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A decade of intelligent packaging for meat with insight from smart packaging literature: Trends, innovations, and future prospects - a systematic review and network analysis

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Abstract

Packaging no longer serves merely as a protector or wrapper for products, but also functions to maintain quality, safety, and extend the shelf life of food products. Especially for meat products, the demand for packaging systems capable of monitoring quality in real-time continues to grow. This is because meat products are susceptible to damage due to contamination and microbial oxidation. Therefore, intelligent packaging offers a solution by integrating sensor and indicator technologies to detect changes in the environment such as pH, temperature, and volatile compounds. This study aims to examine trends, publications, and research developments in intelligent packaging for meat packaging from 2014 to 2024 using bibliometric methods. Additionally, a systematic literature review method was used to examine the application of various types of intelligent packaging on meat. Data was collected from the Scopus database, which covers various applications of intelligent packaging on meat products. The application of intelligent packaging shows an increasing trend each year. The most commonly applied technologies include pH indicators, gas sensors, temperature-time indicators, and RFID. These technologies can be used to monitor the freshness, temperature, and quality of meat. These findings underscore that smart packaging is no longer merely a future innovation but a strategic solution ready for adoption by the food industry to enhance the safety, efficiency, and competitiveness of meat products in the global market.

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Intelligent Packaging, Meat, Indicator, Application.

1. Introduction

In recent decades, packaging no longer only serves as a product protector, but has evolved into an important part of maintaining food quality and safety. The food industry, especially meat, faces major issues such as maintaining quality, microbiological safety, and very short shelf life of products. This has led to an increased need for packaging systems that can provide information about product quality. Intelligent packaging is an innovative solution that utilizes digital technology, sensors, and indicators to monitor product conditions in real-time and provide important information to manufacturers and consumers.

Intelligent packaging part of modern packaging that combines detection, tracking, communication, and product quality monitoring functions during distribution and storage (1). This technology is designed to respond to changes in the packaging environment, such as

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temperature, pH, oxygen levels, carbon dioxide, and other volatile compounds related to the freshness of meat products. Color indicators, biosensors, and Time Temperature Indicators (TTI) are some of the main components of this system. The advantages of intelligent packaging lie not only in its ability to extend shelf life and detect contamination but also in enhancing consumer confidence in the products they purchase (2), and supporting global efforts to reduce food waste. Therefore, the application of intelligent packaging in meat is an important strategy that can address the needs of modern consumers for safe, reliable, and sustainable food.

Studies related to the implementation of smart packaging, which includes intelligent and active packaging, have been conducted by Dirpan et.al (3), is a review of the application of smart packaging consisting of intelligent and active packaging covering all types of foodstuffs. In the context of meat packaging, intelligent packaging is very important because meat is a product that is highly susceptible to microbial damage, oxidation, and enzymatic autolysis (4,5). Technologies such as freshness indicators, time-temperature indicators (TTIs), and gas sensors have been applied to detect changes in meat quality during distribution and storage (6–8). Previous studies have highlighted the potential and implementation of this technology in meat packaging, for example by (9), who gave a presentation on the use of biosensors and antimicrobial indicators in meat packaging. Similarly, (10) reviewed smart packaging systems to extend the shelf life of meat products.

However, to date, there is no scientific review that specifically reviews the development of intelligent packaging trends in meat objectively and holistically with a comprehensive network analysis approach with a systematic review. Most studies discuss general aspects or specific technical or applicative focuses, without looking at the dynamics of scientific development as a whole, such as the distribution of topics, lead authors, most active countries, and collaboration between researchers. This is important in the food sector, as such mapping plays a role in understanding the direction of research, development opportunities, and efforts in facing future challenges.

Therefore, this review aims to present a network analysis of trends and developments in intelligent packaging research in meat packaging from 2014 to 2024. This study not only presents publication statistics but also explores key keywords, countries, and topics with high visibility, as well as the most productive and developing journals, as a basis for further research development. In addition, it is also to present various types of intelligent packaging applications in meat and the performance and weaknesses as intelligent packaging and determine future research opportunities. The results of this review are expected to provide a deeper understanding of the intelligent packaging research landscape in meat, and help researchers, industry players, and policy makers identify directions and strategies for developing packaging technologies that are more innovative, sustainable, and responsive to global food safety challenges.

2. Materials and Methods

This study used network analysis and systematic review. The data used was extracted from the Scopus database using the keywords “Smart packaging" OR "Intelligent Packaging" AND beef OR meat, limiting the search to the article title, abstract and keywords and the publication range from 2014-2024. Documents other than articles, reviews, and conference papers were excluded.

Table 1. Data search process "Intelligent packaging" in Scopus

Formula	Result
Title abs keyword • "Smart packaging" OR "Intelligent Packaging" AND beef OR meat	371
Years: 2014 - 2024	281
Document type: • Article (201) • Review (73) • Conference paper (9) • Language: English • Data base: Scopus	

The data was extracted on April 11, 2025, any changes that occurred after that date are not taken into account in this review.

2.1. Identification

This study uses a combined approach of Systematic Literature Review (SLR) and Network Analysis, each of which is analyzed using the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework and bibliometric methods. This approach was chosen to provide a structured understanding to ensure transparency, completeness, and accuracy in reporting research findings (11,12). In general, this approach provides an understanding of the trends, innovations, and future prospects of intelligent packaging in meat products in the past decade. All literature data was obtained from the Scopus database, which is known for its wide coverage and credibility in the international scientific literature. Data collection was conducted on March 11, 2025, at 13:11 (UTC+8), using the PRISMA method and bibliometric methods to ensure the integrity and accuracy of the publications analyzed. This study not only highlights the dynamics of topic development based on qualitative and quantitative analysis but also reveals the structure and relationships between keywords through network visualization of countries, authors, keywords, and citations.

At the identification stage, the PRISMA method plays a role in systematically and transparently screening various literatures, thus minimizing selection bias and ensuring the coverage of relevant data (13–15). he literature search process is performed using Boolean queries: (TITLE-ABS-KEY ("Smart packaging" OR "Intelligent Packaging") AND TITLE-ABS-KEY (beef) OR TITLE-ABS-KEY (meat)), which is designed to cover relevant studies in the domain of intelligent packaging in meat products. The term "intelligent packaging" was chosen to collect data related to indicator- and sensor-based packaging technologies used in product quality and safety monitoring, while "smart packaging" was chosen to add insight into intelligent packaging that has been applied in smart packaging. Meanwhile, the keywords 'beef' and "meat" were used to cover specific research on beef as well as more general research on various types of meat. This method was carefully designed to strike a balance between specificity and breadth of data, thereby avoiding bias and the inclusion of irrelevant studies while ensuring that only publications with a substantial focus on the application of intelligent packaging in meat were included in further analysis

2.2. Screening

A rigorous literature selection and screening process is an important stage in systematic literature review. The screening stage in systematic review is a crucial step to ensure that only the most relevant, high-quality documents that meet the criteria are included in further analysis (16). The initial identification process resulted in 371 documents from the Scopus database. Further screening with inclusion criteria to filter publications is based on document type and language. Only documents categorized as articles, reviews, and conference papers were considered, as these three types of publications have a methodologically sound scientific structure (n = 293). In addition, language screening by including only English-language documents (n = 281), ensures a common understanding of the content, uniformity of analysis, and ensures the international relevance of the publications analyzed. Documents that did not meet both criteria were eliminated and not analyzed further. Thus, a total of 281 documents were deemed eligible for in-depth analysis. Next, all selected documents were processed in the bibliometric analysis stage using a network approach to identify keyword trends, productivity, collaboration patterns, and research topic structure in the field of intelligent packaging in meat products. This approach not only increases the credibility of the review results, but also provides a strong basis for understanding the research concepts on the topic of intelligent packaging that have developed systematically over the past decade.

The screening process continued in a second stage with a more in-depth selection based on publication type to ensure that only relevant primary empirical studies that made a direct contribution were included in the systematic review. In this process, documents classified as conference papers and reviews (n=82) were excluded from the data set. These two types of publications, while providing useful initial insights and theoretical discussions, generally do not present the full extent of primary data. This is because they are not designed with a rigorous experimental methodology, or do not include the in-depth analysis of results found in original research journal articles (17). Therefore, they did not meet the inclusion standards set for this stage of the systematic review. Only documents in the form of peer-reviewed research articles were retained as they were considered to have higher methodological clarity, data transparency and scientific validity. The results of this screening resulted in a total of 201 documents out of the original 281 that were declared eligible for further processing in the next stage, namely eligibility. This stage is an important basis to ensure that only publications that are relevant, scientifically valid, and appropriate to the research context are analyzed within the framework of this systematic literature review.

Table 2. Inclusion and Exclusion Criteria

Inclusion and Exclusion Criteria
Inclusion criteria 1. Research focuses on the application of intelligent packaging on meat. 2. Research range 2014-2024 3. Research published with article documents, conference papers, reviews 4. This article is in the final publication stage 5. Using English
Exclusion Criteria 1. This research does not focus on the application of intelligent packaging to meat. 2. This research is not published within the time span of 2014 - 2024 3. This research is not published as a research article, conference paper, or review. 4. The article is not in the final publication stage 5. The research is not written in English

2.3. Eligibility and Included

At the Eligibility stage, 201 articles that had passed the previous screening process were then examined in depth based on five predetermined eligibility criteria (Table 3). First, each article was reviewed to ensure that the research objectives were clearly explained, either through explicit statements such as "this study aims to" or implicit forms that indicate the direction and focus of the study explicitly. Second, the articles were analyzed to ensure that the discussion of Intelligent Packaging for meat products was explained in real terms, not just prototypes or theoretical concepts, but had been actually implemented or tested. Third, an assessment is made of the clarity of the research results and the adequacy of supporting data, such as storage temperature, test duration, how the packaging indicators work, and also the limitations of the packaging system studied. The fourth criterion relates to the availability of the full version of the publication, i.e. whether the article can be accessed in its entirety through a subscription to the relevant scientific institution or association, so that the content of the methodology and analysis can be examined comprehensively. Finally, articles were eliminated if they did not directly answer the formulation of the research question, for example articles that discussed packaging in general without focusing on intelligent packaging systems for meat products. After systematically applying these five criteria, 158 articles were eliminated because they did not meet one or more requirements. As a result, only 43 articles met full eligibility and were then included in the fourth stage or included, which is the main basis for conducting systematic analysis in this study.

Table 3. Quality Review Criteria

Quality Criteria
1. The research objectives are clearly stated.
2. The research is clearly applied to meat and not just a prototype.
3. The temperature, duration, packaging method (including indicator results), and results are clearly described.
4. The author identifies the limitations or weaknesses of the research and provides suggestions for further research.
5. The full version of the publication is available through subscriptions to relevant institutions or associations

2.4. Network Analysis

Network analysis is a systematic research approach that analyses scientific publications, particularly journal articles, using quantitative techniques and metric analysis with bibliometric methods. The purpose of this analysis is to understand and identify trends, developments, and the impact of research in a particular field. It also tracks the influence of articles or authors involved in the research and estimates future research developments (18–20). Bibliometric analysis is conducted using metrics such as the number of publications, the number of citations, and the h-index. The number of citations reflects how often a writer's work is cited by other writers, while the h-index measures the number of publications and the number of citations received by that work (18). Bibliometric analysis provides important insights for researchers, policy makers, and those involved in the development of a field of science (21). The data obtained were analyzed using Open Refine and VOS viewer (v.1.6.20), while visualization and statistical analysis were performed with Tableau and R-Studio. All data were then exported using Microsoft Office.

The network analysis stage is carried out using bibliometric methods to identify the structure, dynamics, and conceptual relationships in research on intelligent packaging for meat products, especially beef and meat. Based on figure 1, a total of 281 documents from the Scopus base were obtained, which have been obtained in the initial stage used in this analysis to answer research questions such as publication trends, the most productive journals and countries and topics that have developed over the past decade. The network analysis process began with filtering and standardizing bibliographic data using Open Refine to ensure consistency in author names, affiliations, and keywords. Next, VOS viewer (ver.

1.6.20) was used to construct and visualize bibliometric networks such as co-authorship, keyword co-occurrence, and citation mapping. To enrich visual understanding and statistical exploration, the processed data is further analysed using Tableau and R-Studio, enabling interactive visualization and in-depth quantitative analysis of patterns in the data. All results and graphs from this process are exported and compiled using Microsoft Office for reporting and finalizing the results. This approach provides a strong foundation for evaluating the scientific concepts of this topic, as well as identifying current and emerging research directions in the field of intelligent packaging for meat.

2.5. Systematic Review Analysis

Systematic review analysis is a systematic method used to collect data with explicit methods to answer research questions based on previous research. Systematic review analysis consists of several stages, which include comprehensively searching the literature, developing research results, evaluating the quantity and quality of evidence, and analyzing to determine the conclusion of the research question. Thus, this method can review articles and all available evidence, reduce bias, and produce reliable results (22–24).

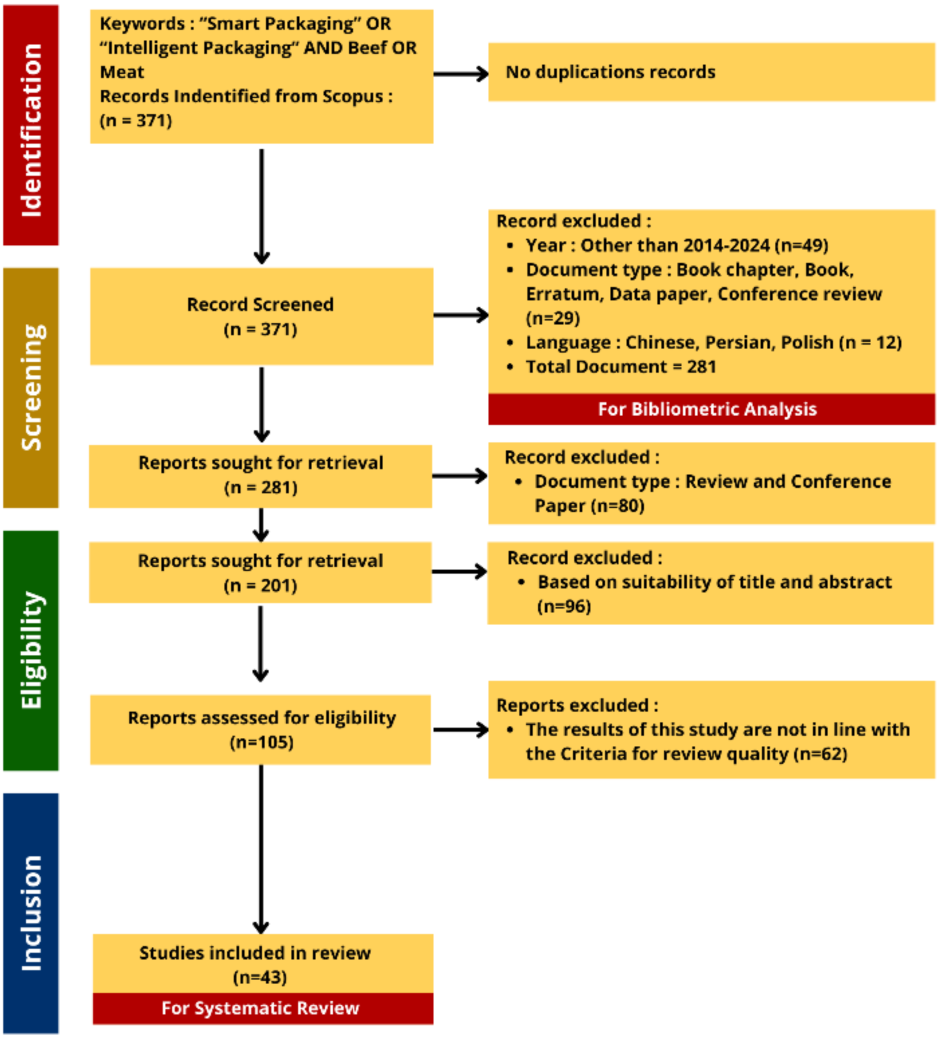


Figure 1. Data analysis mechanism and systematic review, following PRISMA methodology.

2.6. Limitation

As many contributions and benefits as this research can provide, its limitations suggest that more sophisticated methods can be used in future research. This is because this review may not cover all relevant publications as the search results were limited to titles, keywords and abstracts. As a result, the completeness of the data used is limited due to the limited number of relevant publications obtained. Also, since the bibliographic analysis only uses quantitative methods, it may be difficult to understand the content and quality of the publications. Although the tools and technologies used in this study have been scientifically validated, there are concerns about the depth and accuracy of the results due to the lack of qualitative analysis. Thus it is necessary to expand the analysis by including more relevant keywords and adding qualitative analysis in it.

3. Results and Discussion

3.1. Trend Analysis of Intelligent Packaging in Meat

The results of the analysis can be seen in figure 2 which shows a significant increase from 2014 to 2024. This can be seen from the number of available documents, such as reviews, articles and conference papers that show the development of this research. The increasing number of publications on smart packaging, especially intelligent packaging, is influenced by its unique ability to monitor the condition of the packaged product while maintaining quality and extending the product's shelf life. This capability is the main attraction of intelligent packaging compared to conventional packaging, thereby attracting the attention of researchers. Additionally, intelligent packaging offers business opportunities in the era of digitalization and is thus well-suited to the broader realm of Industry 4.0. (7,25). This review uses the search year between 2014 and 2024, with the acquisition of 283 documents, consisting of 201 articles, 73 reviews, and 9 conference papers. Based on the results of the analysis, the type of document with the smallest publication is conference papers where the majority of research article types are publications in the field of intelligent packaging published in various journals. The high difference in the number of article publications can be influenced by the publication of articles that have more potential in improving reputation. This is because research articles tend to be cited because they provide primary data that has the potential to increase researchers' h-index (26). In addition, many reputable journals publish research articles rather than review articles because they offer empirical data that can be retested and validated. Article publication is therefore more desirable to researchers as it potentially paves the way for other opportunities such as research and collaboration.

Indicators for determining research standards and trends in the field are based on the most cited and most prolific journals with discussions on intelligent packaging research. These journals will also help in scientific analysis and research. The number of citations in a journal is usually influenced by its quality, popularity and novelty. In addition, the number of citations in publications also allows for increased collaboration activities between researchers (27,28). Other indicators, such as h-index and quartile values, can also be used to measure the journal's influence on the scientific community in the development of a topic. However, this is only one of the important factors in evaluating the quality of a journal, many other factors can also influence it. Table 4 shows the most productive and most cited journals on the intelligent theme, along with their h-index and quartile values. The documents published in the period 2014-2024 totaled 283 documents, and consisted of about 107 different publication sources involved in the publication. Based on table 4, it can be seen that there are about 10 journals that are most productive in publishing documents that discuss intelligent packaging on meat, which is seen from the number of published documents, h-index, quartile value and number of citations.

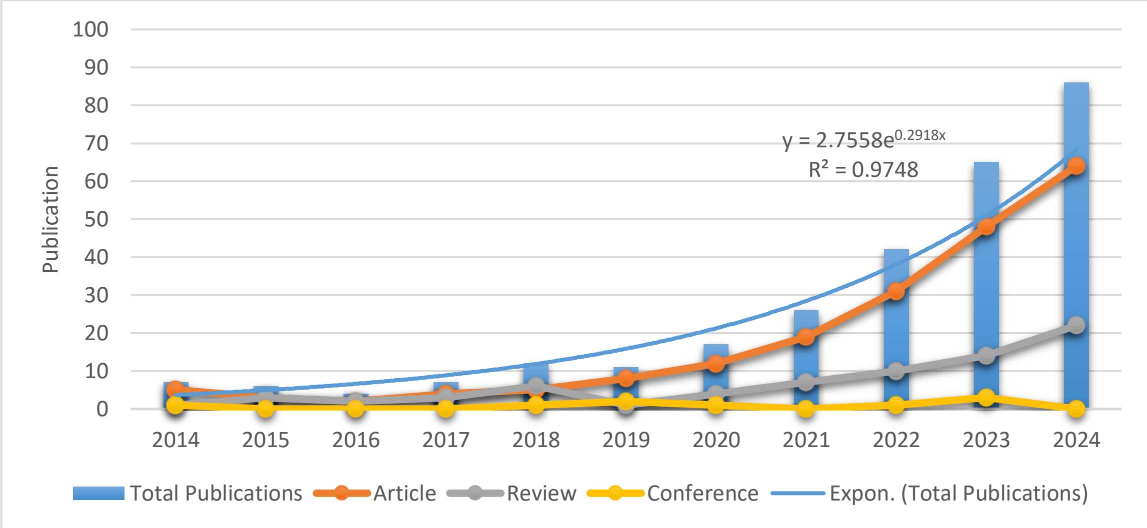


Figure 2. Journal publication trends per year in the field of intelligent packaging for meat.

Table 4. The Most productive sources publishing trends in the field of intelligent packaging for meat

No	Sources	TP[a]	Publisher	*h*_index[b]	Q[c]	TC[d]
1.	International Journal Of Biological Macromolecules	32	Elsevier B.V.	191	1	163
2.	Food Chemistry	29	Elsevier Ltd	324	1	98
3.	Food Packaging and Shelf Life	15	Elsevier B.V	89	1	8
4.	Foods	12	Multidisciplinary Digital Publishing Institute (MDPI)	123	1	11
5.	Food Hydrocolloid	8	Elsevier B.V.	235	1	38
6.	Food Bioscience	8	Elsevier Ltd	77	1	26
7.	Sensors and Actuators B: Chemical	7	Elsevier B.V.	248	1	8
8.	Trends in Food Science and Technology	6	Elsevier Ltd	271	1	11
9.	Meat Science	6	Elsevier Ltd	205	1	0
10.	LWT	6	Academic Press	187	1	3

a Total publication of the journals 2014–2024.
b Journal's h-Index in the scopus data.
c Quartile based on scimago report 2025.
d Total citation 2024
ND =No data.

Based on the data obtained, it can be seen that the International Journal of Biological Macromolecules is the most dominant journal for the number of publications (32 documents), followed by Food Chemistry, and with a total of 29 published documents. The scope of research that focuses on biological macromolecules is the possibility of the high number of publications in the International Journal of Biological Macromolecules. Biological macromolecules are organic materials commonly used in the production of sustainable intelligent packaging (22,29). This allows the high publication of these journals related to the field of intelligent packaging. Based on the number of citations in 2024, International Journal of Biological Macromolecules is also the journal with the highest citation value (163 citations with 21 documents). The most cited document is a review entitled "Stretchable, antifatigue, and intelligent nanocellulose hydrogel colorimetric film for real-time visual detection of beef freshness" which received 20 citations. The journal with the second highest number of citations is Food Chemistry (98 citations). The document with the highest number of citations in this journal is the article entitled "A ratiometric fluorescence amine sensor based on carbon quantum dot-loaded electrospun polyvinylidene fluoride film for visual monitoring of food freshness", with 28 citations.

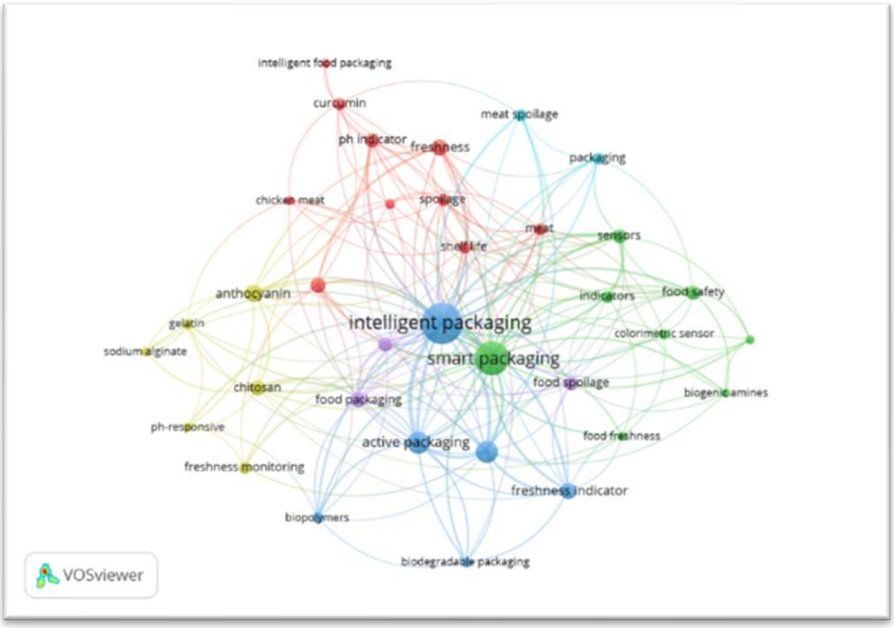
Based on the number of citations data, it can be seen that topics that discuss intelligent packaging on meat are being widely cited at this time. The rise of food loss cases in meat, which reached 23% due to the process of distribution, service, and consumption of food (30). This encourages packaging researchers to develop intelligent packaging to monitor meat quality, so the topic increases every year. In addition, the title with the keywords "real-time monitoring capability, visual detection, colorimetric film and ratiometric fluorescence sensor and meat freshness" is an innovative, applicable, descriptive and informative topic that is easy to find. The topic is interesting because it is in line with supporting the global demand for meat safety and quality so that real-time monitoring and the development of mini, cheap and responsive sensors are needed (7,31,32). In addition, this topic is also closely related to efforts to reduce the number of food waste and food lose. Where the intelligent packaging system is in line with the concept of Smart Supply Chain and Industry 4.0. This is because the concept supports monitoring technology, distribution optimization, and prevention of quality loss in meat products, so researchers are interested in developing a digitalization system for packaging (33). As for other results when viewed as a whole, the journal with the most citations comes from article documents. This shows that on the topic of discussing the application of intelligent packaging in meat, researchers are more likely to cite article documents rather than review results or conference papers. This is because research articles are obtained from scientific research and have been rigorously reviewed. In addition, articles from top journals are considered more weighty so they are widely cited (34).

3.2. Co-occurrence network analysis of author keywords

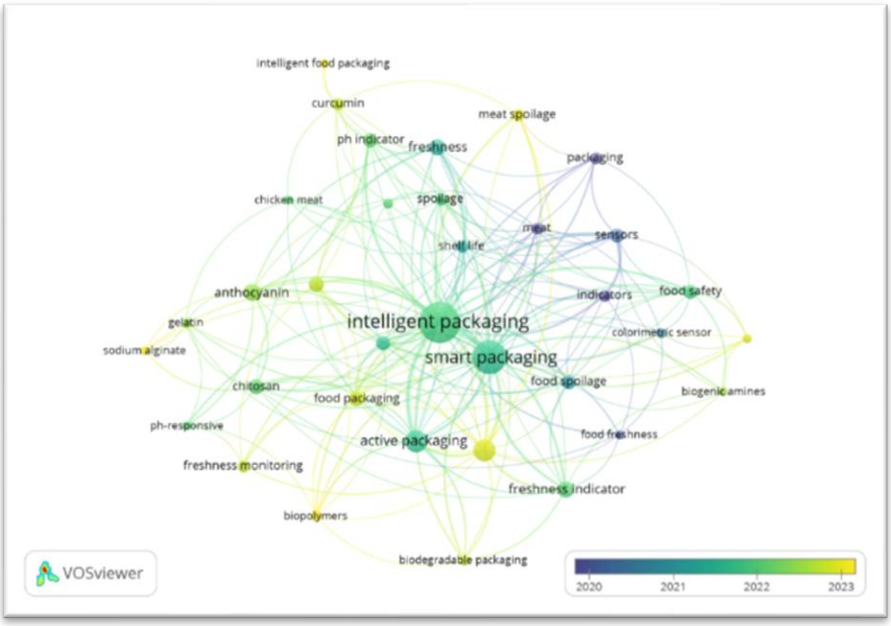
Co-occurrence network of author keyword analysis is an analytical method in visualizing the frequency of relationships between keywords that appear. This method is used to identify the repetition of keywords or the most used by authors who discuss the same topic in a journal or article with other keywords (35,36). The principle of this analysis is that keywords that frequently appear together will be connected to each other in a network. The network is then further analysed to understand the relationship between the keywords (37,38).

The visualization of the relationship between keywords in a network makes it easier for researchers to identify the most relevant, least used and most closely related keywords to the topic being discussed. In addition, this method allows researchers to understand the topic more comprehensively (37). The co-occurrence network analysis of author keywords (figure 3a and 3b) was visualized using VOS viewer software with the keywords "Smart packaging"

OR "Intelligent Packaging" AND beef OR Meat. The minimum number of keyword occurrences was set at 5, and among the 764 keywords, 35 met the threshold, and the total link strength was 410. The number of keywords to be selected is 35 starting from 2014-2024. The co-occurrence network images based on the keywords of the authors of intelligent packaging articles from 2014 to 2024 are presented in figure 3a and b.



(a)



(b)

Figure 3. Co-occurrence network: author keywords used in intelligent packaging articles (a) and author keywords of articles in the field of intelligent packaging (b) from 2014 to 2024.

Co-occurrence network analysis of the author's keywords shown in figure 3a was performed to assess the degree of association between items grouped under the topic "intelligent packaging for meat." The formed network consists of 35 items and is divided into

6 clusters displayed with different colors in figure 3a: cluster 1 (red), cluster 2 (green), cluster 3 (blue), cluster 4 (yellow), cluster 5 (purple), cluster 6 (cyan). Each cluster shows the relationship between keywords in a publication. The color of the circle shows the relationship between keywords in one cluster. While the size of the circle in the cluster shows the number of publications that use the keyword. Where the bigger the circle, the more publications that use it.

Based on figure 3a, the most dominant cluster is cluster 3 (blue), which consists of 6 items with a total of 180 occurrences and focuses on the field of intelligent packaging. In the co-occurrence network analysis of author keywords, intelligent packaging shows relationships with several other clusters, including cluster 2 (green) with 8 items and 119 occurrences focusing on the field of intelligent packaging; cluster 4 (yellow) with 6 items and 54 occurrences focusing on the field of anthocyanins. In addition, cluster 1 (red) with 10 items and 90 occurrences focuses on the field of freshness, cluster 5 (purple) with 3 items and 36 occurrences focuses on the field of food packaging, and cluster 6 (cyan) with 2 items and 17 occurrences focuses on the field of packaging. Based on this, it can be seen that the cluster formed has a role in developing more innovative and sustainable intelligent packaging technology to maintain the quality and safety of meat products. When viewed through the visualization of keyword relationships based on time evolution, the results of bibliometric analysis research on intelligent packaging in meat also show some future research opportunities. Based on the legend that arises, keywords marked with purple columns are keywords that have been widely used in previous research. While the words displayed in the yellow column are new terms that are currently being focused on by researchers, have the potential to be further developed to be combined with other keywords to create novelty in the field of packaging.

3.3. Analysis of Publication Countries

The number of publications published by a country can represent how productive and how many researchers are studying a research field with a certain topic. In figure 4, it can be seen that there are 57 countries that have participated in research on intelligent packaging. China has the highest number of publications (101) in this field, followed by Iran (37), United State (24), India (23), and Brazil (20), as well as Indonesia (14) and other countries.

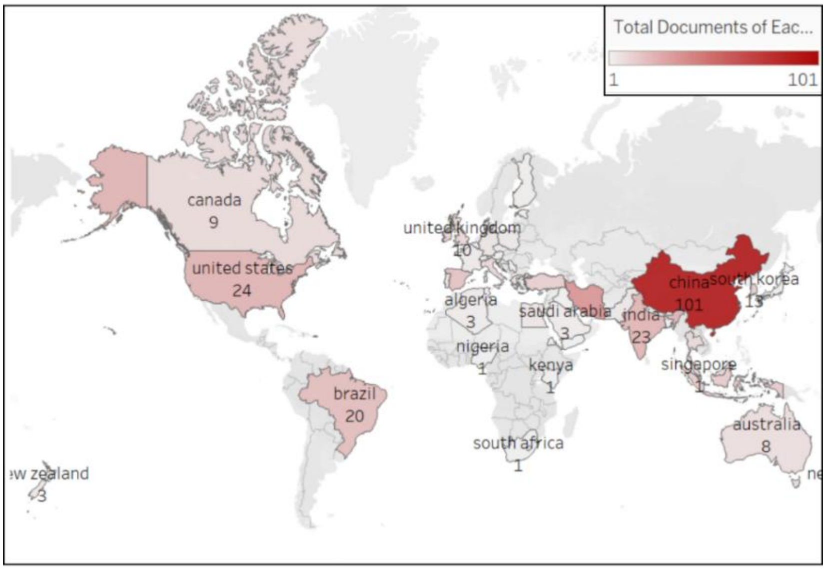


Figure 4. Number of documents issued between countries.

Table 5. Top Countries in terms of productivity.

Country	Total Publication	Total Citation	Total Link Strength
China	101	4,584	52
United State	24	2,107	28
Iran	37	1,796	20
South Korea	13	1,788	6
India	23	1,352	18
Spain	18	1,234	34
United Kingdom	10	1,099	10
Brazil	20	1,099	15
Australia	8	1,083	10
Canada	9	1,078	8
Thailand	9	588	6
Turkey	14	426	24
Ireland	12	372	25
Indonesia	14	279	2
Singapore	1	222	2

Based on this data, it appears that China is the most productive country in terms of publications and research on intelligent packaging for meat. China's status as a developed country, its large population, and strong government support for technological advancement are factors that contribute to China's high productivity in this field. Additionally, the abundance of natural and human resources drives research and development in intelligent packaging technology. This is evidenced by China's significant market interest of 56% in intelligent packaging technology (39,40). In addition to the number of publications produced by each country, the citation rate of each country's articles is also an important factor in analyzing and evaluating the quality of the articles and their role in the progress of research on intelligent packaging. The productivity level of each country is taken based on the 15 countries with the highest number of citations (Table 5). Based on the data, it can be seen that China is the most productive country with a total of 4,584 citations, followed by the United State with 2,107 citations, then Iran with 1,796 citations. This shows that publications from these countries have a significant influence on the development of intelligent packaging for meat research.

3.4. Current Innovation of Intelligent Packaging in Meat

Intelligent packaging for meat continues to evolve through the use of various indicators and sensors that can monitor meat freshness in real time. One innovation in intelligent packaging is the use of natural anthocyanin compounds as pH indicators to detect volatile compounds such as ammonia and trimethylamine that form during the meat spoilage process. For example, the use of blackcurrant anthocyanins results in a color change from pink to yellow in response to increased pH, effectively detecting the freshness of beef at various storage temperatures, as can be seen in table 6 (41). Furthermore, other natural materials such as Rosa canina petal extract and telang flower extract have been shown to effectively indicate clear color changes during storage, although they still have limitations in terms of reversibility and sensitivity to high humidity (42,43).

Another important innovation is the combination of nanomaterials and fluorescence sensors such as carbon quantum dots (CQD) and silicon quantum dots (SiQD), which are capable of detecting decay gases more accurately. For example, SiQD and AgNC (silver nanoclusters) are used as gas sensors to detect hydrogen sulfide (H_2S) and methyl mercaptan (CH_3SH) through colorimetric changes that can be measured visually (44). In terms of temperature and storage time, the Time-Temperature Indicator (TTI) approach is also starting to be implemented, such as the use of a eutectic mixture of soybean and tetradecane to keep the packaging temperature stable below the temperature threshold for fresh meat (45).

The latest trends also point toward the integration of digital technology, such as the use of UHF RFID tags that can detect changes in temperature and meat hardness during thawing through RSSI (Received Signal Strength Indicator) values, which demonstrate the potential for digital connectivity in the cold chain (46). However, this technology is still largely confined to laboratories and faces technical issues such as indicator sensitivity, sensor irreversibility, and high production costs. Therefore, future innovations should focus on environmentally friendly materials, indicator sensitivity, and comprehensive integration of smart technology into supply chain systems.

3.5. Application of Intelligent Packaging in Meat

Intelligent packaging applications for meat have been developed, such as pH indicators, time-temperature indicators (TTI), gas sensors, and RFID (Table 6). These packages can be integrated directly into the packaging to monitor meat quality in real time. The pH indicator changes in response to pH changes caused by spoilage occurring in the meat, while the gas sensor detects the accumulation of volatile compounds such as ammonia or H_2S as early signs of spoilage. With this application, consumers and producers can identify meat quality without opening the packaging, improving food safety, reducing waste, and strengthening trust in a more transparent and efficient supply chain. A schematic overview of the intelligent indicators on meat packaging before and after spoilage can be seen in figure 5

Table 6. Intelligent Packaging Application for Meat

Type of Meat	Storage Temperature	Intelligent Materials	Intelligent Packaging Principle	How the Packaging Works	Weakness	Ref.
Angus Beef	4°C (8 days)	Composite Anthocyanin Microcapsule (CAM)	pH indicator	Volatile amines increase pH → anthocyanin structure changes → color changes Day 0 (pink) = fresh meat. Day 4 (purple ash) = less fresh Day 7 (green) = spoiled	At CAM concentrations >15% aggregation increases → film structure decreases resulting in decreased mechanical strength (cracks).	(47)
Beef	4°C (6 days)	Silicon Quantum Dots (SiQD) Silver Nanoclusters (AgNC)	Gas indicator	Ratio metric fluorescent sensors are sensitive to H_2S and CH_3SH. AgNC emits red light blue-green SiQD. When H_2S/CH_3SH decay is present, it	The sensor is irreversible	(44)

Type of Meat	Storage Temperature	Intelligent Materials	Intelligent Packaging Principle	How the Packaging Works	Weakness	Ref.
				forms Ag-S bonds → inhibits AgNC fluorescence → SiQD becomes more dominant → the reddish purple color changes from being Cyan.		
Beef	4 ± 1ºC (6 days)	Anthocyanin - Rosa Canina petal Extract (RCE 3.5%)	pH indicators	Color changes due to the reaction of anthocyanins to pH changes of volatile amine compounds (ammonia) during spoilage. White (fresh) Dark blue (spoiled)	The sensor is irreversible	(42)
Beef	4ºC (10 days) 25ºC (48 hour) 35ºC (24 hour)	Anthocyanin - Blackcurrant (BC)	pH indicator	Anthocyanins change color based on changes in pH and the presence of volatile ammonia produced when meat begins to spoil. (pink → black → yellow) Color change during spoilage: 4°C (9-10 days) 25°C (24-48 hours) 35°C (18-24 hours)	• The sensor is irreversible. • High BC concentrations (0.24-0.32 g) are less sensitive	(41)
Beef	1 ± 0.5°C (8 days) Exposure to temperature (23°C) for 2-3 hours/day for fluctuation	-Eutectic mixture of soybean oil and tetradecane (S+T) : *Thermo-Regulating Material* (TRM). -Expanded Graphite (EG) -Rice Husk (RH) -TRM commercial (G-pack)	Time-Temperature Indicator (TTI)	TRM packaging to absorb and release heat to maintain a stable temperature (<7°C) for 2-3 hours. Sensors will record temperature data and monitor temperature conditions below the threshold. 8 days storage of fresh meat	• TRM has low thermal conductivity without EG • Insulation layer (RH) is prone to cracking	(45)
-Beef (tenderloin) -Pork (tenderloin) -Shrimp -Salmon	4ºC (7 days)	based Carbon Quantum Dots (CQD) in PVDF matrix	Freshness Indicator (fluorescence-based)	Ratio metric measure the color change of fluorescent (F495/F550) to volatile amine (TMA). The higher the amine, the greater the color change. (Greenish Yellow - Blue)	• Sensitivity is reduced in high-fat products, due to fatty acid interference. • CQD/PVDF is less stable in high humidity (CQD diffusion).	(48)

Type of Meat	Storage Temperature	Intelligent Materials	Intelligent Packaging Principle	How the Packaging Works	Weakness	Ref.
Beef (Tenderloin)	4 ± 1ºC (21 days)	Bromothymol Blue (BTB) dan Phenol Red (PR)	pH sensing indicator	BTB + PR will respond to pH changes due to ammonia formation. (Dark yellow - Reddish yellow)	Paper-based packaging is less resistant to high humidity.	(49)
Beef Tenderloin Pork Tenderloin	4ºC (6 days)	Fluorescein isothiocyanate (FITC) red carbon quantum dots (R-CQD)	Gas Indicator	FITC will experience an increase in intensity (green fluorescence) when reacting with trimethylamine (TMA), while R-CQD remains constant. (Red - Orange - Brown)	The sensitivity of the indicator decreases at high humidity (90% RH) because the reaction rate slows down.	(50)
Chanos chanos	28 ± 2°C (8 hour) 4 ± 0.2°C (7 hour)	-Bromocresol purple (BCP) -Bromothymol blue (BTB)	pH indicator	The color of the indicator changes as the pH rises due to volatile base compounds (TVBN) from fish spoilage. BCP: Day 0 / Hour 0: Yellow (fresh) Day 4 / Hour 4: Pink (semi-fresh) Day 7 / Hour 8: Purple (spoiled) BTB: Day 0 / Hour 0: Orange Day 4 / Hour 4: Yellowish green Day 7 / Hour 8: Bluish green	Potential for false negatives if packaging is open/damaged	(51)
Chicken breast	4 ± 0.5 °C (10 days)	Bromothymol blue (BTB) Phenol red (PR)	pH indicator	The BTB indicator shows a three-stage color change: Days 0-2: Dark blue (fresh) Days 2-4: Turquoise (still viable) Days ≥ 6: Green (stale)	Indicator PR is less effective, because the color change is not clear.	(52)
Chicken breast	4 °C (8 days)	Curcumin - Curcuma longa	pH indicator	The film responds to changes in pH and ammonia vapor (TVB-N) formed due to spoilage. (Bright yellow → Orange red)	Discoloration is less effective for early detection (days 1-3)	(53)
Chicken breast fillet	4 ± 0.2°C (15 days)	Methyl Red (MR) Bromocresol Purple (BCP)	pH indicator	Volatile amines from spoiled meat raise the pH inside the package → cause a color change in the MR (pink → yellow) and BCP (yellow → purple) indicators.	The sensor cannot be in direct contact with the meat.	(54)

Type of Meat	Storage Temperature	Intelligent Materials	Intelligent Packaging Principle	How the Packaging Works	Weakness	Ref.
Chicken fillet	4°C (7 days)	Haematoxylin	pH indicator	The film detects the pH of chicken meat through changes caused by volatile compounds produced during spoilage. (light purple - dark red)	The presence of Chitosan hydrophilic groups can increase water absorption (swelling index).	(55)
Chicken meat	30 ± 2°C (6 hour)	Anthocyanin - Banana flower petal (BBA), PVA, glycerol, dan modified banana starch (BMS)	pH-sensing indicator	Changes in meat pH due to spoilage will be responded by the pH-sensitive film of anthocyanin (BBA) (Pink - yellowish green).	Color is less stable at pH 8-10	(56)
Chicken meat	4°C (32 hour)	Anthocyanin- (Butterfly Pea Flower Extract) BPE	pH indicator	Film color changes as pH increases due to spoilage (bluish red → purple → yellowish green)	Addition of BPE >3% decreased the tensile strength of the film. Anthocyanin sensitivity was reduced after 16 hours.	(43)
Chicken meat	25°C (3 days)	Quercetin (QUE)/Eucalyptus Leaf Extract (ELE)	pH indicator	CG-QUE0.3 and CG-ELE0.3 films changed color in response to pH changes due to the interaction of volatile nitrogen compounds (TVB-N) which increased during spoilage. The color of the film changed: (QUE: red → orange) (ELE: green → yellow).	The quality of ELE indicators is influenced by plant variety and extraction method.	(57)
Chicken breast meat boiler	4°C (12 days)	Whatman paper that has been coated with Phenol Red (PR)	pH indicator.	Phenol Red will change color as the pH increases due to meat spoilage. (Yellow → Red)	There has been no testing of the effect of humidity and light intensity on the accuracy of the indicator.	(58)
Frozen meat	-13°C = tested during thawing for 20 minutes at room temperature 25-30°C.	UHF RFID Tag EL-U8-9424-W RFID Reader Electron HW-VY06K RSSI (Received Signal Strength Indicator)	RFID-RSSI	RFID-based sensing (Radiofrequency Identification tag): uses changes in RSSI value due to changes in meat temperature & hardness. RSSI value = -46 to -62dBm Temperature = -13 to 4oC Hardness = ~80 - ~20 HA	Only detects quality based on temperature and hardness changes.	(46)

Type of Meat	Storage Temperature	Intelligent Materials	Intelligent Packaging Principle	How the Packaging Works	Weakness	Ref.
Ground beef	4°C (9 days)	Anthocyanin Ixiolirion Tataricum (ITA)	pH indicator	Ammonia & amine compounds produced by spoilage raise the pH - anthocyanin structure changes → Fresh (red) Medium (purple-blue) Rotten (green)	Not completely reversible (Return to original color after exposure to ammonia).	(59)
Lamb	25°C (72 hour)	Barberry anthocyanin (BA) Methylcellulose (MC) Chitosan nanofiber (ChNF)	Gas indicators	The response of the indicator film to ammonia gas that is formed during the decay process results in a color change. (Pink → Yellow)	The addition of BA decreased the mechanical properties (Tensile strength and Elastic modulus).	(60)
Mutton	4°C (10 days)	Anthocyanin Lyceum ruthenium (ALR)	pH indicator	Basic volatile compounds (such as NH_3 and amines) from meat spoilage raise pH → cause changes in anthocyanin structure → change in film color (halochromic) (Red → Purple → Blue → Yellow)	higher ALR concentration (7%) decreased the flexibility level of the film	(61)
Minced beef	4 ± 1°C (15 days)	Anthocyanin - *Prunus Domestica Extract* (PDE)	pH-sensing indicator. Gas indicator.	Discoloration of KC-PVA electro spun fibers due to changes in pH and gases produced by meat spoilage (TVB-N and ammonia) (White → Purplish → Red → Brown)	High production cost, >50% of total packaging cost.	(62)
Minced beef	4°C (14 days)	Carboxymethyl Cellulose (CMC)	pH indicator	Freshness indicator based on color change due to increase in pH and TVB-N during storage. (Pink → Purple)	Irreversible	(63)
Minced beef	4°C (7days)	Grape anthocyanins (GA)	pH indicator	Film response to pH increase due to the formation of volatile compounds resulting in color change. Pink (day 1) Purple (days 3-5) Blue (day 7)	An increase in water solubility of up to 24.17% has the potential for anthocyanin leaching.	(64)
• Minced beef. • Chicken breast fillet.	4 °C • Minced beef and chicken fillet (10 days)	Anthocyanin - Malva Sylvestri flower extract	pH indicator	Protein products produce volatile basic compounds as they decompose → raise the pH inside the package → trigger	Indicator performance is less than optimal on minced meat & chicken fillet. The indicator is not	(65)

Type of Meat	Storage Temperature	Intelligent Materials	Intelligent Packaging Principle	How the Packaging Works	Weakness	Ref.
• SHrimp.	• Shrimp (6 days)			anthocyanin discoloration of the film. (purple → blue → green) **Shrimp:** - Day 0: Purple - Day 2: Blue - Day 4: Green-blue - Day 6: Bright green **Minced meat:** - Day 0-6: stable color - Day 8: Blue - Day 10: Green **Chicken fillet:** - Day 0-6: stable - Day 10: Green	able to distinguish the medium fresh stage clearly.	
Minced Pork	4ºC (12 days)	Bromothymol Blue (BTB) as pH-sensitive. Alginate-methylcellulose hydrogel as a sensor matrix that absorbs ammonia vapor	pH indicator	BTB absorbs ammonia vapor and allows an acid-base reaction to occur resulting in a color change on day 2. Day 2 : Orange-yellow Day 6 : Bright yellow	Sensitivity reduced at high RH (98%)	(66)
Pork	25ºC (48 hour)	Anthocyanin-Purple Sweet Potato Extract (PSPE)	pH Indicator	Anthocyanins respond to pH changes due to the spoilage process. Red (0-12h) pink (12-20h) Dark green (48h)	There is no explanation of the effect of high humidity.	(67)
Pork	25ºC	Purple Sweet Potato Anthocyanins – (PSPAs)	pH sensing indicator	The color of the film changes according to the pH stimulus arising from meat spoilage (Brown to light green) The released eugenol will gradually inhibit microbial growth and oxidation.	• Label changes are less obvious during spoilage. • Not tested under cold chain conditions	(68)
Pork	4ºC (12 days)	Black Rice Bran Anthocyanin (BRBA)	pH indicator	The color film indicator changes as the pH increases due to the decomposition of proteins that produce volatile basic compounds during the spoilage process. (red → purple → greenish → yellow)	Increasing BRBA increases the water vapor permeability (WVP) value so that the structure becomes looser.	(69)
Pork	4ºC (9 days)	Anthocyanin-Blueberry	pH Indicator	Detects color changes with RGB format due to the reaction	Addition of MSNs in an orderly arrangement	(70)

Type of Meat	Storage Temperature	Intelligent Materials	Intelligent Packaging Principle	How the Packaging Works	Weakness	Ref.
				between anthocyanins and pH changes due to spoilage, which can be monitored from a mobile phone. Yellow (Fresh) Brown (Rotten)	between zein and blueberry extracts and increased film fragility.	
Pork	25°C (96 hour)	Alizarin (AL)	pH indicator	Alizarin changes color according to pH due to ammonia volatile compounds from meat spoilage: Yellow (fresh) Pink (medium) Purple (spoiled)	The addition of PD-VA coating resulted in low tensile strength (TS) (0.23 MPa).	(71)
Pork	4°C (6 days)	Roselle Anthocyanins (RS)	pH Indicator	The film shows discoloration due to the increase in pH and TVB-N value during storage. Pink (fresh) Blue (spoiled)	The addition of CEO material to the film is relatively more expensive.	(72)
Pork	25 °C (3 days) 4 °C (12 days)	Anthocyanin - Bilberry Extract (BE)	pH indicator	Anthocyanins in BE undergo structural and color changes due to pH changes caused by spoilage. Temperature 25°C: - Day 0: Brown - Day 3: Brownish green (spoilage) Temperature 4 °C: - Days 0-6: Brown - Day 6-12: Brownish green	• The change is less obvious at neutral pH.	(73)
Pork	4°C (10 days)	Purple Sweet Potato Anthocyanin (PSPA)	pH indicator	Film-based pH-sensitive colorimetric film that responds to changes in pH and ammonia that occur during spoilage. Pink (fresh) Light brown (spoilage) Brownish green (spoilage).	• Less obvious indicator color change at transition stage. • Dependence on low temperature for optimal performance	(74)
Pork	4 °C (148 hour) 15 °C (47 hour) 25 °C (20 hour)	Phospholipase A1: enzyme for hydrolysis reactions PVA microspheres: support for enzyme immobilization	Time-Temperature Indicator (TTI)	Enzymatic-based Time-Temperature Indicator (TTI): enzymes trigger the hydrolysis of lecithin, which lowers the pH and then affects the BVB indicator so that it changes color as	Not yet tested under transportation conditions	(75)

Type of Meat	Storage Temperature	Intelligent Materials	Intelligent Packaging Principle	How the Packaging Works	Weakness	Ref.
		BVB (pH indicator)		time and temperature increase. -Dark blue (fresh) Bluish-green -Pale yellow (spoiled)		
Pork - Fresh, lean hamstrings	20°C (70 hour) 4°C (10 days)	Anthocyanin (ACNs) - Blueberry	pH-sensing indicator	Changes in pH due to meat spoilage cause changes in the structure of ACNs, so that the film changes color. (Red → Blue).	The addition of Sodium alginate (SA), which is hydrophilic, can dissolve ACNs when the meat secretes liquid, thus reducing the effectiveness of the indicator.	(76)
Pork (lean part, pork loin)	4°C (4 days) 25°C (24 hour)	Purple cabbage anthocyanin (PCA)	pH indicator	A pH-sensitive bilayer film that releases PCA when the pH rises, so the film changes color. Pink (fresh) Dark purple (damaged).	• The color change of the indicator in the pH range of 4-6 is not clear. • Anthocyanins with high concentration (ZCLP16%) are less stable.	(77)
Shrimp	25°C (36 hour)	Co-MOF (Cobalt-based Metal-Organic Framework) with added Sodium Alginate (SA)	Gas indicators	Co-MOF reacts with ammonia (NH_3) produced during spoilage, resulting in the formation of Co-N fish which causes discoloration. Pale pink (fresh) Dark brown (spoiled)	Initial color, pale pink less conspicuous for visual detection	(78)
Shrimp	25°C (48 hour)	ZIF67 (zeolite-67 imidazolate framework) and Cellulose acetate (CA)	Gas Indicator	The film responds to ammonia gas produced during shrimp spoilage through color changes. (Blue → Brown)	Not sensitive to pH changes	(79)
Shrimp	–20°C, 28°C, and 4°C (5 days)	H+DQ2 (AIE indicator)	Gas indicator	Freshness indicator based on fluorescence and color change of AIE (aggregation-induced emission) H+DQ2 detects ammonia vapor generated by spoilage, thus changing the color of the film. (Red brick → Yellow)	• Requires a UV lamp to detect fluorescence, making it impractical in all conditions.	(80)

Type of Meat	Storage Temperature	Intelligent Materials	Intelligent Packaging Principle	How the Packaging Works	Weakness	Ref.
Silver carp	25°C (3 days)	Anthocyanin-Ekstract Murbei (MBE)	pH sensing indicator	MBE is responsive to pH so it changes the color of the package indicator based on the change in pH. Purple (fresh) Gray/brown (spoiled) Yellow (spoiled)	• Films are irreversible • The addition of MBE decreases the flexibility of the film.	(81)
Tilapia fillet	25 ± 2 °C (96 hour)	Anthocyanin - Grape pomace extract (GPE)	pH indicator	The color of the film changes as the pH increases due to fish spoilage. (Pink → Green)	• Less suitable for low-protein foods that do not produce volatile amines. • Color transition takes a long time.	(82)
• White shrimp (Fenneropenaeus chinensis) • Pork (loin)	4°C Udang (6 days), Pork (12 days)	Hyacinth bean anthocyanins (HBA)	pH indicator	The film responds to the pH changes that occur during spoilage, thus changing the color of the film. Purple (Fresh) Green (spoiled)	• Color transition takes a long time. • Indicator sensitivity is limited to foods with significant pH changes.	(83)

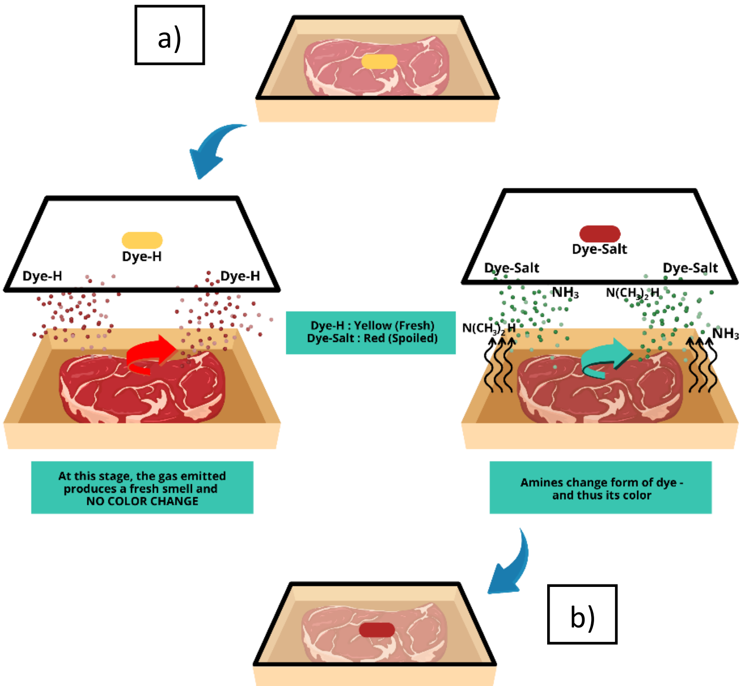


Figure 5. Schematic of intelligent packaging indicators on meat before (a) and after (b) spoilage.

3.5.1 pH Indicator

Consumer demands for quality and safe food products encourage the development of intelligent packaging. Intelligent packaging is able to provide real-time information with colorometric indicators related to the condition of the packaged product (84,85). As one of the colorimetric indicators, pH-sensitive indicators in particular, have been widely developed and used in pH-sensitive (halochromic) intelligent packaging films based on synthetic or natural food colorings (86,87). The pH indicator is classified as a freshness indicator which is different from the temperature indicator. This is because freshness indicators provide a direct measurement of food quality by analyzing certain chemicals produced by specific microorganisms. The use of pH-based indicators (pH-sensitive indicators) results in a change in the pH level, which then causes a color change in the sensor, thus directly indicating the condition of the food in the package (88).

This pH-based indicator can be applied to various food products, such as meat, fruits, and seafood. Applied to meat and fish products, the amount of Total Volatile Basic Nitrogen (TVBN) is used as a critical factor to identify the level of spoilage. The TVBN sensor uses a colorimetric approach by detecting pH changes associated with volatile amines produced by spoilage microorganisms (89,90). The pH of meat increases during storage as a result of protein degradation by spoilage microbes. This process produces foul-smelling compounds such as ammonia (NH_3), skatole and indole bases, as well as hydrogen sulfide (H_2S), amines, cadaverine, and mercaptans (91–94). These volatile compounds gradually accumulate in the package, causing a rise in pH, so that the indicator undergoes a gradual color change as the meat decays (95).

3.5.2 Gas Indicator

The application of gas indicators as intelligent packaging in food products serves to monitor food quality based on gas content within the packaging. These gases can affect the quality and freshness of packaged products (96,97). Meat products are susceptible to spoilage due to microbial activity and produce gases such as ammonia (NH_3), hydrogen sulfide (H_2S), and carbon dioxide (CO_2). The principle of gas indicators as intelligent packaging is based on color changes resulting from chemical reactions that occur in the indicator when it interacts with gases. Gas indicators in intelligent packaging typically consist of materials sensitive to specific gases. When gases produced by food in the packaging interact with the indicator, the active components in the indicator react with the gases, causing a visible color change. By detecting gas levels, the packaging can provide visual information about the quality of the meat directly to consumers or distributors without needing to open the packaging (7,98).

3.5.3 Time-Temperature Indicator (TTI)

The Time-Temperature Indicator (TTI) is a intelligent packaging technology designed to monitor the temperature and storage duration of food products, which can be viewed during the storage and distribution process (99). TTI, in the form of labels or tags, can detect temperature and time from the start of the production process through storage and distribution until the product reaches the consumer (100). The basic concept of TTI is that food quality, including meat products, is strongly influenced by ambient temperature. Temperature-sensitive meat products can experience accelerated biological and chemical deterioration if they are not stored under stable chilled conditions. TTI serves to ensure that food products are stored under conditions that are suitable for their characteristics. This is important because time and temperature are important factors that can cause various deterioration, such as physical, chemical and microbiological damage to food (101).

The main principle of using TTI is based on changes in chemical, mechanical, electrochemical, enzymatic, and microbiological reactions characterized by visual color changes due to changes in temperature and storage time (99). TTI works with physical or chemical changes that occur over time and temperature. The longer the indicator is exposed to high temperatures, the faster the color change occurs (102). Time-Temperature Indicator (TTI) systems are generally categorized based on physical, chemical, enzymatic, and biological systems (figure 6).

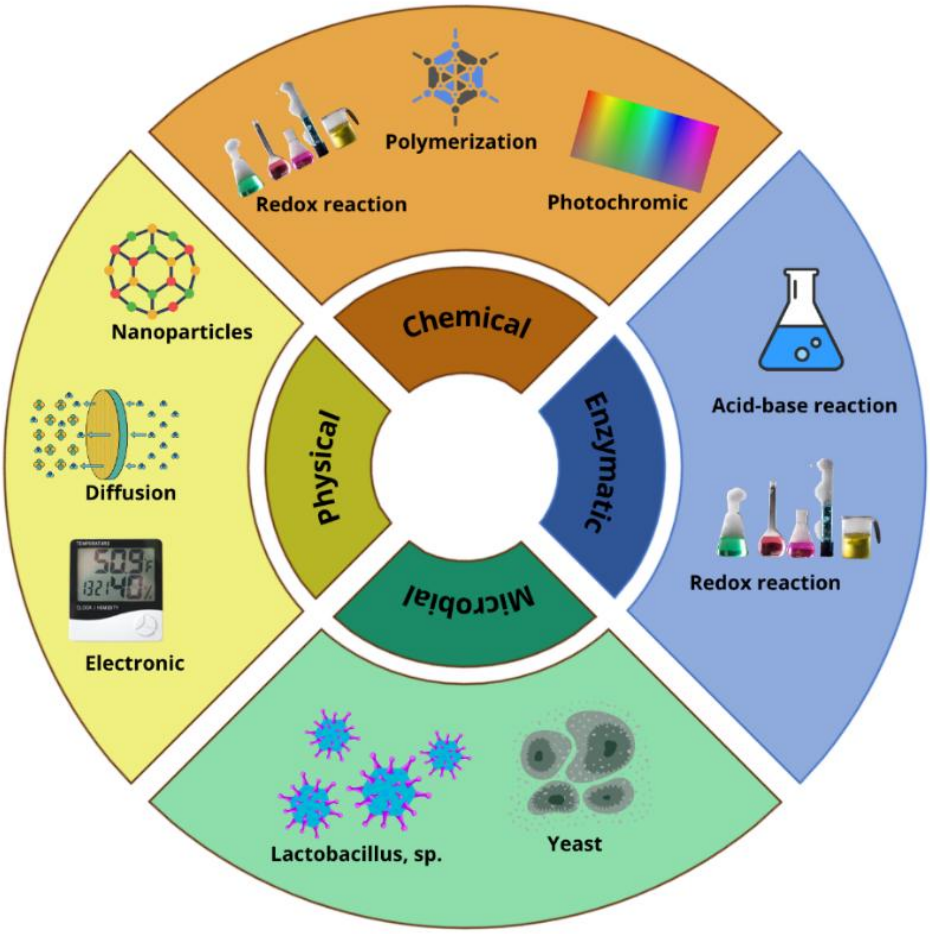


Figure 6. The different types of TTIs are based on their operational principles.

Chemical-based TTI systems can be divided into three types of mechanisms, namely polymerization, photochromic, and oxidation reactions. The mechanism of color change occurs irreversibly due to several chemical reactions, such as the formation of polymers in polymerization-based TTIs, changes in the wavelength of light due to exposure to UV light in photochromic TTIs, and the reaction between oxygen from the air with indicator components accompanied by light accumulation to produce a creamy color change in oxidation-based TTIs (103). Physical TTI systems can be classified into diffusion-based TTI, nanoparticle-based TTI, electronic TTI, etc. based on their working principle due to the diffusion reaction of fatty acid esters through porous materials in response to temperature and time, which results in visual changes proportional to the thermal state of the product. Then nanoparticle-based TTI is a change in the morphology or surface structure of nanoparticles due to thermal energy, which triggers irreversible optical (thermochromic) color shifts as a historical marker of product storage temperature and time. Electronic TTI uses thermal sensors to convert temperature signals into electrical signals. This signal is then processed by microprocessor circuitry and produces a visual or digital color output that accurately displays the thermal history and quality condition of the product (99,103,104).

Enzymatic-based TTIs are divided into acid-base and redox reactions. Acid-base reaction-based TTIs are color changes in pH indicators caused by enzymatic reactions by substrates that act as components in the indicator. This color change will be more clearly visible when over time and temperature increases because it will accelerate the work of enzymes in breaking down the substrate. Redox reaction-based TTIs are color changes resulting from the oxidation of the substrate by enzymes such as laccase or peroxidase, thus providing a visual indication of the thermal history of the product (103,105,106). The biologically-based Time-Temperature Indicator (TTI) utilizes the activity of microorganisms such as yeast and Lactobacillus spp. to produce pH changes that can be observed through changes in the color of the indicator. In yeast-based systems, the mechanism relies on anaerobic respiration that produces acid as a metabolic product when the microorganisms grow within a certain temperature, usually between 5°C and 40°C. The acid produced causes the pH indicator to gradually change color, showing the accumulated effects of time and temperature. Meanwhile, in Lactobacillus spp. based TTIs, such as Lactobacillus rhamnosus LGG, fermentation of sugars such as glucose or lactose produces lactic acid which also lowers the pH and triggers a color change of the indicator. Both systems show potential as freshness indicators for food products, especially chilled and temperature-sensitive products (103,107).

Table 7. Principle of Time-Temperature Indicator system

Method	TTI Principles System
Physical	Diffusion, Nanoparticle and Electronic
Chemical	Polymerization, Photochromic, and Oxidation Reaction
Enzymatic	Acid-Base Reaction, Redox Reaction, and Acid-Base Reaction
Biological	Yeast and Lactobacillus

3.5.4 Radio Frequency Identification (RFID)

Radio Frequency Identification (RFID) is a intelligent packaging technology that uses wireless devices to automatically identify and track packaged products. The principle of RFID in intelligent packaging is through radio signals fired at tags that will be read by RFID readers. RFID in intelligent packaging allows monitoring of product conditions without physically opening the packaging, helping to maintain product freshness until it reaches consumers. The application of RFID in meat products serves to ensure the safety, quality, and traceability of the supply chain, especially in cold chain systems (1,108,109).

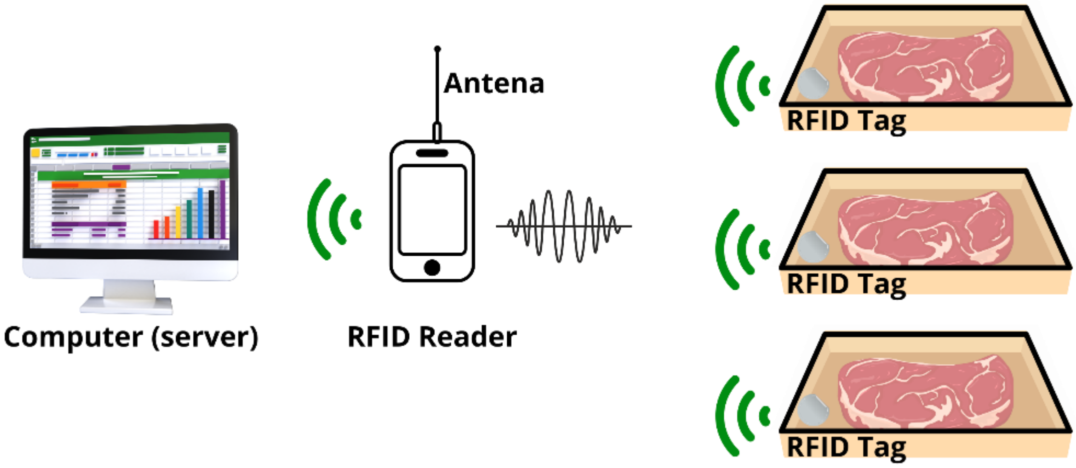


Figure 7. RFID-based meat monitoring system.

The three main components of an RFID system are the RFID label (tag), RFID reader, and server. RFID labels are usually attached to packaging and have microchips and antennas that store product data such as processing time, storage temperature, and product identity. The reader captures signals from the label and transfers the data to the central system via radio waves, while the database system (server) processes the information to display it in visual form (110,111). The working principle of RFID begins when the reader sends electromagnetic waves toward the tag. These waves then trigger the tag, which in turn sends information back to the reader. The returned signal contains the tag ID and product condition data (46,112). The application of RFID in meat is used to record data in real-time during the storage and distribution process, combined with temperature sensors. Sensors integrated with RFID tags can measure temperature periodically and send data to a monitoring system, which then displays the data graphically or issues a warning signal if the temperature exceeds a predetermined threshold (46,111).

3.6. Future Perspective

The application of intelligent packaging in meat products shows promising prospects in improving quality, safety, and transparency of information to consumers through real-time monitoring of product conditions. Although many studies have revealed the great potential of this packaging, there are still various challenges that must be overcome for wider implementation. Future research on intelligent packaging should focus on developing materials that not only have good physical and barrier properties, but are also environmentally friendly and biodegradable to support sustainability. In addition, the integration of cutting-edge technologies such as the Internet of Things (IoT) and Artificial Intelligence (AI) into intelligent packaging is essential to improve the efficiency and accuracy of meat quality monitoring throughout the supply chain. The process of validating the application of intelligent packaging in real supply chains is a crucial step necessary to ensure that this technology is not limited to the laboratory stage, but can be applied commercially. With more focused research, it is hoped that intelligent packaging can become the future solution for more efficient, effective, safe, and sustainable food packaging.

4. Conclusions

The results of this study show the development of intelligent packaging research discussed using bibliometric methods and systematic reviews. It can be seen that the number of documents related to intelligent packaging has increased every year since 2014. China is the most productive country in intelligent packaging research, which is characterized by the highest number of publications. In addition, the International Journal of Biological Macromolecules is the most productive journal, where the type of document with considerable influence in the development of the field of intelligent packaging is the article document. Keyword analysis shows that intelligent packaging research points for food packaging focus on intelligent packaging, smart packaging, pH indicators, anthocyanins, and freshness indicators. The results of keyword analysis based on time range show several keywords that are currently trending topics, namely intelligent food packaging, meat spoilage, food packaging, sodium alginate, and biopolymers. The most widely used types of intelligent packaging in meat packaging include pH indicators, time-temperature indicators, gas sensors, and RFID. These packaging technologies can be used to monitor the freshness, temperature, and quality of meat.

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Author Contributions

Conceptualization, S.H.H and A.Y.N.; methodology, A.Y.N. and S.H.H; software, A.Y.N.; validation, S.H.H. and I.; formal analysis, S.H.H., A.Y.N, and I.; investigation, S.H.H.; resources, A.Y.N; data curation, A.Y.N. and I.; writing—original draft preparation, A.Y.N.; writing—review and editing, S.H.H., A.Y.N., and I.; visualization, A.Y.N.; supervision, S.H.H. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

Author declare no conflict of interest

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