publications, h-index, and average citations per publication (ACPP) in the top ten journals

Most Frequent Keywords and Keywords Growth

Fig 6A and Fig 6B represent the most widely used keywords on biodegradable multifunctional food packaging in the period 2014-2023. Both the bar plot and word cloud format has been introduced in the same figure for quantification, as well as, easy visual recognition. As can be seen, antioxidant, chitosan, films, edible films, and mechanical properties received the most attention in the said period under consideration. These keywords are directly related to biodegradable active packaging materials. The antioxidant property has proved itself to be very important active food packaging for the preservation of food for a longer time [54]. Chitosan, an important biopolymer, has been used for several years for inhibiting microbial growth in the packed food [55]. Edible films and films appeared in the keywords list due to the investigations on the biodegradable materials for packaging were mostly based on biopolymer matrices and thus the resulting films are expected to be edible in nature [56]. As biopolymer films suffer from severe mechanical weakness, mechanical properties needs to be improved for making them suitable for food packaging [57]. The next five keywords in the list are, nanoparticles, shelf-life, antimicrobial activity, barrier properties, and starch. Nanoparticles have been used for several years for improving properties of the films, as well as, introducing active agent for preserving food for longer time [58]. The shelf-life appeared in the important keywords list associated with its strong connection with the said topic. Foods generally get spoiled from the growth of microbes inside them. The antimicrobial films thus play a vital role in active packaging. The antimicrobial, as well as, antibacterial property thus plays important role in the fabrication of biodegradable films for active food packaging. For preserving food for longer period another parameter viz. barrier properties appears to be very much relevant. Biopolymers have received immense attention in food packaging research in the last decades owing to their easy availability from renewable resources and ease of processing [59]. Starch, a well accepted biopolymer, has been investigated thoroughly in the considered time frame resulting in its appearance in the list of mostly used keywords. The essential oils from different natural resources are introduced into the biopolymer matrices to make the film active. The spoiled food releases different acidic or alkaline chemicals leading to the alternation of pH of the film. Anthocyanin and other phenolic compounds are introduced into the film to monitor the spoiling of food resulting from the pH change [60-62]. The spoilage of beef and fish results in an increase in pH associated with the liberation of ammonia vapour [63]. The color of the film thus changes from colorless to yellow at pH 6 and orange-red at pH 11[64]. On the other hand, the pH of cow milk decreases (starting from 6.8) on spoiling due to the increase in acidic content in the spoiled milk [65]

The growth of the most important keywords related to our investigation has been plotted in Fig 6C. As evident from the plot, all the keywords lie in an almost linear zone till 2017. After 2017, growth of all the keywords begins, suggesting the growth of the current study in the last 6-7 years. Antioxidant and Chitosan have become increasingly important and become most important in the last couple of years. After 2017, the most important growth was displayed by Edible films, Mechanical properties, and Films. It is worthy to mention that, they are still important in the last couple of years after Antioxidant and Chitosan. In summary, all the related keywords have become increasingly important in the last five years suggesting enhanced interest of the worldwide scientific community in the biodegradable next generation packaging research.

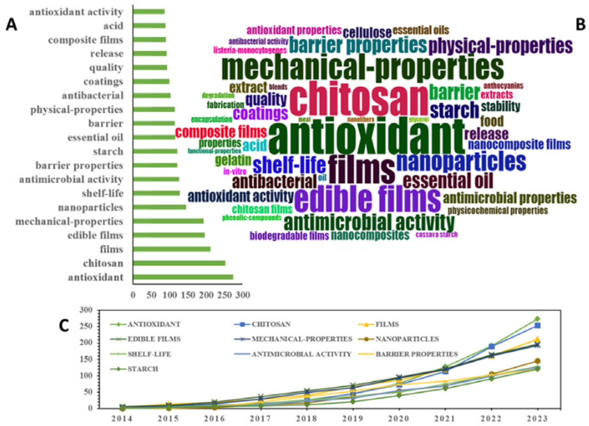

Figure 6. (A) Mostly used keywords on biodegradable smart or active packaging as bar plot and (B) keywords cloud of the most mentioned keywords; (C) Growth of the most active keywords in the considered time frame

Trend Topics Analysis

Fig 7 depicts the evolving trends in the top twenty keywords related to biodegradable multifunctional food packaging during the period 2014-2023. The horizontal line is indicative of the coverage year in the use of keywords and the position of the bubble indicates the year in which the use of the keyword was maximized. Additionally, the size of the bubble is directly related to the frequency of the term mentioned in the publications retrieved from the database. As evident from the figure, the size of the bubbles was maximized in the period 2021-2023, supporting greater number of publications in this period. The most widely used keywords are, 'antioxidant', 'chitosan', and 'nanoparticles' covering the years 2020-2023, maximized at 2022. Another three keywords, viz. 'films', 'edible films', and 'mechanical properties' are found to dominate in the period 2018-2022, being maximized in 2021. So, the trend topic analysis represents six keywords related to multifunctional food packaging in the recent years of investigation. Chitosan has proved itself as an attractive biopolymer for active packaging. As biopolymers are primarily utilized in the fabrication of packaging films, the films appeared as edible. It is worthy to mention that, the biopolymer films suffer from severe mechanical weakness. Thus, the mechanical properties of the composite films appeared as important in the articles retrieved. In the period, 2018-2022, another three keywords, 'barrier properties', 'nanocomposites', 'essential oil' appears to be dominates, maximizing in 2020. Essential oils have been used for the past years for the preservation of food for longer periods. The naturally extracted essential oils are thus utilized in the fabrication of active food packaging materials. Moreover, the barrier properties appear as important when it comes to food packaging.

The incorporation of different nanofillers (nanoparticles, nanosheets, nanoflakes) leads to the improvement in several properties in the nanocomposites. However, the early period of research on multifunctional food packaging was found to be very much chaotic and no inference can be done at the initial phase of any research area. As the development of biodegradable multifunctional food packaging materials was initiated during 2013-2016, there was lack of consistency in the use of keywords and thus a chaotic nature in trend topics analysis plot is evident.

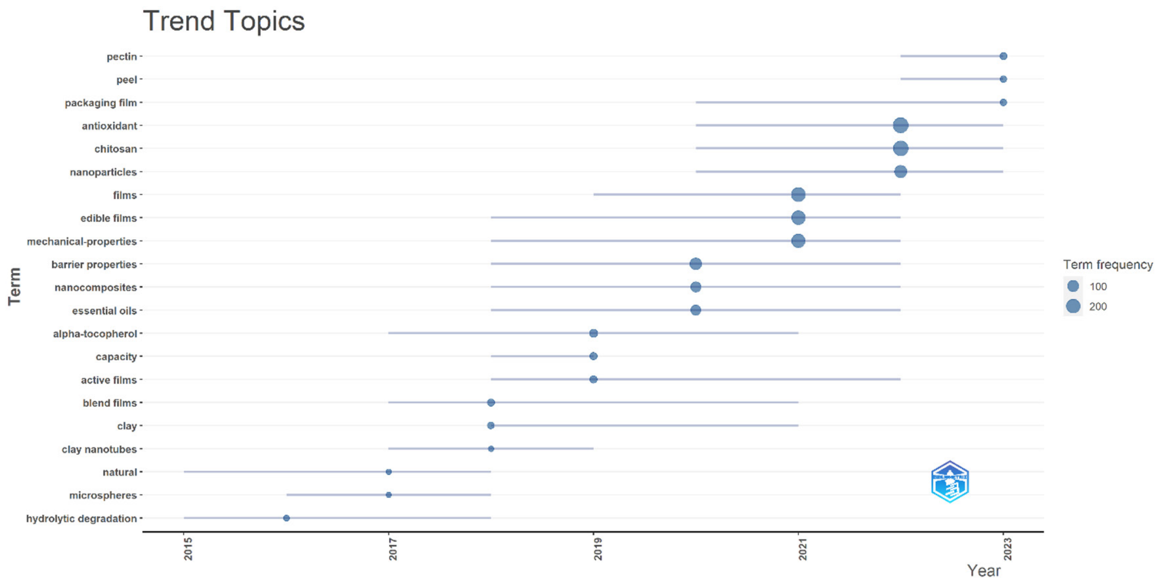

Figure 7. Trend topics analysis for the period 2014-2023

Sustainable Development Goals

Fig 8 predicts the suitable sustainable development goals (SDGs) mentioned in different literatures considered in our study. Sustainable development goals are set by United Nation, targeted to be fulfilled by a certain period. In 2015, seventeen such goals were fixed to be achieved by 2030. These SDGs are also called global goals, focusing mainly on zero poverty, protection of earth and ensuring peace and prosperity of people. The literatures on biodegradable multifunctional food packaging materials predict five major SDGs (SDG 3, 6, 11, 12, and 13) to be associated with this topic. The SDG 3 i.e. "Good Health and Well Being" achieved the maximum mention associated with its close association with the biodegradable smart or active packaging. It was followed by SDG 12 i.e. "Responsible Consumption and Production", SDG 13 i.e. "Climate Action". All the SDGs achieved are closely related with the eco-friendly packaging systems as considered in our present investigation which speaks about sustainability of environment and health of lives on earth.

Analysis of Collaborative Networks between Countries and Authors

Fig 9 represents the network linkages between different countries in terms of co-authorship. The consideration of minimum 10 publications in each author along with 10 minimum citations results in 36 countries which have connections. As evident from the data, China had published highest number of documents (296) followed by Brazil (204), India (141), Iran (133), and Spain (131). Although, the number of documents produced by Spain is less among the five, the link strength is found to be highest in Spain (104). China followed Spain in terms of link strength, and had link strength of 97 during the period considered in the present investigation. USA is found to possess fair link strength (96) after China and Spain. Brazil, with a fairly good number of documents (204) had the least collaborative network strength (41). India with 140 published articles are found to possess mention worthy linkage strength (59). In summing up the results of collaboration between countries, Spain is found to possess highest number of collaboration, while least number of collaborations in Brazil among the five most publishing countries.

The collaboration between different authors in terms of co-authorship has been depicted in Fig 10. The optimization of related parameters (minimum publication = 05; minimum citation per article = 05) results in 110 authors, of which 18 are found to be connected. As evident from the figure, both Mcclements DJ and Ehsani Ali have the same number of documents (12), although Ehsani Ali have more impressive collaborative networks. The link strength of Ehsani Ali (30) is greater than Mcclements DJ (20). This was followed by Hamishehkar H (11 documents and 16 link strength) Sani MA (10 documents 24 link strength). The other authors with appreciably good collaborations are, Tavassoli M, Alizadeh-Sani M with 26 and 12 link strength, respectively.

Analysis Connecting Networks between Journals

The connective links between different journals was studied by studying citations of the published articles in different journals and plotted in Fig 11. In this analysis, the minimum number of publications and minimum number of citations were fixed at 20. Out of the total 242 sources (journals), 15 sources are found to meet the threshold and possesses active connections. The number of documents is found to be highest (154) in 'International Journal of Biological Macromolecules' followed by 'Food Packaging and Shelf Life' (122), 'Food Hydrocolloids' (76), and Polymers (62). The link strength was also found to be maximized in 'International Journal of Biological Macromolecules' displaying a total link strength of 586. This was followed by sources like 'Food Hydrocolloids' (461), 'Food Packaging and Shelf Life' (457), and 'Carbohydrate Polymers'. The other mention-worthy sources with fairly good link strengths are, 'LWT Food Science and Technology' (176), 'Food Chemistry' (161) and 'Polymers' (146).

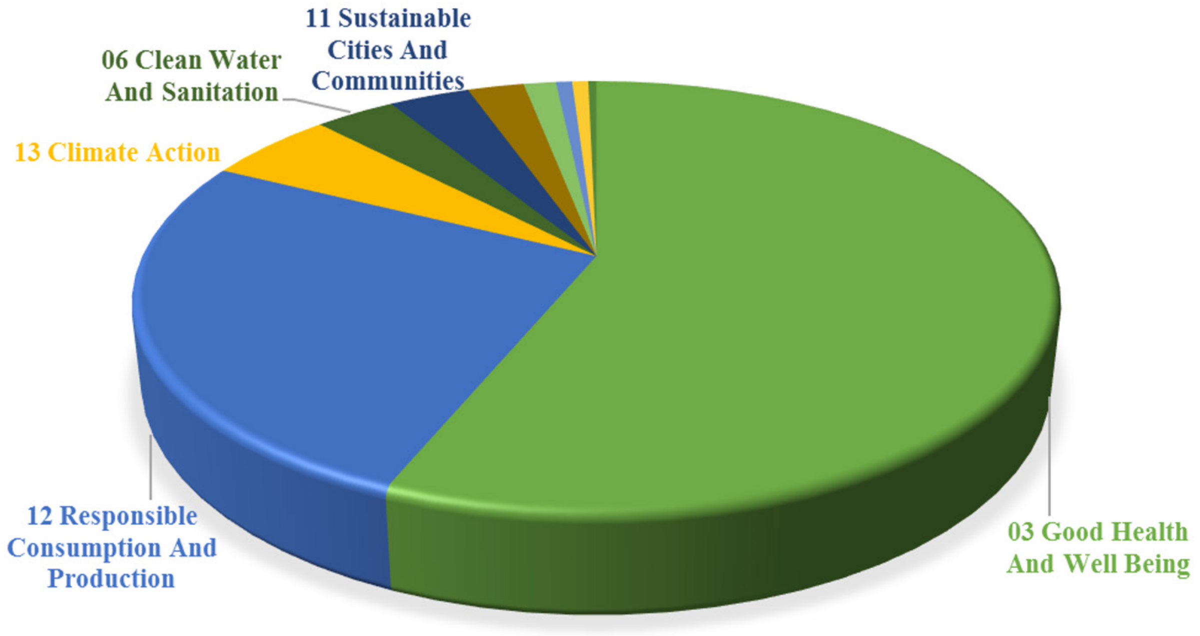

Figure 8. Sustainable development goals mentioned in different articles in the period 2014-2023

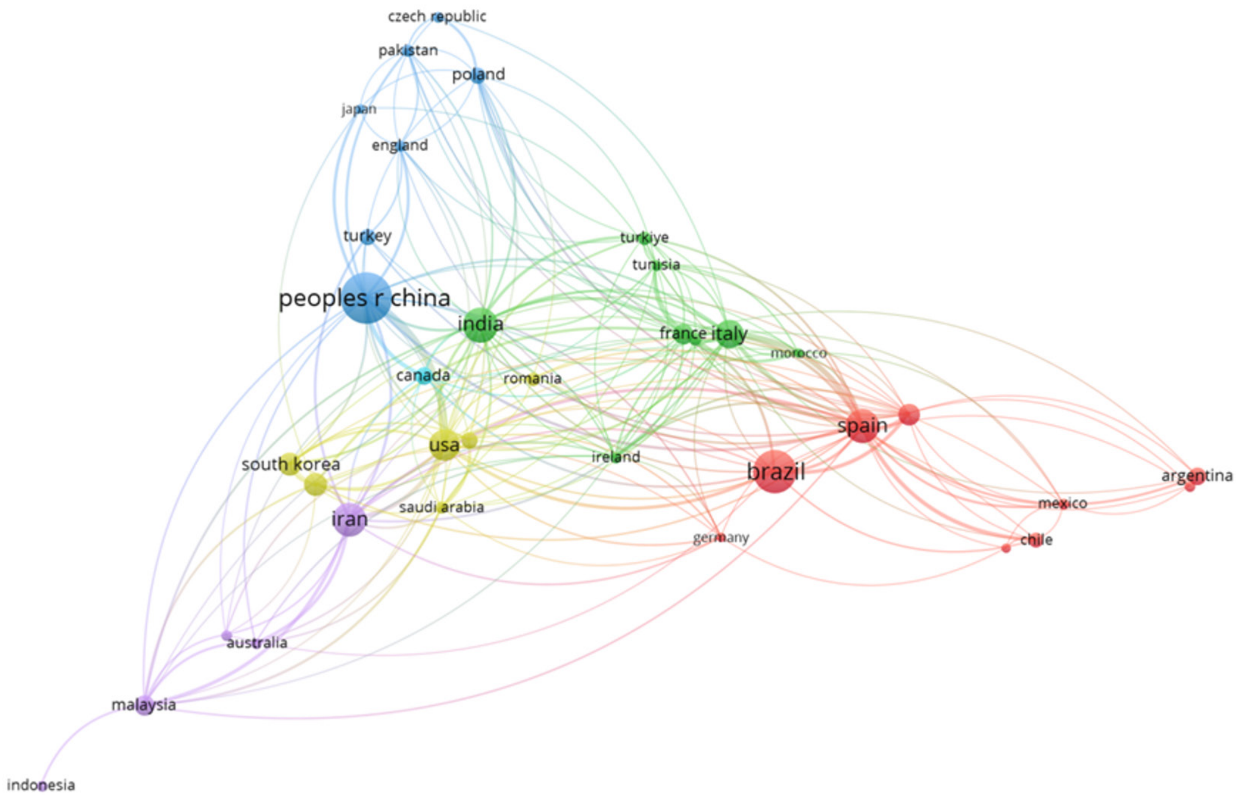

Figure 9. Collaborative networks between different countries in biodegradable smart and active packaging research during 2014-2023

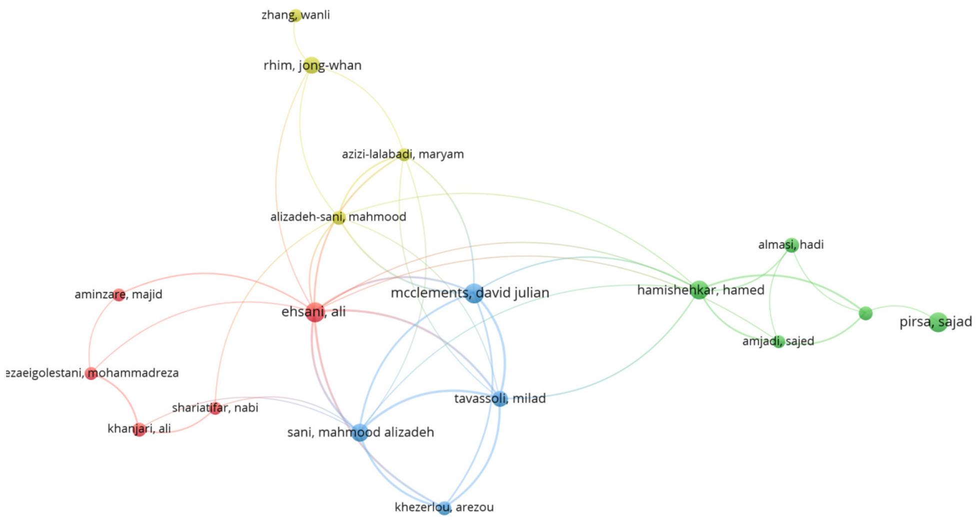

Figure 10. Collaborative networks between different authors in biodegradable smart and active packaging research during 2018-2022

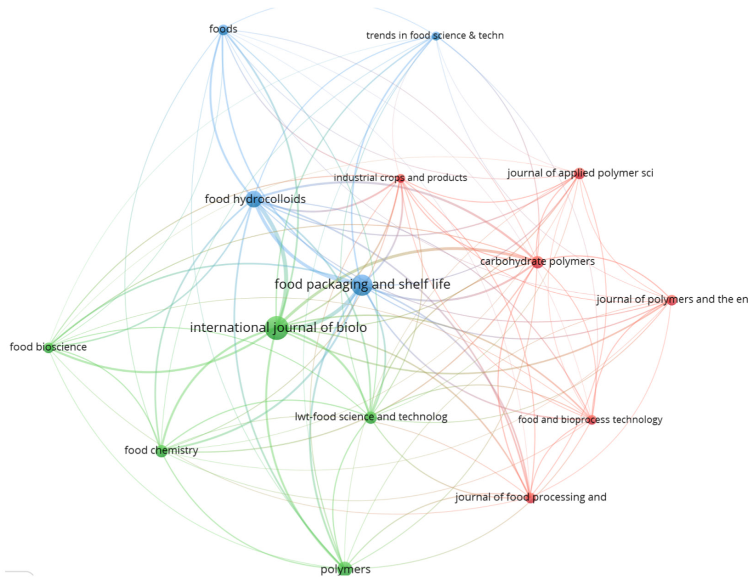

Figure 11. Interconnecting networks between sources publishing articles in biodegradable smart and active packaging during 2018-2022

Analysis of Co-occurrence of Keywords

Fig 12 depicts the co-occurrences of most relevant keywords during the period 2018-2022. To obtain this representation the minimum number of occurrences of the keywords was optimized to 100. This results in 24 interconnected keywords. As evident from the figure, 'Chitosan' had the highest number of mention (364) along with highest link strength (1047). This was followed by 'active packaging' and 'antioxidant' with occurrences 353 and 342, respectively. Although, the link strength of 'antioxidant' (982) is slightly greater than that of 'active packaging' (949). The other keywords with mention worthy occurrences and link strengths are, 'Edible Films' (231, 802), 'mechanical properties' (200, 642), 'antimicrobial activity' (191, 563) and 'Barrier Properties' (160, 552).

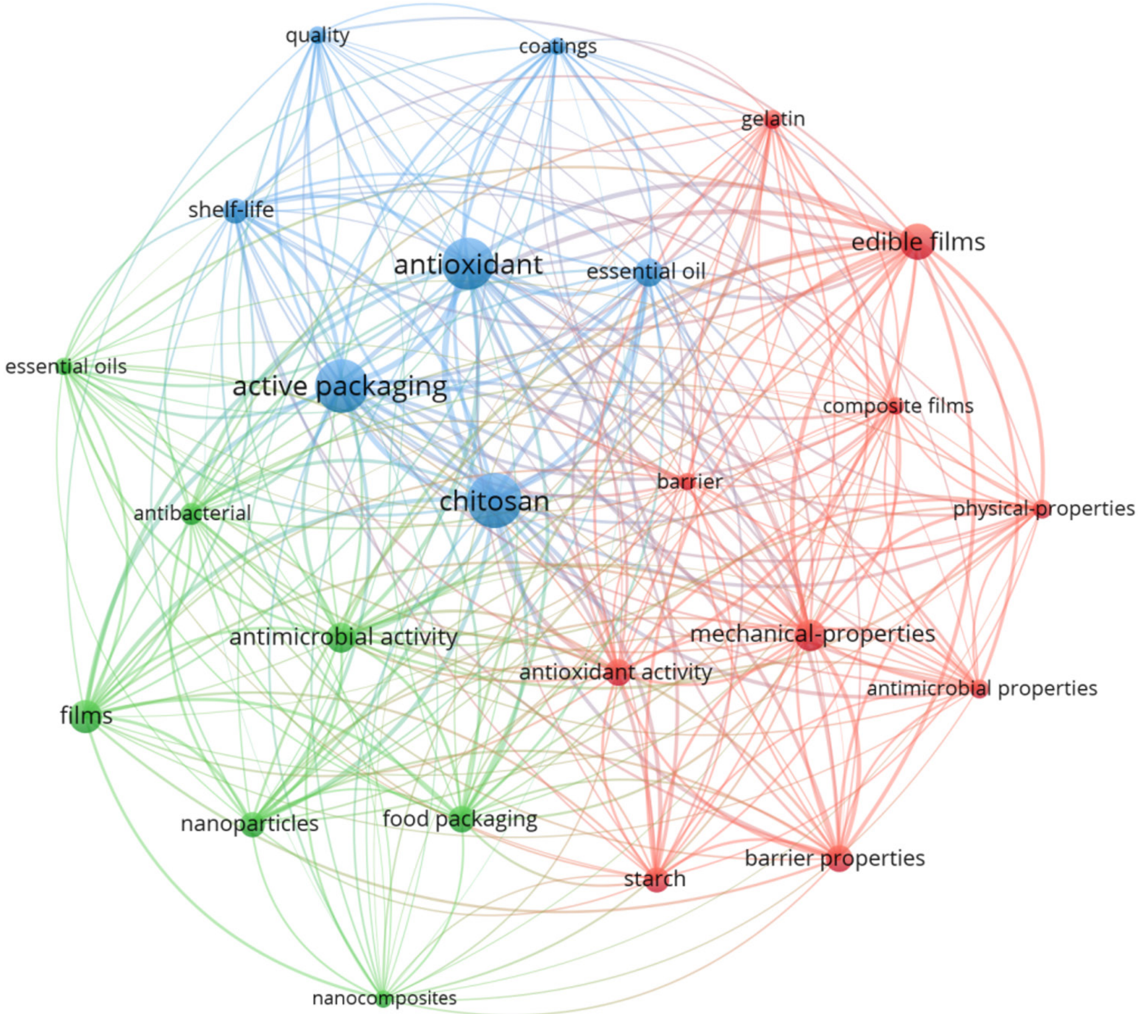

Figure 12. Co-occurrence of most relevant keywords and evolution in biodegradable smart and active packaging research during 2018-2022

DISCUSSION

The present review considers the advancement in the active and smart food packaging systems in the last ten years. The bibliometric parameters related to the present investigation were retrieved from the Web of Science database. The raw data were analyzed by software packages like the Bibliometrix-Biblioshiny package of R, and VOS viewer. As observed, a total 1891 articles were published during 2014-2023, of which 1399 articles were found to be most correlated with the present review.

The global participation in the advanced packaging research finds that the majority of research articles are from China, Brazil, Iran, India, and Spain (in sequence). Although, the ACPP results predict the sequence as, USA, Portugal, Thailand, and Spain, signifying more globally acceptable results from articles produced by these countries. Moreover, the year-wise growth of the present research topic by the top five countries predicts Brazil as the leader in smart and active food packaging research till 2022. However, in the later period, China exceeded Brazil in the number of articles produced. Although the SCP of China and Brazil were equal, the MCP of China was significantly greater than that of Brazil. The greater collaborative links of China as compared to that of Brazil are also evident from the co-authorship analysis via VOS viewer. Very surprisingly, Spain possess the highest inter connecting collaboration links and thus the MCP and SCP of Spain was found to be equal.

The top five producing authors on the present topic are, Wang Y, Liu Y, Wang X, Li J, and Song KB. The highest number of collaborating networks was found to be produced by Mcclements DJ and Ehsani Ali. Thus, the co-authorship analysis predicts Mcclements DJ and Ehsani Ali to be the most competent in global collaboration relating to smart and active food packaging research.

The analysis of the sources of the articles finds 'International Journal of Biological Macromolecules' as the most producing journal in the said topic during 2014-2023, followed by 'Food Packaging and Shelf Life', 'Food Hydrocolloids', 'Polymer', and 'LWT-Science and Technology'. On investigating the citation parameters, the highest ACPP and h-index is found to be highest in 'Food Hydrocolloids'. However, the interconnecting networks between journals in terms of citation predict the 'International Journal of Biological Macromolecules' as the most connected in terms of citations, followed by 'Food Hydrocolloids' and 'Food Packaging and Shelf life'. In summarizing the sources of the articles produced during 2014-2023, it can be concluded that, all the articles were published in food chemistry and polymer chemistry related, highly reputed journals of international repute. .

The analysis of the most frequent keywords related to this topic predict 'antioxidant' as the mostly used author keyword during the said period, followed by 'chitosan', 'films', 'edible-films' and 'mechanical properties'. The growth of the related keywords in the last 5-7 years is indicative of the growing interest in active and smart food packaging systems in the recent years. The analysis of the trending topic predicts, terms like 'antioxidant', 'chitosan', and 'nanoparticles' covering the years 2020-2023, maximized in 2022. Another three keywords, viz. 'films', 'edible films', and 'mechanical properties' are found to dominate in the period 2018-2022, being maximized in 2021. The trend topics data are thus indicative of the motivation of the worldwide scientific community towards sustainable advanced packaging systems utilizing naturally occurring biopolymer resources, resulting the films to be edible. In addition biopolymer films usually suffer from mechanical weakness, thus the enhancement in mechanical properties is very important to make the films eligible for packaging applications; thus, the investigation of mechanical properties has appeared as trending in the recent years. Nanomaterials, such as, zinc oxide, titanium dioxide [66], silver [67], gold [68] etc. are used in the packaging systems in order to make the film eligible for active packaging, restricting the growth of microbes in the packaged food. Chitosan has proved itself as very promising in the active food packaging very recently. The antioxidant property, appearing in the trend topics list (centered at 2021), is a very much important parameter in the active food packaging [69]. Thus, the trend topic data is indicative of a clear switch towards nanopackaging and active packaging.in the most recent years. However, the smart/intelligent packaging systems have still not been explored much and thus have created a lacuna in the advanced packaging systems. The interconnection of keywords was obtained from the VOS viewer network structure. The greater frequency of keywords is associated with their greater number of mentions in the articles considered in our analysis and the number of links signifies their connection with other keyword. The highest mentioned keyword, 'Chitosan' was found to possess the highest link strength signifying its strong correlation with other keywords. The other keywords with the greater number of mentions and link strengths are, 'active packaging', 'antioxidant', 'edible films' 'mechanical properties', 'antimicrobial activity' etc. All these keywords are strongly associated with active packaging systems. However, a lesser connection and appearances has been found with the keywords related to smart packaging systems. Thus, the fabrication of eco-friendly composites for intelligent food packaging has not yet been explored much and has remained as a field of extensive investigation for worldwide scientific community doing research in biodegradable food packaging materials.

FUTURE SCOPE

In investigating the articles related to biodegradable smart packaging, it was found that natural resources, such as, starch, cellulose, and chitosan were used primarily as the matrix polymer. Very few non-renewable polymers, viz. poly(-lactic acid) [70], poly(vinyl alcohol) [71] were also found to be utilized as biodegradable matrix polymers. The main demerits of naturally occurring biopolymers are their severe mechanical weakness, along with their high hygroscopic nature. Several nanomaterials, such as, zinc oxide [72], titanium oxide [66], and graphene oxide [73] were used to overcome the shortcomings associated with these pristine polymers. The incorporated nanoparticles were also reported to preserve the freshness of food for a longer time and inhibit its spoiling. However, the water repellency of the composite films were not well been explored. Wet foods liberate water vapor present in them, and thus the packaging films may get destroyed if not significantly robust enough to restrict water. The chemical structure of the biopolymers suggest enormous hydroxyl groups in the biopolymer surfaces, making them hygroscopic. Crosslinking with suitable molecules thus appeared as a more convenient method to restrict water and make the films robust. Thus, more research focus should be put on generating hydrophobicity of the composite films by considering chemical forces and interaction.

In addition, fabrication of active packaging systems were explored much utilizing renewable biopolymer resources, inorganic nanomaterials, and natural plant extracts. The sustained release from the packaging films restricts the microbial growth and helps in the preservation of food for a longer period. On the other hand, the intelligent films offers the spoilage of food from the color change of the indicator film. Several, natural extracts were incorporated into the biopolymer matrix to track the food spoilage from the change in color of the packaging films. The spoilage of food generates volatile chemicals leading to changes in the pH of the films. Naturally occurring indicators are introduced into the matrix to make the pH change visible. Although, active packaging systems were widely explored in the last decade, very little work has been done on the smart packaging utilizing natural extracts and thus has created a lacuna in the biodegradable advanced packaging systems. Moreover, there is a significant scarcity of investigation in the complete advanced packaging systems, which not only restricts food spoilage, but also indicates the spoilage of food from the visual change of packaging systems.

CONCLUSIONS

The progression in the biodegradable active and smart packaging research in the last decade has been quantitatively reviewed in the present manuscript. The Web of Science database was utilized in the present topic as it gives more relevant articles compared to the other existing databases. As evident from the data, the number of publications was in an inclining trend, suggesting the growing interest of the research community towards biodegradable active and smart packaging research. Moreover, the last five years of research on biodegradable smart packaging systems produced more articles compared to the earlier five years, signifying the enhanced research interest of the scientific community in recent years. The participation of the countries around the globe predicted, countries like China, Brazil, Iran, India, and Spain are major contributors to this research. However, articles from the USA, Portugal, Thailand, and Spain received more citations, indicating their wider acceptance in the global scientific community. China had the highest number of collaborative networks, while Brazil had the fewest. Spain, despite fewer publications, had a significant number of collaborations. From 2014 to 2023, leading journals publishing on this topic included 'International Journal of Biological Macromolecules', 'Food Packaging and Shelf Life', 'Food Hydrocolloids', 'Polymer', and 'LWT-Science and Technology'. The most frequent keywords in this research were 'antioxidant', 'chitosan', 'edible films', 'films', and 'mechanical properties'. Most studies used biopolymers, which are edible but have mechanical weaknesses, making the study of their mechanical properties crucial. Chitosan is widely used due to its effectiveness in active packaging systems, and antioxidants are commonly mentioned due to their relevance in active packaging. The analysis of the trend topics also suggests properties, such as mechanical properties and antioxidants, matrix materials, such as chitosan, and nanomaterials as reinforcements as the prime topics in the recent years of biodegradable active and smart food packaging research. The analysis also highlighted gaps in research. For instance, water resistivity and chemical interactions between components, crucial for wet food packaging, are not well-explored. Smart packaging systems using natural extracts and the dual use of packaging for both smart and active functions also remain challenging areas.

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DATA AVAILABILITY STATEMENT

No data was used for the research described in the article.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

USE OF AI FOR WRITING ASSISTANCE

Not declared.

ETHICS

There are no ethical issues with the publication of this manuscript.

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