# Bibliometric Analysis on Recent Advances and Development of Microcontroller Application in The Postharvest System

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**Abstract:** Postharvest is a vital stage in agricultural production which is prone to causing losses due to improper implementation. Using a microcontroller that allows automation and increased precision in the postharvest process will likely reduce costs and potential losses. This research conducted a bibliometric study on applying microcontrollers in postharvest systems in Scopus-indexed publications from 2003 to 2022. The aim was to reveal microcontroller developments, evaluate current research topics, and discuss future challenges facing microcontroller applications in postharvest systems. First, this paper presents a bibliometric review of the role of microcontrollers in postharvest. Second, co-citation, coupling, and cluster analysis methods were used to analyze collaboration networks, and VOSviewer was used to visualize these networks. Third, Biblioshiny was used to analyze thematic trends of microcontroller applications. Finally, the paper discusses the challenges of using microcontrollers and provides suggestions for overcoming them. The results show that institutions from China and Italy lead research production in this field, with globally popular studies focusing primarily on fruit, digital storage, moisture determination, and cost. In addition, the thematic evolution of keywords indicating response time, cost, and design reliability issues have become basic and emerging topics in microcontroller application research for postharvest systems in recent years.

**Keywords:** biblioshiny; microcontroller; postharvest technology; thematic trends analysis; VOSviewer

## INTRODUCTION

### Background

Reducing food losses across the entire food value chain (agricultural production, postharvest handling and trade, processing, food service industry, retail, and households) is essential to increasing the efficiency of our food systems (Beretta et al., 2013). Postharvest losses (PHL) lead to food and income losses for farmers and consumers worldwide (Kikulwe et al., 2018). Approximately 13 million tonnes of cereals, or greater than 15 percent of total cereal production, are lost annually in Africa due to postharvest operations (FAO, 2017). Reducing postharvest losses (PHL) is a crucial pathway to food and nutrition security in less developed countries (LDCs) (Affognon et al., 2015). Reducing food losses is vital to increasing food availability without requiring additional production resources. It can contribute to rural development and poverty reduction by improving agribusiness livelihoods in LDCs (Hodges et al., 2011). A 50% reduction of grain loss and waste along the value chain seems achievable for feeding 3-4 billion more people sustainably without raising the genetic yields of crop cultivars (Mesterházy et al., 2020).

A postharvest system that involves many activities, such as harvesting, transporting, storing, packaging, and distributing products, aims to reduce losses by maintaining product quality and quantity. However, in the postharvest system, manual activities are still the most preferred method, for example, sorting and quality evaluation. This method can result in problems such as high labor costs, worker fatigue, inconsistency, variability, and a lack of trained labor (Jarimopas & Jaisin, 2008). In addition, conventional methods for assessing fruit quality are typically time-consuming, destructive, require numerous samples for statistical significance, and result in a substantial loss of good fruit (Ibba et al., 2020). Therefore, the research challenge in postharvest systems is to develop more effective technological tools to create and manage crop value while improving food safety and quality (Shewfelt et al., 2014).

Process automation in agriculture has received a lot of attention in recent years. All aspects of agricultural mechanization revolve around automation. Shortages of available labor, increased recruiting costs, and the need to improve process efficiency and effectiveness have also been key factors driving automation in postharvest systems. In addition, there is currently a growing need for monitoring and controlling fruit and crop quality throughout the production chain (Ibba et al., 2020). Therefore, using sensors and embedded systems has been less widespread than today (Chakraborty et al., 2023).

Monitoring equipment for automation requires significant capital investments. Low-cost open-source microcontroller platforms have been employed in agriculture to monitor and control different variables of importance for crop production (Montoya et al., 2020). Embedded microcontroller technology allows for easy sensor interface and intelligent programming (Hebel, 2006). A sensor system transforms a physical quantity into an analog signal sent to an analog-to-digital converter (ADC) and a microcontroller for digitization and further processing. Once the measurement is digital, the microcontroller can execute tasks according to the measurement (Zhang & Rasmussen, 2020).

Affordable scientific instruments, laboratory equipment, and even postharvest system support equipment have been made possible by the development of user-friendly open-source microcontrollers, readily available electronics, and adaptable production techniques (Isaac et al., 2017). Some low-cost microcontroller-based monitoring systems for measuring air temperature, relative humidity, pH, electrical conductivity, and moisture content were being developed by various researchers worldwide (Arah et al., 2016; Montoya et al., 2020; Rosales et al., 2022). This indicates that microcontroller technology is increasingly in demand for application in postharvest systems. Unfortunately, there is no comprehensive information about current conditions and further directions for developing microcontroller applications in postharvest systems.

Bibliometric analysis can effectively map research developments using microcontrollers in postharvest systems. Bibliometric analysis is a quantitative analysis technique used to study patterns of scientific publications and research trends in a particular field (Kusuma & Jamaludin, 2022). By reviewing previous studies, it can be understood to what extent knowledge about using microcontrollers in postharvest has progressed and identify challenges that still need to be overcome. Through this bibliometric analysis, the resulting information was expected to be useful for researchers and decision-makers in determining the direction of further research and policies related to using microcontrollers in postharvest systems.

**Objective**

This study aimed to study collaboration networks, topic developments, and solutions to the main challenges for microcontroller application research in postharvest systems with bibliometric analysis using VOSviewer and Biblioshiny.

**METHODS**

Literature reviews generally analyze relevant literature on a particular topic to identify trends and developments. In this paper, the literature review was carried out using the bibliometric analysis method instead of the structured literature review method. This is because bibliometric analysis methods can collect more extensive data quickly and produce more objective and measurable information about the topics' productivity, impact, and trends compared to structured review methods (Wang et al., 2021). In contrast to the structured review method, which uses descriptive and qualitative approaches to identify and evaluate the quality of the literature, the bibliometric analysis method uses bibliographical data and bibliometric metrics to measure the impact of the literature. However, in order to be able to interpret the results of the bibliometric analysis accurately and in-depth, a scientific background on the topics discussed is still required.

A bibliometric analysis aims to summarize a large amount of bibliometric data to present the intellectual structural conditions and emerging trends of a topic or field of research. This analysis is more suitable for use when the scope of the study is broad, and the dataset is too large to be reviewed manually (Donthu et al., 2021). This analysis has been successfully used to identify trends, key contributors, as well as patterns and research directions in several fields, such as the use of IoT in supply chain management (Ben-Daya et al., 2019), food safety in the context of climate change (Sweileh, 2020), and the use of drones in agriculture (Rejeb et al., 2022). Based on a bibliometric analysis of 166 publications screened from 2008 to 2017, Ben-Daya et al. (2019) explored IoT applications in supply chain management. They succeeded in identifying gaps in the literature regarding the potential role of IoT in addressing supply chain management challenges. They suggest future research directions, including optimizing sensor placement for maintenance, virtual network flow design, costing of IoT technology, real-time vehicle routing, and quality-controlled logistics for perishable goods. Armed with a bibliometric analysis, their paper can provide insight for researchers and practitioners interested in the field.

**Data Collections**

According to Zupic and Čater (2014), the bibliometric analysis workflow comprises five stages: study design, data collection, data analysis, data visualization, and interpretation. Generally, no fixed conditions in the data filter/exclusion are involved. Nevertheless, according to Aria and Cuccurullo (2017), the time span is one of the most critical things in study design in bibliometric analysis. Bibliometric analysis is carried out at specific points in time to represent a static picture of the field so that information and a basis are needed in deciding the selected period at the data collection stage.

According to Waltman (2016), several database and publication criteria must be excluded from the review analysis. The three most essential databases are available for conducting citation analysis: WoS, Scopus, and Google Scholar. While many databases are available, they usually only cover a limited number of scientific fields. Moreover, some of these databases do not contain publication reference data, so they cannot be used to calculate citation impact indicators. Scopus is a subscription-based database owned by Elsevier and was launched in 2004. Scopus was chosen as the database in this bibliometric analysis following Mongeon and Paul-Hus (2016), who found that Scopus includes a more significant number of journals than WoS, and almost all journals covered by WoS are also covered by Scopus.

Regarding the selection of publications, there are general criteria for excluding publications from the calculation of citation impact indicators based on the type of publication document (Waltman, 2016). In Scopus, each publication has a document type. For example, essential document types in Scopus include article, review, conference paper, book chapter, letter, and editorial. The main reason for excluding certain document types is that publications of different document types are difficult to compare. Problems may arise, such as the average number of citations per publication. For example, publications in editorial format tend to have a low scientific impact. They are cited less than other types of documents, which can cause the average value of citations per publication from an author to be lower. This can be avoided by excluding editorial and other types of documents of a similar nature when collecting data. Another criterion for excluding publications from the analysis was the language in which the publication was written. Van Raan et al. (2011) suggest that in a comparative analysis of countries or research institutions, publications not written in English should be excluded from the analysis. Non-English language publications receive fewer citations on average than English language publications because most researchers cannot read publications that are not in English.

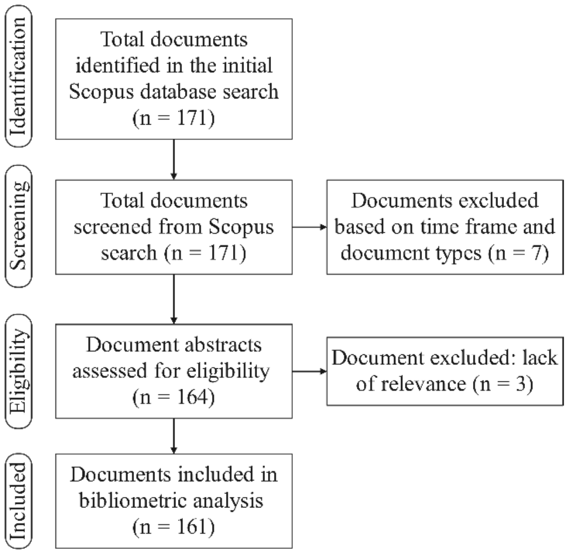



**Figure 1**. Flow chart of literature selection for bibliometric analysis

The data source considered in this analysis was a collection of scientific articles indexed in the Scopus database that were recorded until the time of searching in January 2023. Data collection and selection were carried out following the methodology flowchart (Figure 1). In the initial stage, 171 documents were selected after a topic search using Boolean logic. The logic was (microcontroller* OR micro-control* OR mcu OR Arduino OR esp32 OR esp8266 OR atmega) AND (postharvest* OR post-harvest*). In the next stage, the data set was screened based on the year of publication and the type of article, leaving 164 documents. Documents included in the analysis only came from the last 20 years (2003-2022) and excluded documents from 2023 due to incomplete bibliometric data. In addition, the selected documents only come from articles, reviews, and conference proceedings to ensure the information is updated. In the final stage, the search result data was processed using Microsoft Excel to check the conformity of the documents with the research topic while eliminating duplication. After selection, the total number of articles used in this bibliometric analysis was 161 articles.

**Bibliometric Analysis**

To ensure the success of bibliometric analysis in answering the objectives, this paper carried out three stages of analysis in the form of bibliometric review, network analysis, and thematic map analysis using VOSViewer (version 1.6.18) and R Biblioshiny (version 4.0) software. First, a bibliometric review was conducted by analyzing the number of articles each year, the most frequently cited journals, the distribution of article quantity, citation structure, and the institutional structure involved in writing articles. Second, network analysis was done by analyzing three parameters: co-authorship, co-citation, and bibliographic coupling. Co-authorship identifies collaboration between article authors by analyzing collaboration patterns between authors in relevant articles. Co-citation identifies articles frequently cited together to identify the most influential groups of articles. Meanwhile, bibliographic coupling identifies the relationship between articles with the same reference.

Finally, thematic map analysis utilized thematic networks, strategic diagrams, and thematic evolution. The thematic network identified the relationship between topics discussed in various articles based on the level of co-occurrence. At the same time, the strategic diagram described the grouping of topics or problems based on the level of influence in driving research direction and the tendency for more research. Thematic evolution describes the latest developments and advances in microcontroller applications in postharvest systems from time to time by analyzing changes in the frequency of associated terms. Several alternative solutions to existing problems related to the use of microcontroller technology in postharvest systems were also discussed.

## RESULTS AND DISCUSSION

### Journal Review

Based on the bibliometric data we collected, it was found that the IOP Conference Series: Earth and Environmental Science is the source that has published the most research on microcontroller applications in postharvest systems (Table 1). In addition, several journals frequently publish similar research, such as Computers and Electronics in Agriculture, Sensors (Switzerland), and Journal of Food Engineering. Generally, international proceedings have a higher acceptance rate and a faster publication time than international journals. In addition, international proceedings also offer an opportunity for writers to be able to present their work directly to a broader audience. This causes the tendency of researchers to prefer to publish the latest results of their research in international proceedings. International journals are still crucial for publishing trusted and scientifically verified research results. The total number of citations per year from international journals, such as Computers and Electronics in Agriculture, is 15 times more than proceedings.

**Table 1.** Top 10 sources by the number of publications

| R | Journal / Conference | N | SJR 2010 | SJR 2016 | SJR 2021 | FY | TC | TC/N | TC/Y | Y |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | *IOP Conference Series: Earth and Environmental Science* | 6 | - | 0.199 | 0.202 | 2019 | 3 | 0.50 | 0.75 | 2008 |
| 2 | *Computers and Electronics in Agriculture* | 5 | 0.66 | 0.873 | 1.595 | 2016 | 83 | 16.60 | 11.86 | 1985 |
| 3 | *Sensors (Switzerland)* | 5 | 0.579 | 0.623 | 0.803 | 2013 | 124 | 24.80 | 12.40 | 2001 |
| 4 | *Journal of Food Engineering* | 4 | 1.447 | 1.476 | 1.115 | 2003 | 163 | 40.75 | 8.15 | 1982 |
| 5 | *Acta Horticulturae* | 3 | 0.213 | 0.181 | 0.163 | 2006 | 1 | 0.33 | 0.06 | 1976 |
| 6 | *Journal of Physics: Conference Series* | 3 | 0.288 | 0.24 | 0.21 | 2020 | 1 | 0.33 | 0.33 | 2005 |
| 7 | *Transactions of the ASABE* | 3 | 0.677 | 0.455 | 0.319 | 2013 | 31 | 10.33 | 3.10 | 2006 |
| 8 | *AIP Conference Proceedings* | 2 | 0.166 | 0.165 | 0.189 | 2018 | 4 | 2.00 | 0.80 | 1973 |
| 9 | *Applied Sciences (Switzerland)* | 2 | - | 0.315 | 0.507 | 2019 | 1 | 0.50 | 0.25 | 2011 |
| 10 | *Biosystems Engineering* | 2 | 0.714 | 0.722 | 1.017 | 2020 | 43 | 21.50 | 14.33 | 2002 |

**Note:** N represents the number of articles related to the topic and indexed by Scopus. SJR represents the SCImago Journal Rank. FY represents the year when articles related to the topic were first indexed. TC represents the total citation. Y represents the earliest year reported by InCites Journal Citation Reports (JCR).

Computers and Electronics in Agriculture is a journal that publishes research articles on various topics, including using sensors and monitoring systems for precision agriculture, developing image processing systems for crop analysis, and using information and communication technology in agricultural management since 1985. This journal, published by Elsevier, has been noted to experience periodic increases in SCImago Journal Rank (SJR). SJR is an index that represents the scientific impact given by a scientific journal. SJR is calculated based on the average number of citations per article published in a journal for the last three years.

**Quantity Distribution**

Based on the analysis of the quantity distribution of articles, it was found that the number of publications related to microcontroller applications in postharvest systems did fluctuate from year to year. However, this number was consistently above 15 papers/year after 2018 or higher than previous years. (Figure 2). In addition, specific years have experienced a significant increase in publications, such as 2015, 2018, and 2020. This shows that this topic is increasingly important and has become a research interest for researchers whom several factors may influence increasing awareness about the importance of an efficient postharvest system coupled with advances in sensor and microcontroller technology is considered a factor supporting the increase in these publications. In addition, since the food security program was designated as point 2 in the Sustainable Development Goals (SDG) by United Nations in 2015 (Pérez-Escamilla, 2017), the government has provided support for promoting sustainable agriculture so that it has contributed to growing research on microcontroller applications to improve postharvest systems.

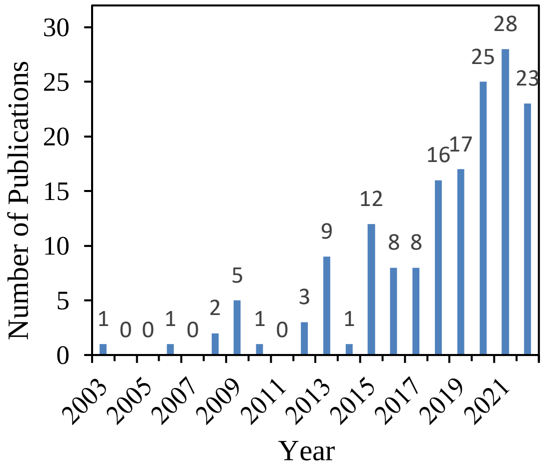



**Figure 2.** The change trends in the number of publications

**Citation Structure**

Besides experiencing an increase in the number, publications regarding microcontroller applications in postharvest systems were also being cited more frequently by other studies from time to time. The article group published in 2003 was the highest average total citations per article among other article year groups (Table 2). However, the only article published in 2003 concerning developing sensors for sensing fruit hardness (García-Ramos et al., 2003) is not the most cited article. Instead, the article by Das et al. (2016) on the creation of an ultra-portable wireless spectrometer for testing fruit ripeness and the article by Jarimopas and Jaisin (2008) on the creation of a machine vision system for sorting sweet tamarins became the most cited articles, 131 and 67 citations respectively. This also caused a spike in the number of citations per article in 2008 and 2016. Furthermore, the group of articles published in 2016 became the most cited on average per year for the past eight -years, namely 3.41 citations per year. Although this value may change as the number of citations increases, the high number of citations still indicates that articles published in 2016 have impacted articles published afterward. Many articles published that year discussed the application and development of microcontroller-based spectrometers, especially for non-destructive fruit quality assessment.

**Table 2.** Citation structure in terms of microcontroller in postharvest system-related papers according to Scopus

| Article Year | N | Mean TC/Art | Mean TC/Year | Citable Years |
|---|---|---|---|---|
| 2022 | 23 | 0.48 | 0.24 | 2 |
| 2021 | 28 | 1.82 | 0.61 | 3 |
| 2020 | 25 | 9.76 | 2.44 | 4 |
| 2019 | 17 | 7.24 | 1.45 | 5 |
| 2018 | 16 | 7.19 | 1.20 | 6 |
| 2017 | 8 | 6.00 | 0.86 | 7 |
| 2016 | 8 | 27.25 | 3.41 | 8 |
| 2015 | 12 | 15.00 | 1.67 | 9 |
| 2014 | 1 | 1.00 | 0.10 | 10 |
| 2013 | 9 | 12.22 | 1.11 | 11 |
| 2012 | 3 | 2.33 | 0.19 | 12 |
| 2011 | 0 | 0.00 | 0.00 | 13 |
| 2010 | 1 | 1.00 | 0.07 | 14 |
| 2009 | 5 | 10.00 | 0.67 | 15 |
| 2008 | 2 | 36.50 | 2.28 | 16 |
| 2007 | 0 | 0.00 | 0 | 17 |
| 2006 | 1 | 0.00 | 0 | 18 |
| 2005 | 0 | 0.00 | 0 | 19 |
| 2004 | 0 | 0.00 | 0 | 20 |
| 2003 | 1 | 57.00 | 2.71 | 21 |

**Institutional Structure**

Institutional structure analysis in this research was used to identify the most productive and influential institutions in applying microcontrollers in postharvest systems. Armed with data on the number of articles produced by each institution, the proportion of their contribution to the total articles, and the number of citations received by each article, this analysis can be used to evaluate the institution's performance in this research field. China Agricultural University is ranked first with 16 articles, or about 10% of the total articles analyzed. Università degli Studi di Milano is in second place with 14 articles or about 8.8% of the total articles.

Institutions from China and Italy led this research, with the China Agricultural University and Università degli Studi di Milano listed as the institutions with the highest number of articles (Table 3). Although the development of microcontrollers differs from the research focus of the two institutions, both make the development of postharvest techniques and technology a field of study. This is marked by their closeness to research centers related to postharvest technology, both managed internally and externally, for example, with the National Engineering Research Center of Fruit and Vegetable Processing and the Research Centre for Engineering and Agro-Food Processing at the Council for Agricultural Research and Economics (CREA - IT).

**Table 3.** The statistical analysis of Institutions

| R | Institution | N | P (%) |
|---|---|---|---|
| 1 | China Agricultural University | 16 | 10.0 |
| 2 | Università degli Studi di Milano | 14 | 8.8 |
| 3 | Northwest A&F University | 11 | 6.9 |
| 4 | Jiangsu University | 9 | 5.6 |
| 5 | Sastra Deemed University | 9 | 5.6 |
| 6 | University of Palermo | 8 | 5.0 |
| 7 | Beijing Research Center of Intelligent Equipment for Agriculture | 7 | 4.4 |
| 8 | Free University of Bolzano-Bozen | 7 | 4.4 |
| 9 | Nanjing Agricultural University | 7 | 4.4 |
| 10 | Research Centre for Engineering and Agro-Food Processing | 7 | 4.4 |

**Note:** N represents the number of articles. P represents the proportion of articles each institution publishes to the total number.

## Co-authorship Network Analysis

Co-authorship network analysis was used to study collaboration patterns between authors in a research field. This method utilizes information about co-authorship (writing partnership) between authors, in which two or more authors work together to create and publish a scientific article. In co-authorship network analysis, the co-authorship between authors is represented by the nodes in the network. In contrast, the partnership is represented by the connections or edges between the nodes. In a co-authorship network, nodes can represent single authors or groups of authors, and edges indicate that these authors have worked together on scientific work.

Of the 609 authors in the data set, there are only 44 authors whose names are listed in at least two different documents. Of the 44 authors, several are not connected with others in co-authorship. Furthermore, the co-authorship network that involves the most authors is formed from the ten authors in Figure 3.

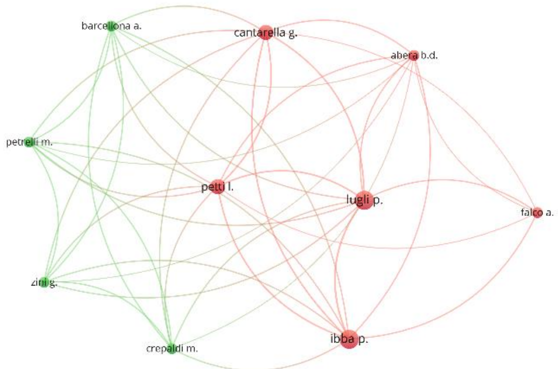



**Figure 3.** VOSviewer network visualization map of co-authorship

Based on Figure 3, Pietro Ibba and Paolo Lugli are connected with eight other authors, making them one of the most collaborating authors in co-publishing articles with four articles. Furthermore, in any article involving ten authors, Ibba is the first author, while Lugli is always the co-author. Ibba and Lugli are researchers from the Faculty of Science and Technology - Free University of Bolzano, Italy. Their most cited work is their research on bio-impedance in assessing fruit ripeness (Ibba et al., 2020).

On the other hand, the co-authorship analysis conducted on the author's country of origin category found that authors from India, Italy, the USA, and Egypt had a greater variety of international collaboration partners compared to other countries, namely 4, 3, 3, and 2, respectively (Figure 4). Researchers from India collaborated in writing scientific articles related to microcontroller applications in postharvest systems with researchers from Eritrea, Indonesia, Nigeria, and the USA. On the other hand, although researchers from China write the most articles in this field (marked in solid blue), they partner less internationally in publishing their work.

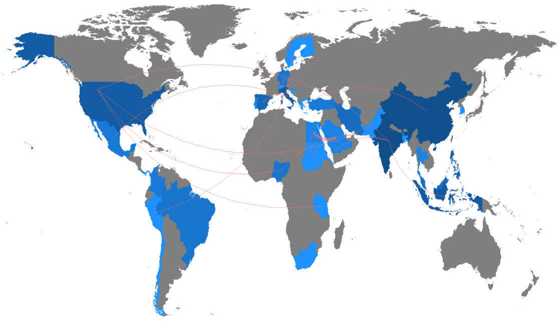


**Figure 4**. Collaboration map of the most productive countries generated by R Biblioshiny

**Co-citation Network Analysis**

Co-citation network analysis is a technique for mapping the relationship between documents or groups of documents cited simultaneously by other documents. In co-citation analysis, specific sources (i.e., the journal publishing the article) were selected based on the citation frequency on the citation frequency of at least 20 times. As a result, only 18 sources appeared in the analysis (Figure 5). Pairs of nodes connected by a link indicate that the two sources appear as references in at least one other article. The thicker the link between node pairs, the more articles cite the pair of documents simultaneously. From the data set analyzed, postharvest biology and technology journals have the most co-citation relationships with other sources, namely 17 sources. This journal was also the most cited source, with 134 citations. In addition, co-citation analysis also showed that most articles from postharvest biology and technology journals were cited together with articles from journals of food engineering.

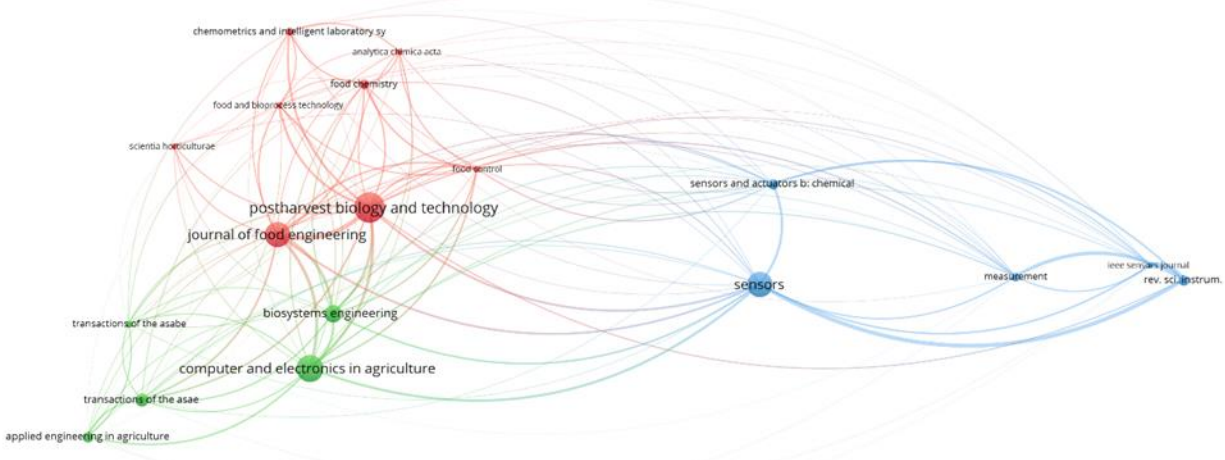
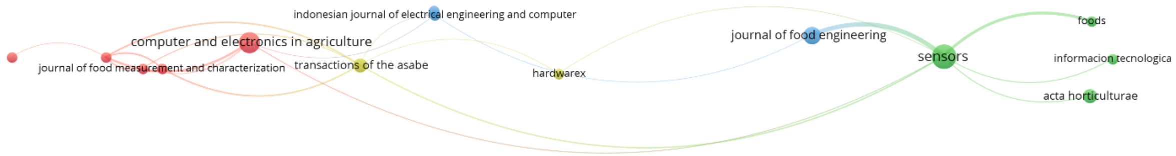



**Figure 5**. VOSviewer network visualization map of source co-citation

The co-citation relationship between postharvest biology and technology journals and other sources was high, indicating that the journal was the primary reference source in this research field. In addition, the strong co-citation relationship between postharvest biology and technology journals and the Journal of food engineering indicated that the two journals have a similar research focus and support each other regarding references. Therefore, researchers can consider the two journals as the primary reference source in researching the same topic.


(a)




(b)

**Figure 6**. The results of the coupling analysis based on (a) countries and (b) sources

**Bibliographic Coupling Network Analysis**

Bibliographic coupling analysis is a technique used to evaluate the relationship between pairs of documents that cite the same references. In this study, the coupling analysis was conducted based on the country of origin of the authors as well as the publication sources where documents on this topic were published. For the country-based analysis, only countries that produced a minimum of three documents were included, resulting in 16 countries being considered out of 37. As seen in Figure 6a, India and China had the largest node sizes, indicating the highest number of references used by documents from these two countries. Furthermore, a link between India and Indonesia indicated that both countries had cited the same article. Thicker links indicated that both countries used more of the same references. This finding suggests that India and Indonesia share similar interests in topic development and research direction pattern.

In addition, for the source-based analysis, only sources with a minimum of two documents in the dataset were considered, resulting in only 14 sources being successfully mapped out of a total of 121 sources (see Figure 6b). The sensor journal had the highest number of documents citing the same article as other sources. Furthermore, documents published in the sensor journal were substantially similar to those published in the Journal of Food Engineering in selecting reference articles.

**Keyword Co-occurrence Network Analysis**

Co-occurrence analysis aims to determine the relationship between how often keywords appear together and how these keywords are connected to form topic clusters. Using a thesaurus that lists synonyms for keywords and limits the occurrence of keywords at least five times, 50 keywords are obtained from 1771. In Figure 7, the node size indicates the number of documents that include each keyword, while the thickness of the link indicates the frequency of occurrence of the two linked keywords together. Fruits is the keyword that appears the most and is linked to other keywords, namely 50 total occurrences and 45 co-occurrences with other keywords in the data set. This shows that research on microcontrollers in post-food systems is mainly related to fruit.

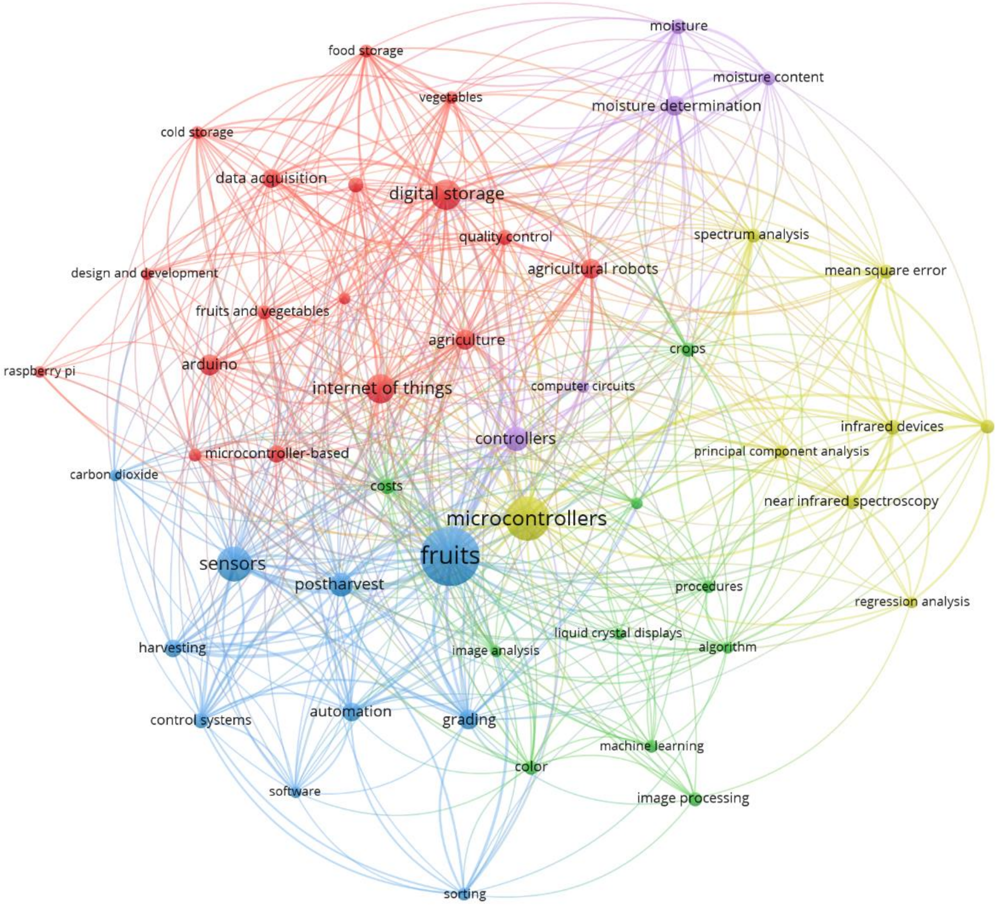



**Figure 7**. VOSviewer network visualization map of keyword co-occurrence

The different colors in Figure 7 show the various research sub-topics formed from interconnected keyword clusters. There are five keyword clusters in the data set summarized in Table 4. The first cluster (red) contains keywords including digital storage, internet of things, and Arduino, which appear most often with 20, 19, and 12 occurrences, respectively. Digital storage often appears with fruit, monitoring, and fruit storage with 9, 5, and 5 occurrences, respectively. The pattern of keyword relationships in this cluster indicates the development of research topics related to Arduino applications, digital storage, and the IoT (Internet of Things) concept in agriculture, especially for monitoring and quality control of fruits and vegetables during storage. Storage is a process to maintain the quality of agricultural products and prevent them from spoiling within a certain period so that they can overcome price fluctuations and product supply. The application of a microcontroller for rice storage in silos has been carried out by Dal-uyen et al. (2019). Using Arduino devices that are easy to obtain and open-source, the main problem, namely condensation, can be solved by monitoring temperature and RH data in real-time, which is then used to control the fan and heater of the silo aeration system.

The second cluster (green) contains keywords including cost, color, and crops as the most frequently appearing ones with 8, 7, and 7 occurrences, respectively. The cost keyword most frequently appears with fruit, digital storage, and agriculture, with 5, 3, and 3 occurrences, respectively. The emergence of keywords such as image processing, image analysis, and machine learning indicates that This cluster contains research on developing postharvest crop quality analysis procedures based on the image processing method to reduce costs.

**Table 4.** The main keywords identified based on a clustering method

| Cluster | Cluster keywords and the most frequent keywords |
|---|---|
| 1 | **17 keywords:** digital storage, internet of things, Arduino, agricultural robots, agriculture, data acquisition, microcontroller-based, monitoring, quality control, fruits and vegetables, cold storage, data handling, food storage, vegetables, design and development, fruit quality, raspberry pi<br>**The most frequent keyword:** digital storage, occurrences = 20 |
| 2 | **10 keywords:** costs, color, crops, image processing, machine learning, procedures, algorithm, electronic equipment, image analysis, liquid crystal displays<br>**The most frequent keyword:** cost, occurrences = 8 |
| 3 | **10 keywords:** fruits, sensors, postharvest, grading, automation, harvesting, control systems, sorting, carbon dioxide, software<br>**The most frequent keyword:** fruits, occurrences = 50 |
| 4 | **8 keywords:** microcontrollers, infrared devices, least squares approximations, mean square error, near infrared spectroscopy, spectrum analysis, principal component analysis, regression analysis<br>**The most frequent keyword:** microcontrollers, occurrences = 33 |
| 5 | **5 keywords:** controllers, moisture determination, moisture, moisture content, computer circuits<br>**The most frequent keyword:** controllers, occurrences = 15 |

The third cluster (blue) contains keywords including fruits, sensor, and postharvest as the most frequently appearing, with 50, 24, and 14 occurrences, respectively. Fruits are Each section-of most connected with microcontrollers, sensors, and digital storage, with 12, 11, and 9 occurrences, respectively. The emergence of other keywords, such as grading, automation, and sorting, indicates that this cluster contains research on developing postharvest grading and sorting process automation in fruit using a control system equipped with sensors. Sorting is the elimination of rotten, damaged, and diseased products from good products to prevent the spread of infection. At the same time, grading categorizes products based on specific parameters, making further handling easier. Automation in grading and sorting can increase process efficiency, reduce the amount of labor, and increase the added value of products in the market. The development of microcontroller-based sorting and grading machines is intended to overcome the complexity of the structure and the high cost of existing machines. Omidi-Arjenaki et al. (2012) used machine vision to sort tomatoes based on the average histogram of color components. Meanwhile, Zuo and Xu (2013) succeeded in developing a Kiwi fruit grading machine using the STC89C52 microcontroller as the controller core, Labview software as the user interface and Data Acquisition (DAQ), and Matlab software for image processing.

The fourth cluster (yellow) contains keywords including microcontrollers, infrared devices, and least squares approximations as the most frequent occurrences, with 33, 8, and 7 occurrences, respectively. Microcontrollers are most connected with fruits, sensors, and controllers, with 12, 9, and 9 occurrences, respectively. The emergence of other keywords, such as near-infrared spectroscopy and spectrum analysis, indicates that this cluster contains research on developing microcontroller-based infrared spectroscopy applications for measuring postharvest quality with various data processing methods. Spectrometer analysis is the simultaneous detection of several quality parameters based on spectral information resulting from the interaction between the food matrix and the light reflected from the product. The development of microcontroller-based portable spectrometers is increasing by offering advantages in size, spectral range, and price. However, the prediction results and model performance on portable spectrometers are strongly influenced by environmental conditions, such as fluctuations in temperature and sunlight, which can interfere with optical propagation properties, light behavior, and spectral patterns. Das et al. (2016) utilize a nozzlelike enclosure for collecting light, thereby shielding any stray light contribution, making the portable spectrometer suitable for field-based applications. In the research by Fan et al. (2020), spectral fluctuations due to the aging of the light source and loss of battery energy have been reduced by utilizing dynamic correction using a switch system. In addition, the number of essential variables needed to predict the outcome of the response can be reduced using the multiple linear regression (MLR) algorithm. Giovenzana et al. (2015) succeeded in utilizing MLR using only four wavelengths to produce overall calibration and ripeness prediction results for a white wine that are no less accurate than partial least squares (PLS) results using full visible-near infrared (Vis-NIR) spectra.

The fifth cluster (yellow) contains keywords including controllers, moisture determination, and moisture as the most frequent occurrences, with 15, 11, and 8 occurrences, respectively. The controllers are mostly linked to microcontrollers and fruits, with 9 and 6 occurrences, respectively. Based on the pattern of keyword connections, the research in this cluster is more concerned with the development of computer circuit-based moisture determination methods, as was done by Mireei et al. (2016).

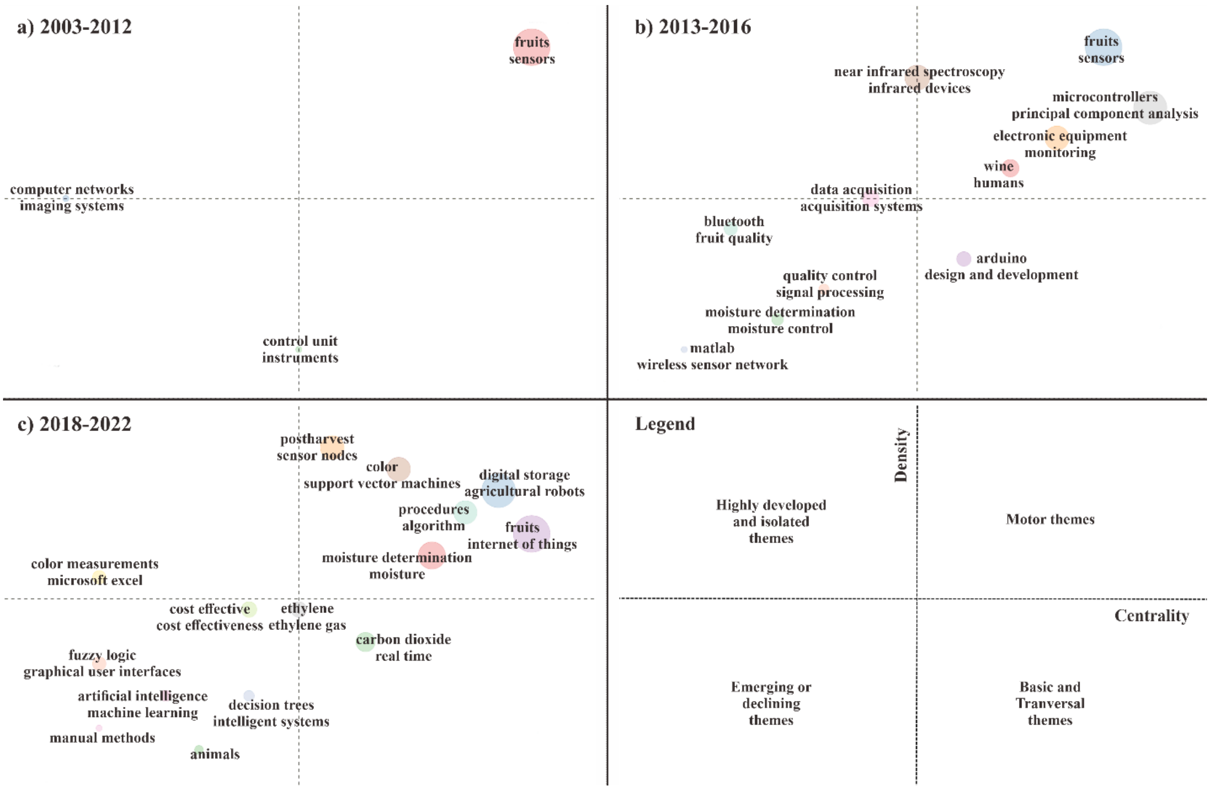



**Figure 8.** Keyword thematic map for microcontroller in postharvest system-related articles from 2003 to 2022 generated by R Biblioshiny

## Keyword Evolution Trends

The strategy diagram in Figure 8 shows keyword trends in the microcontroller application theme for postharvest systems in three different period ranges. Each section of this diagram consists of four quadrants, each representing a thematic keyword. The areas in the upper right quadrant (motor themes) represent well-developed and robust topics in the microcontroller application field. Meanwhile, the area in the upper left quadrant represents a particular topic and is not included in the main focus. The area in the lower left quadrant contains topics with low density and focus, representing topics that have recently appeared or disappeared. The areas in the lower right quadrant represent the most common basic and transverse topics, although internal development is lower than the upper right quadrant. The topics in the lower left and right quadrants can be a source of inspiration and potential reference for further research in microcontroller applications for postharvest systems.

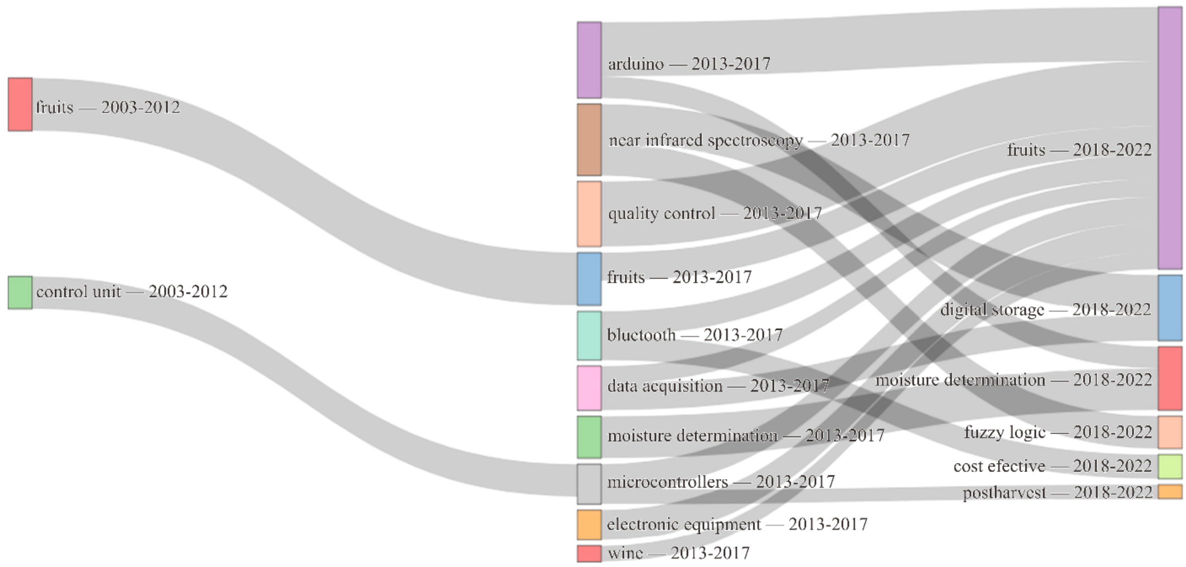



**Figure 9**. Sankey diagram based on keyword thematic evolution from 2003 to 2022 generated by R Biblioshiny

Based on the Sankey diagram (Figure 9) and the results of the thematic map analysis, the following two features are most needed to be discussed: a) the basic and transversal themes show that the issues of ethylene, carbon dioxide, and real-time have become the basic themes for microcontroller applications in postharvest systems in several last years. From 2003 to 2012, the basic theme focused more on control units and instruments. From 2013 to 2016, the basic theme focused more on Arduino and design/development. The challenges and solutions section introduces design/development challenges and real-time workability in more detail. b) the emerging theme demonstrating cost-effectiveness and data acquisition has been developed recently. The problem of cost-effectiveness is the most crucial reason for applying microcontrollers. In recent years, research aimed at providing more affordable microcontroller application scenarios for postharvest systems, more robust/reliable designs, and the ability for systems to work in real-time has become major study hotspots and urgent issues.

**Challenges and Potential Solutions for Microcontroller Applications in Postharvest Systems**

Based on the keyword co-occurrence network and thematic evolution results, cost, real-time, and design keywords are becoming challenging mainstream research topics. Topics related to cost appeared eight times, topics related to real-time/response time appeared three times, and topics related to design five times. So that in this subsection, the challenges of response time, cost, and design reliability were analyzed and discussed in more detail. This review aimed to transform microcontroller applications from an original hot concept into a viable technological paradigm for better engineering in postharvest systems.

a) **Time response challenge**. Measuring the quality of postharvest products is vital in maintaining product quality and durability. In measuring the quality of postharvest products, a fast response time is needed to immediately know the quality of the product, especially for sorting and grading processes. One of the techniques used in measuring the quality of postharvest products is the Vis-NIR technique. Vis-NIR spectrometry works based on indirect measurements that require chemometric support to utilize the appropriate spectra. Some products are not suitable for measuring with this technique because not all compounds or components in the product have a unique spectrum that is easy to identify. However, this technique allows measurements to be carried out non-destructively with several product quality parameters that can be measured simultaneously.

The development of microcontroller-based portable Vis-NIR spectrometers as control/processing units is increasingly in demand because it allows use outside the laboratory. Giovenzana et al. (2015) utilized the PICTM microcontroller to verify system status, send signals to other units, make decisions, and coordinate the spectrometer's overall operation in determining the grapes' ripeness. Meanwhile, in Das et al. (2016), Arduino Pro Mini converts the analog video signal from the spectrometer chip into digital data and sends it wirelessly to a smartphone. The data is then processed and analyzed using a machine learning algorithm to determine the maturity level of the fruit. This development allows the application of Vis-NIR technology to be carried out in-line measurement, namely direct measurement, when the product is being processed in real-time. Thus, all samples can be measured directly to increase time efficiency and accuracy in measuring the quality of postharvest products.

**b) Cost challenges**. With the help of a microcontroller, it is possible to design postharvest equipment that is cost-effective in investment, energy, and maintenance. In addition, the ability of the microcontroller system to utilize various types of sensors makes this system more flexible and cost-effective for further development compared to similar instruments. However, cost efficiency in applying microcontrollers for postharvest systems remains challenging due to the many aspects that must be considered.

The selection of hardware that does not match the application's needs can waste money. Using NodeMCU and ESP32 microcontrollers is considered more profitable than Arduino because it has higher specifications at a lower price. NodeMCU and ESP32 feature integrated wireless, operate at higher clock speeds and have larger memory capacities. This allows the development of more complex applications at relatively more affordable costs.

Applications that waste storage and memory space on the microcontroller and consume a lot of bandwidth and energy can be very costly, especially in remote locations. To minimize this, avoiding algorithms with rarely used variables is necessary. In addition, choosing the proper protocol for communication between devices such as MQTT (Message Queuing Telemetry Transport) is considered to help save memory, bandwidth, and energy usage. This protocol uses topic-based messages so that it only sends or receives messages that are relevant to the task and ignores messages that are not needed. Resource savings also arise from this protocol's ability to compress message sizes into smaller ones.

High costs can also arise from long-term power-consuming applications. Developers should consider selecting modules that are efficient in power usage. For example, for IoT applications, Bluetooth is preferable to WiFi and Zigbee because Bluetooth can work at lower power than WiFi, and data transfer rates are higher than Zigbee (Sainz et al., 2013). In addition, using deep sleep mode on the microcontroller can minimize power consumption by turning off most of the features, such as wireless connections, thus enabling battery-powered applications to last longer. By paying attention to these things, microcontroller applications can be developed more effectively and efficiently.

**c) Design reliability challenges**. Postharvest products are very susceptible to damage, so processing time is limited. To minimize losses, a reliable microcontroller-based postharvest handling system must be designed to carry out tasks without interruption. Postharvest products can also experience changes in production volume. Thus, the system must be designed with scalability in mind that can handle high production volumes without sacrificing efficiency and reliability.

Several designs have been developed to suit the current needs of the agricultural business and industry. One such design is a postharvest handling system based on a microcontroller with a modular architecture, such as the respiration rate measuring instrument (González-Buesa & Salvador, 2019). Modular architectures make system development and maintenance easier. In addition, the current design also begins to consider the ease of use. The user-friendly design enables the use of the system by many people with different technological backgrounds. For example, this step can be taken by including clear and systematic flowcharts. Flowcharts can help programmers determine errors and make it easier for users to understand how the system works.

One of the obstacles in applying microcontrollers for postharvest systems is the limited processing capability of microcontrollers available on the market. For example, in the development of microcontroller-based spectrometers, the ADC (analog to digital converter) resolution of currently available microcontrollers is limited to only 10-bits or lower than commercial spectrometers, which are up to 16 bits (Das et al., 2016). This causes small changes in the observed light intensity undetectable with sufficiently high sensitivity. With more rapid advances in this field, better microcontrollers with higher bit depths will likely be available soon.

## CONCLUSIONS AND RECOMMENDATIONS

### Conlusions

Based on a systematic evaluation of this topic from a bibliometric perspective, several findings related to research collaboration networks, the development of thematic trends, and solutions to challenges for microcontrollers in postharvest systems were obtained. China and Italy are the countries that produce the most research on this topic, even though both of them lack international collaboration in their production. The central studies of microcontrollers for postharvest systems focus a lot on fruit, digital storage, moisture determination, and costs. Furthermore, the evolution of thematic keywords shows that response time, cost, and design issues have become basic and emerging themes for this topic in recent years. Developing the use of machine learning algorithms by in-line measurement; communication protocols that are more power, bandwidth, and memory efficient; and modular architecture accompanied by systematic flow diagrams are considered a potential solution in overcoming microcontroller constraints for postharvest systems.

### Recommendations

For future studies, it is recommended that researchers collaborate internationally to address challenges and improve microcontroller applications for postharvest systems. Emphasize optimizing response time, cost-effectiveness, and overall system design to enhance efficiency and effectiveness in agricultural postharvest practices.

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## CONFLICT OF INTEREST

The authors declare no conflicts of interest associated with the research. The authors also affirm that the study was conducted impartially without external influence. There are no financial or personal relationships that could have influenced the research outcomes or the article's content.

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