

Global research network analysis of fresh produce postharvest technology: Innovative trends for loss reduction

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Highlights

- The majority (65 %) of fresh produce postharvest research surged from 2010 to 2020.
- *Botrytis cinerea* and *Penicillium* are top fresh produce postharvest pathogens.
- Focus was on green postharvest control alternatives in the last three decades.
- China and the USA are the global leaders in fresh produce postharvest research.
- LMICs are still lagging in postharvest research and collaboration.

ABSTRACT

Globally, fruit and vegetables (fresh produce) are important for nutrition, health, food security, and economic growth. However, this type of produce is highly impacted by huge global postharvest losses ranging between 28 % and 55 % annually with low and middle-income countries (LMICs) being the most affected. Tremendous efforts have been made in terms of research and innovation to address the issue of fresh produce postharvest losses over time. Hence, this study aimed to understand the trends in fresh produce postharvest research focusing on innovations for loss reduction over the last three decades using bibliographic network analysis. This involved the retrieval of postharvest-related research documents on fruit and vegetables from the Web of Science database published between January 1990 and December 2020. The retrieved documents were used to generate maps using the VOS viewer

software to visualize the key research areas and technology trends towards reducing fruit and vegetables postharvest losses as well as collaborations among countries. The study results showed an exponential increase in postharvest research on fresh produce over the past three decades with around 65 % of the work happening in the last decade (2010-2020). Research trends showed that postharvest loss reduction (PHLR) innovations focus has shifted from common chemical control to search for alternative control strategies. Most notable is the shift towards plant-based compounds, edible coatings, and biofilms for disease control and fresh produce shelf-life extension. Study results showed that China and USA are the major global players in fresh produce postharvest research, while South Africa and Egypt are the key players in Africa. Despite the milestones in fresh produce postharvest research, LMICs still experience high postharvest losses shifting the debate on access to information and the adoption of novel technologies. The study recommends the need to strengthen PHLR research investment and collaboration, particularly among LMICs to reduce the burden of food losses and waste and strengthen food security. This can be achieved by increasing adoption of the novel technologies by the industries.

Keywords: Disease control, Food security, Fruits and vegetables, Shelf-life extension, Postharvest quality.

1. Introduction

Fresh produce particularly, fruits and vegetables play an important role in ensuring food and nutritional security as well as enhancing global trade and economic growth (Schreinemachers et al., 2018). For instance, the global annual farm gate value of fruits and vegetables is reported to be approximately USD 1 trillion which is more than that of all agricultural food grains combined (USD 837 billion) (Schreinemachers et al., 2018). Despite their economic potential, fruits, and vegetables remain prone to high postharvest losses (Rahiel

et al., 2018) which remains a major threat to food security. This is particularly true in low-and middle-income countries (LMICs) (Kumar & Kalita, 2017).

Among all the food commodities globally, fruits and vegetables record the highest postharvest losses ranging between 28-55 % of the total production and accounting for approximately USD 750 billion per annum (Opara et al., 2021; Ueda et al., 2022). In extreme cases, postharvest losses of fresh produce can be as high as 60 % depending on the produce type (Yahia et al., 2019). These losses have been attributed to various aspects such as mechanical and biological (pest and diseases) damages (Dharmathilake et al., 2019) with the latter being estimated to cause over 40 % of the total losses in fruits and vegetables (Tripathi et al., 2022).

In this regard, numerous studies have been done to develop technologies targeted towards reducing postharvest losses. For instance, in close to half a century, postharvest research has increased and shifted focus to incorporate various novel technologies. These now cover aspects such as harvesting, handling, packing, transportation, and storage to extend shelf-life, retain and improve quality, reduce loss, and ensure safety after harvest. The more recent shift towards transdisciplinary research has also contributed to researchers, institutions (public and private), countries, and funding bodies engaging in collaboration more and securing international funding that focuses more on the global challenges around food availability and supply by minimising losses and retaining quality and safety up to the point of consumption.

This study aimed to bring a clear understanding of postharvest loss reduction (PHLR) related research trends in fresh produce particularly in fruits and vegetables over the last three decades (1990-2020). Consequently, through a meta-data analysis and visualization of the postharvest research dynamics, this study endeavoured on depicting the current key innovation areas in postharvest disease control and shelf-life extension of fresh produce. In addition, the

major players in terms of research and funding, continental collaborations, publishing trends, and journals were analysed. These findings are key in projecting the future of fresh produce postharvest handling for appropriate timely interventions toward recent and future loss management trends to safeguard food security.

2. Materials and Methods

2.1 Data extraction

To have a clear picture of the research trends in fresh produce (fruit and vegetables) postharvest research field, a bibliometric network analysis of all PHLR-related published work from 1st January 1990 to 31st December 2020 was done as described by Zou et al. (2018). The bibliometric analysis was to show the research trends related to postharvest handling of fresh produce and the technological shifts in disease control and loss reduction over the last three decades. Major countries that have participated in postharvest research and collaborations as well as the preferred journals of publications were additionally analysed.

Postharvest loss reduction-related research documents (articles, reviewed articles, proceeding papers, and book chapters) used in the study were extracted from the Web of Science (<https://clarivate.com/webofsciencegroup/solutions/web-of-science/>). The documents were retrieved using a combination of the following search terms: “(“fruit” or “vegetables”) and (“disease” or “pathogen”) and (“biological control” or “chemical control” or “alternative control” or “quality” or “shelf-life” or “shelf life”)”. The retrieved documents were then screened in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines (Page et al., 2021; Figure 1).

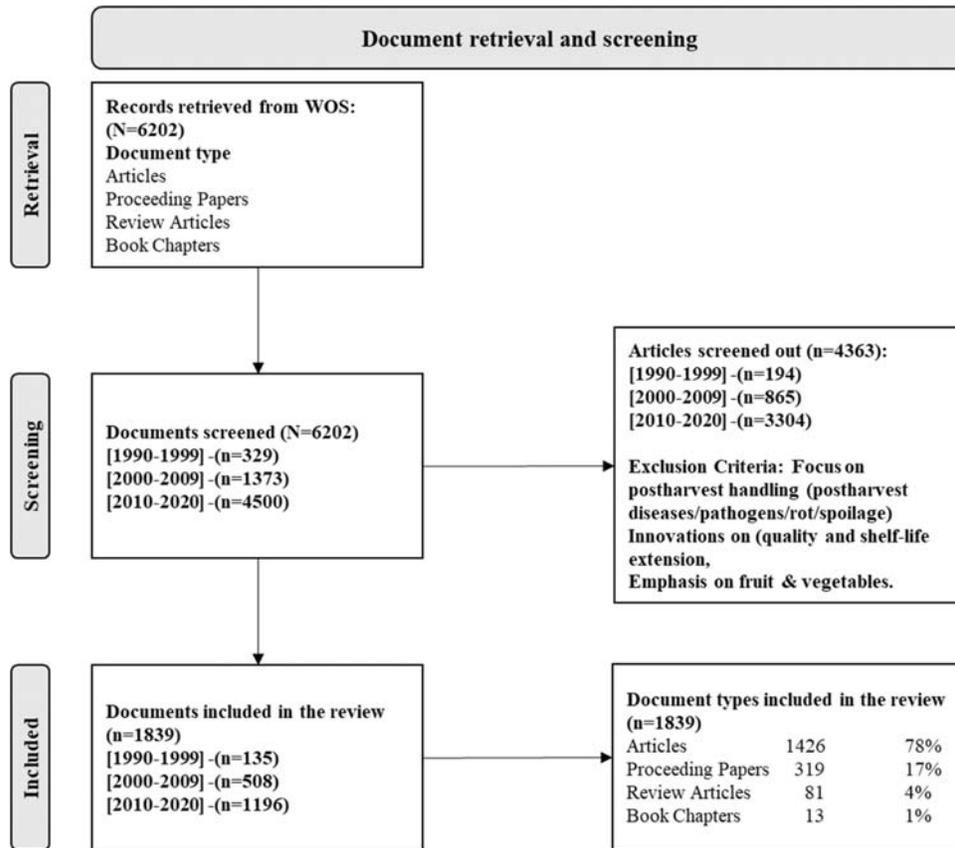


Figure 1: PRISMA flow summary on the retrieval and screening of the documents used in the review.

2.2 Inclusion and exclusion criteria

Only documents related to postharvest handling of fruits and vegetables were considered for the network analysis. Specific themes i.e., “postharvest pathogens and diseases” as well as “innovations towards postharvest loss reduction” were used for the network analysis. From a total of 6202 retrieved documents only 1839 publications were considered eligible for further analysis.

2.3 Network analyses

VOS viewer software version 1.6.18 was used in the generation of the bibliometric maps as it allows the creation and visualisation of the different parameters under the study (Eck & Waltman, 2014; Skaf et al., 2020). A visualisation map showing the key areas of PHLR-

related research was created using the co-occurrence as the type of analysis with keywords being the units of analysis. The keywords factored were mainly on fresh produce quality and storage, major pathogens, and control strategies. Keywords appearing on the map were recurrent in at least twenty (20) different documents. Visualisation map of major postharvest diseases affecting the fresh produce and technological control shifts over time was also generated. Apart from the general PHLR trend breakdown, the analysis of the most researched agricultural fresh produce was also carried out. Country postharvest research and collaborations map was generated by undertaking a co-authorship analysis with the countries as the unit of analysis. Countries having at least five of the selected research articles on postharvest handling of fruits and vegetables were included in the network visualisation map. Visualisation map of common scientific journals publishing postharvest research related works was also generated by running citation analysis with document source being the unit of analysis. Journals that had published at least 10 of the screened PHLR related articles between 1990-2020 were considered in generation of the visualisation map.

3. Results

3.1 Analysis trends on postharvest loss reduction related research

As per the retrieved and analysed documents, the last three decades have seen, tremendous growth in fresh produce (fruit and vegetables) postharvest research. This was shown by the number of postharvest research documents published in different journals annually between 1990 and 2020 (Figure 2). The results showed an exponential growth in PHLR research with much of it (65 %) being recorded in the last decade (2010-2020). According to the Web of Science collection database, the first recorded paper on PHLR-related research was published in 1956, thereafter, a slow but steady growth in the number of publications was seen. The retrieved documents indicated that much of fruit and vegetable

PHLR-related work was published starting in the early 1990s, with the highest number (165) of documents being published in 2020 (Figure 2).

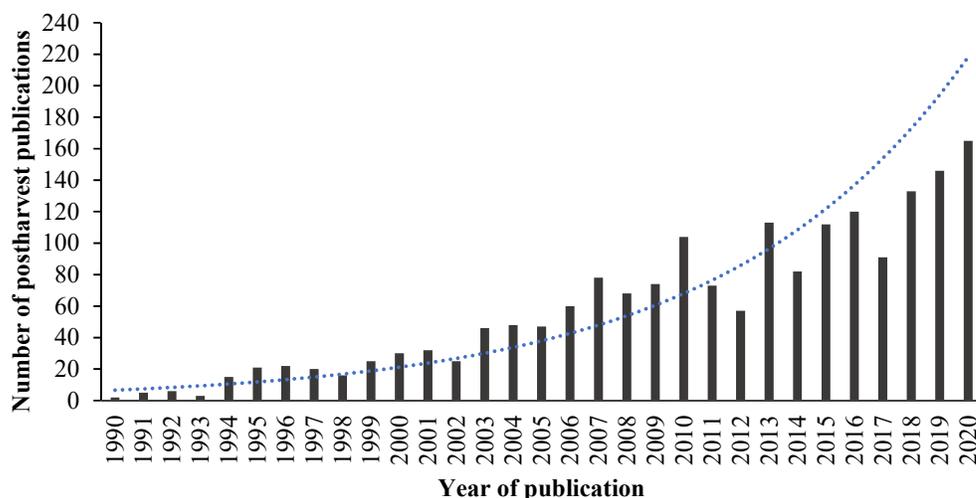


Figure 2: Publication trends in the field of postharvest loss reduction (PHLR) related research from 1990 to 2020 (Documents extracted from the Web of Science Collection as per the predefined search terms).

The analysis showed that the top ten most researched fruits and vegetables were apples, citrus, tomato, mango, peach, grapes, strawberry, banana, sweet cherries, and lettuce (Figure 3). Other top-researched fruits included blueberries, avocado, pears, and litchi. Although not at the top of the list, vegetables such as broccoli, onions, cabbages, cucumbers, and eggplants have also been widely researched at the postharvest level. The data also showed over time growth in all the ten most researched fruits (Figure 3). Further analysis showed that the top-researched fruits and vegetables are also among the highly ranked fresh produce crops of economic importance globally as indicated by their high annual production data (Table 1).

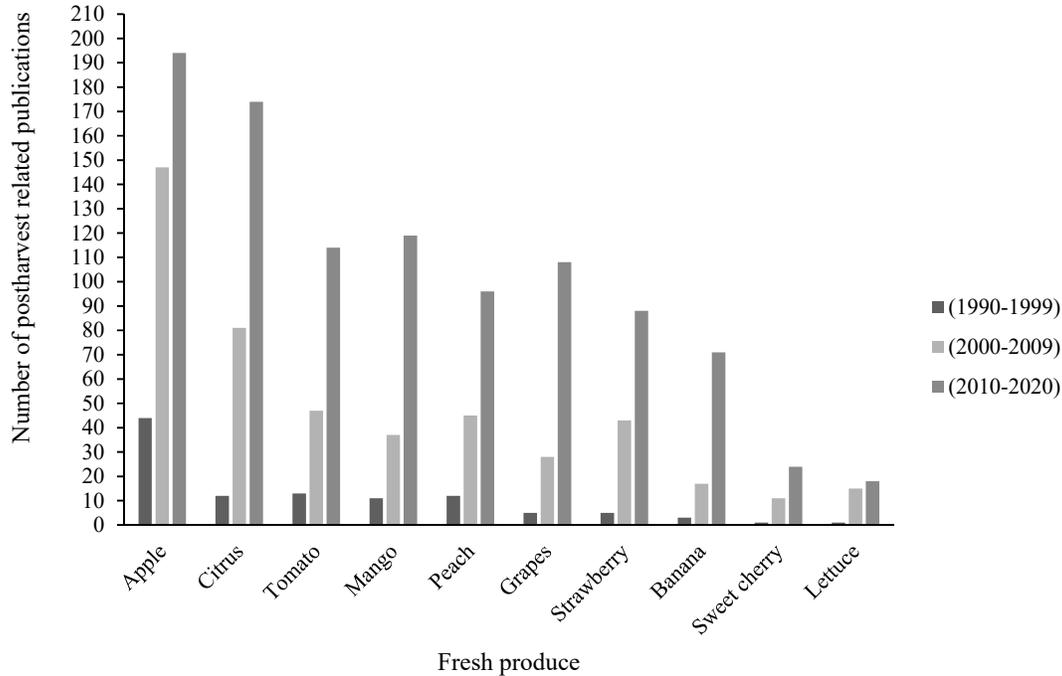


Figure 3: Postharvest trend analysis of the ten most researched agricultural fresh produce in the world as per the retrieved and screened documents from the Web of Science Collection.

Table 1: Global production (metric tonnes) of the most produced fruits between 2017-2021

Produce	2017	2018	2019	2020	2021
Bananas	113,226,251	116,775,502	117,677,765	121,397,848	124,978,578
Watermelons	100,949,292	100,959,810	101,841,525	101,916,818	101,634,720
Apples	83,085,659	85,903,043	87,509,103	90,490,295	93,144,358
Oranges	73,442,596	73,276,531	76,216,362	76,566,647	75,567,952
Grapes	73,549,311	80,015,897	77,087,415	76,997,321	73,524,196
Mangoes	52,620,298	54,307,128	56,532,219	56,685,547	57,011,283
Plantains	38,243,772	38,352,612	44,534,879	45,385,816	45,321,643
Tangerines	32,947,177	34,471,432	38,947,541	39,105,345	41,950,302
Pineapples	27,415,670	28,295,699	28,167,314	27,244,583	28,647,866
Pears	23,822,374	23,721,253	24,266,772	24,986,262	25,658,713
Peaches and nectarines	23,732,143	23,895,259	24,610,870	24,267,464	24,994,352
Lemons and limes	17,424,293	19,397,975	19,712,617	20,462,547	20,828,739
Papayas	13,418,053	13,798,774	14,210,842	14,186,675	14,097,721
Plums and sloes	11,494,838	12,251,148	12,131,192	12,105,278	12,014,482
Dates	8,396,456	8,745,896	9,214,828	9,517,451	9,656,378
Grapefruit and pomelos	8,668,411	9,039,496	9,300,250	9,381,190	9,556,999
Strawberries	8,243,751	8,538,477	9,012,639	8,893,591	9,175,384
Avocados	6,294,332	6,791,541	7,166,739	8,104,028	8,685,672
Kiwi fruit	3,989,893	4,253,475	4,308,672	4,431,570	4,467,099
Persimmons	4,547,892	4,247,388	4,246,319	4,230,463	4,332,167
Apricots	4,789,361	3,890,829	4,051,543	3,717,003	3,578,412
Cherries, sweet	2,449,772	2,569,614	2,630,541	2,632,985	2,732,413

(Source: Agriculture and Agri-Food Canada, 2023:

<https://agriculture.canada.ca/en/sector/horticulture/reports/statistical-overview-canadian-fruit-industry-2022#a4.1.1>).

major postharvest pathogens identified through the analysis included *Botrytis cinerea* (gray mold), *Penicillium species* (blue mold and green mold), *Colletotrichum species* (anthracnose), and *Rhizopus stolonifera* (Rhizopus rot). Other pathogens of economic importance researched on during this period included *Alternaria alternata*, *Fusarium*, *Monilinia*, and *Aspergillus* species. From the listed pathogens, *B. cinerea*, *Penicillium species*, and *Colletotrichum species* have remained the main pathogens of interest affecting fruit quality at storage over the last three decades (Figure 5).

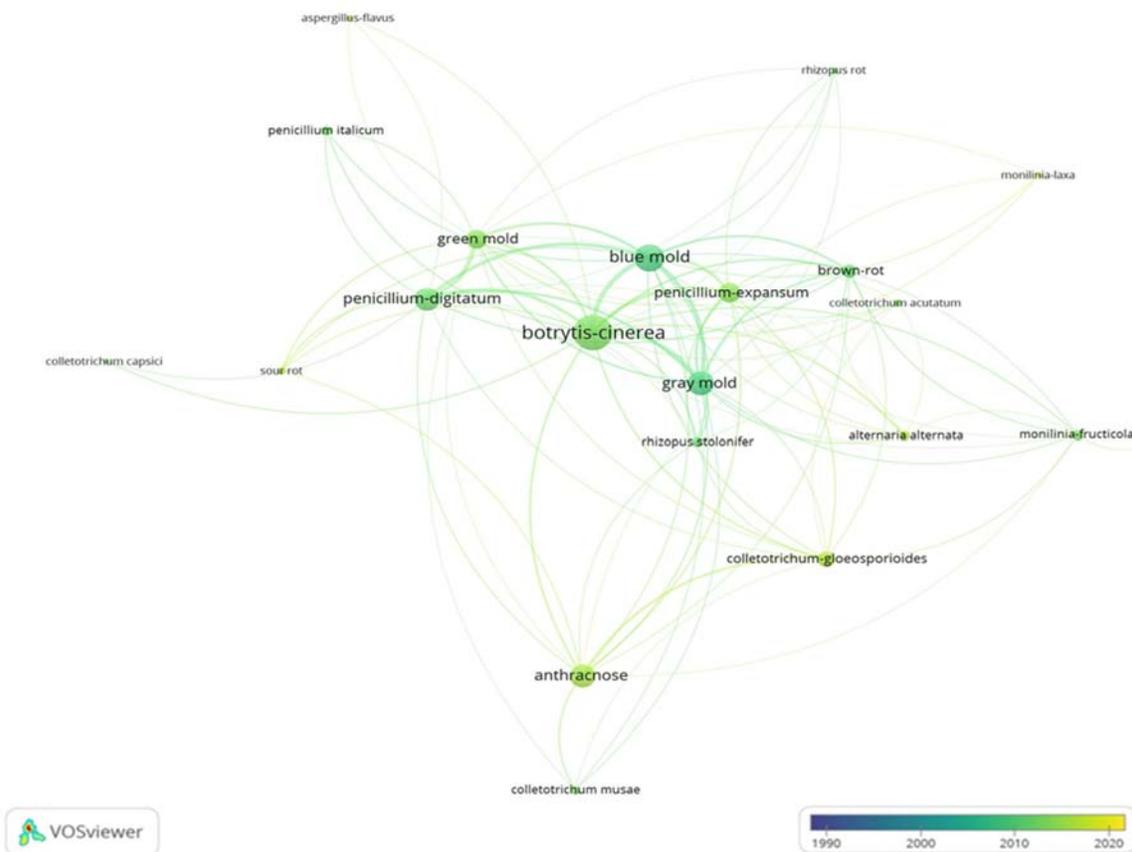


Figure 5: Most researched fruit and vegetable postharvest pathogens and diseases over the last three decades [1990-2020]. * The bigger the size of the circle, the higher the emphasis of research on that pathogen and related disease. The colour codes depict the time when the particular pathogen or disease was most researched on.

3.4 Postharvest loss reduction technological trends

Apart from the postharvest pathogens of fresh produce, analysis on control strategies and innovations was conducted. The findings of the study revealed that chemical control and

biological control methods were the most researched and used strategies to manage postharvest diseases and related losses during the years 1990-1999 (Figure 6 A). Apart from chemical (e.g., fludioxonil and benzimidazole fungicides) and biological control, the years 2000-2009 saw the introduction of other strategies such as the use of 1-methylcyclopropene, controlled atmosphere packaging, and edible coatings (including chitosan), plant extracts and essential oils (Figure 6 B). Research carried out between 2010-2020 expanded on previous research on chemical/fungicide and biological controls (Figure 7). The last decade depicted research focus on other chemical compounds (e.g., sodium bicarbonate, calcium chloride, and nitric oxide) with less residual effect while having the potential to lengthen the shelf-life of fresh produce.

This last decade was also characterized by an increased shift towards the exploitation of several plant extracts and organic oils as alternative strategies for postharvest loss reduction (Figure 7). Physical methods such as gamma irradiations, ultraviolet radiation (UV-C), and ozone treatments were also widely researched on during the period 2010-2020 (Figure 7). Generally, the result analysis showed continuous growth in biological control and other chemical control alternatives over the last three decades (Figures 6A, 6B & 7).

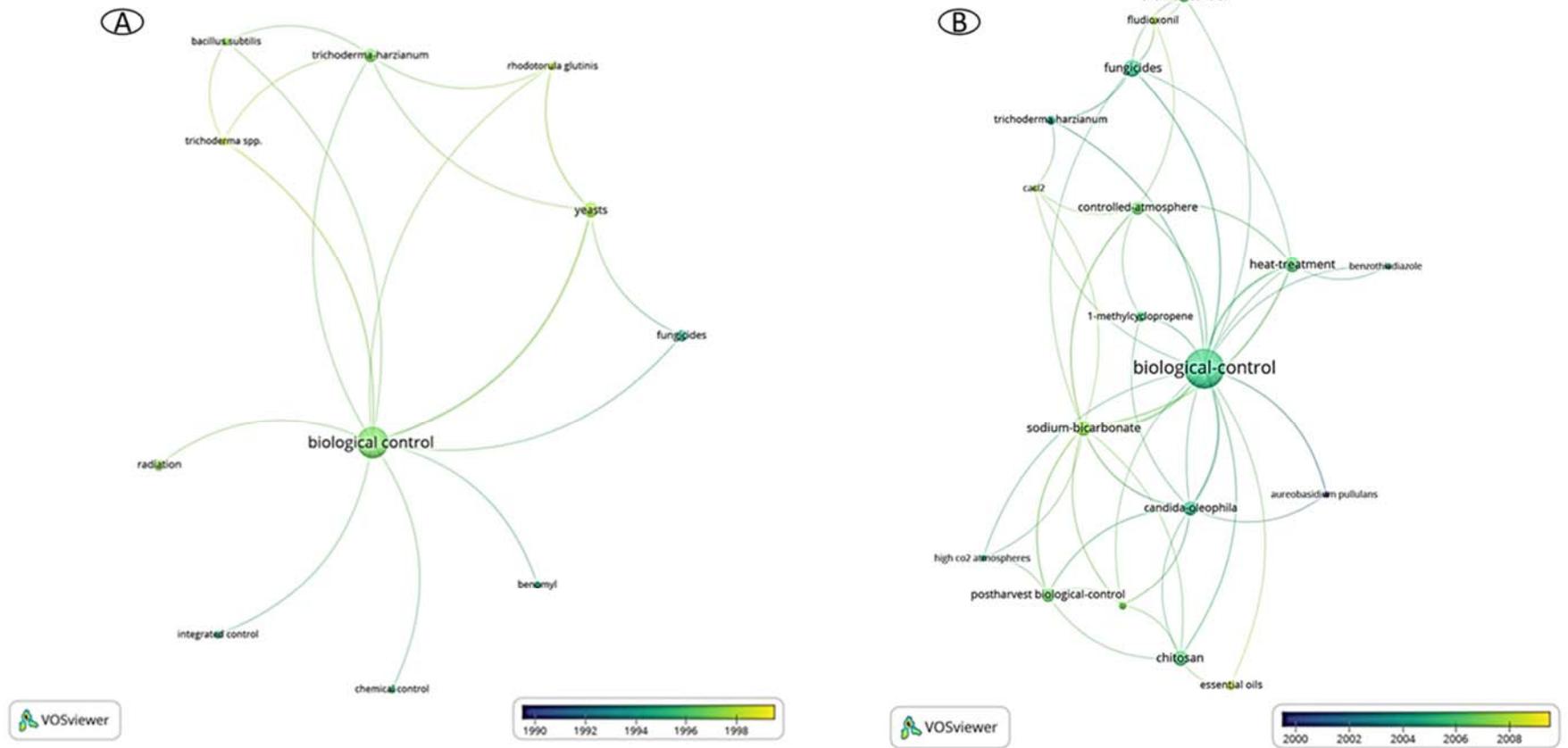


Figure 6: Fresh produce postharvest pathogens/disease and loss control technological trends comparison between [1990-1999] and [2000-2009].

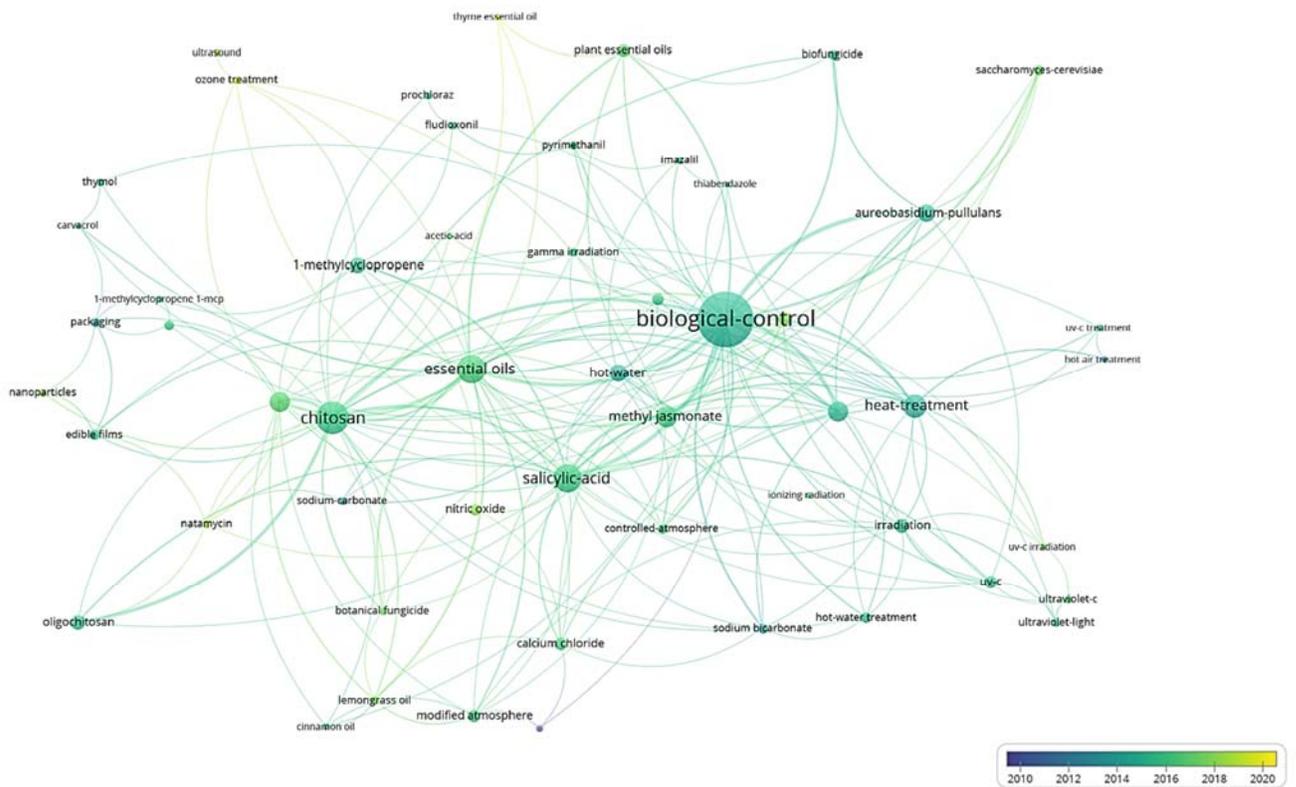


Figure 7: Key researched fresh produce postharvest pathogens/disease and loss control technological strategies between 2010-2020.

3.5 Country postharvest fresh produce research and collaboration ranking

A co-authorship analysis of the total screened documents showed research and collaborations between 84 countries across the globe. A total of 48 countries appeared on the network visualisation map after passing the criteria of at least five published research documents as well as having collaboration links with other countries (Figure 8). China, the United States of America (USA), Italy, Brazil, and Spain were ranked top leading countries involved in postharvest research in the world based on the number of research papers published and uploaded in the Web of Science database since 1990 to 2020 as indicated by the extracted and screened documents (Table 2). Other major countries involved in postharvest research included India, Israel, Australia, Thailand, Mexico, Canada, South Africa, Malaysia, England,

Iran, Pakistan, South Korea and Egypt (Figure 8). South Africa and Egypt emerged as the leading countries in Africa extensively involved in fresh produce PHLR-related research and collaborations having a total of 54 and 34 postharvest publications on fruits and vegetables to date based on extracted documents from the Web of Science database respectively. Other African countries identified to be active in fresh produce postharvest research include Morocco, Ghana, and Tunisia.

Table 2: Country ranking based on published articles on fresh produce postharvest research as per the Web of Science Collection between 1990-2020

Country	Documents	Total number of citations	Link strength
China	375	13568	88
USA	268	11624	115
Italy	131	5938	57
Brazil	109	1939	28
Spain	104	4333	43

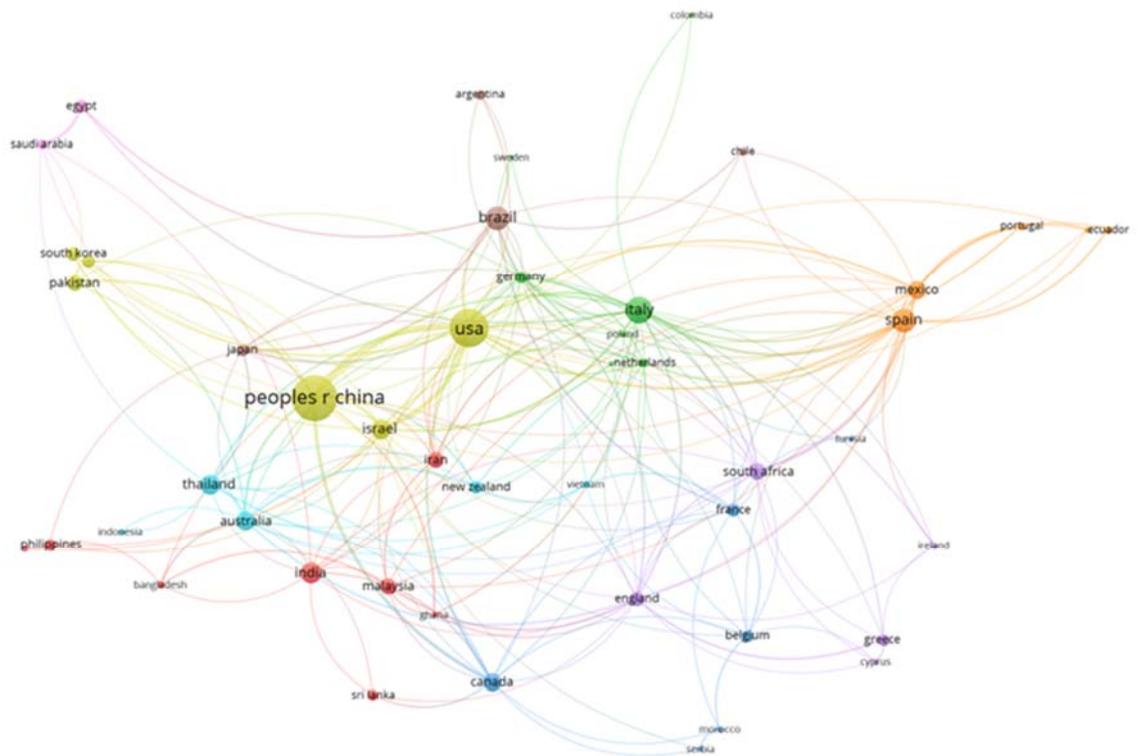


Figure 8: Fresh produce postharvest loss reduction (PHLR) related research and collaboration ranking between countries during 1990 – 2020. *The bigger the size of the county’s circle, the more investment and involvement in postharvest research. The colour coding shows the collaboration clusters among the major postharvest research players.

3.6 Network analysis on key postharvest-related journals

An analysis of 1839 fruit and vegetables PHLR-related publications from the Web of Science generated a total of 508 journals where most scientists published their work. Only 34 of these journals met the minimum criteria of the cut-off of at least 10 of the selected PHLR-related publications to be included in the generation of visualisation map (Figure 9). Journal of Postharvest Biology and Technology emerged as the top-ranked journal in this field of study having published 198 publications out of the total 1839 screened documents. It was followed by the Journal of Biological Control with 65 publications (Figure 9). The rest of the top five journals publishing PHLR-related research works are shown in Table 3 and reflect the formal science communication platforms.

Table 3: Journal ranking based on the number of articles published on fresh produce postharvest loss reduction (PHLR) related research

Journal title	IF 2019	IF 2020	IF 2021	IF 2022-2023	Total documents	Citations	Total link strength
Postharvest Biology and Technology	4.303	5.537	6.751	6.751	198	10583	1271
Biological Control	2.754	3.687	3.857	4.2	65	2565	514
Scientia Horticulturae	2.769	3.463	4.342	4.342	61	1850	316
Crop Protection	2.381	2.571	2.8	3.036	57	2629	430
International Journal of Food Microbiology	4.187	5.277	5.4	5.4	40	2172	382

IF, Impact factor.

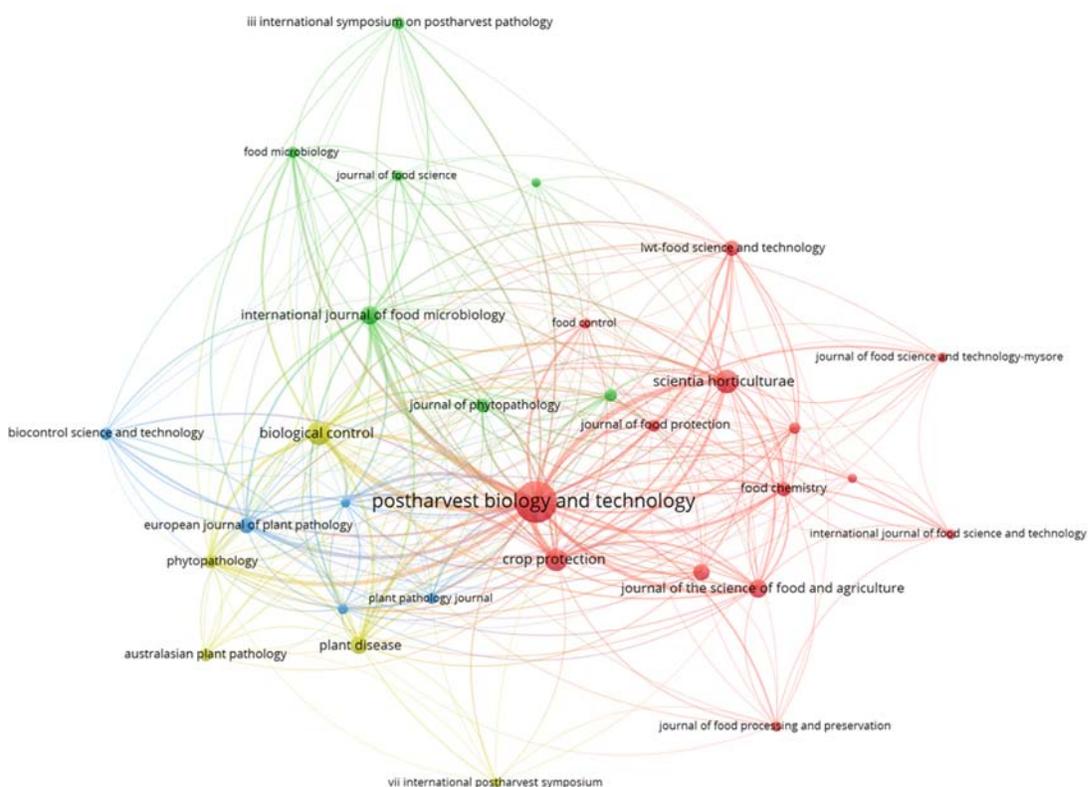


Figure 9: Visualization map of the top ranked journals that published fruit and vegetables postharvest loss reduction-related articles between 1990-2020. * The circle size corresponds to the number of articles published by the respective journal.

4. Discussion

The current study gives an overview of the fruit and vegetable PHLR-related research, and the findings indicated a tremendous exponential growth in their PHLR research in the last

three decades. Approximately 65 % of this growth was observed in the last decade. This growth can be attributed to the recognition of fresh produce particularly fruits and vegetables as a major player in global agricultural production, trade, and food security (Schreinemachers et al., 2018). Statistics show that the global annual income generated from fruits and vegetables exceeds USD 1 trillion (Schreinemachers et al., 2018) highlighting the economic importance of fresh produce. Similarly, the high fresh produce postharvest losses which are approximated to between 30-55 % of the total annual production globally is notable, hence attracting a lot of postharvest research attention with the focus on developing more effective control measures to mitigate the losses (Sugri et al., 2021).

The increased interest in postharvest research in the last decade as confirmed in this study could also have been driven by the worldwide efforts towards the reduction of food loss and waste (FLW) to address food insecurity (Porat et al., 2018). The need to reduce FLW has also been emphasized in the United Nations sustainable development goals (SDGs) number 12.3, which is targeted at halving FLW by the year 2030 thus forcing the member states to undertake postharvest research geared towards meeting the SDG target of ensuring food security for all (Kumar & Choubey, 2021). The urgent need to reduce postharvest losses and increase the food supply to feed the projected global population of over nine billion people by 2050, can be considered another major contributing factor to the increased PHLR research in the last 10 years. Stathers et al. (2020), indicated that reducing postharvest losses is a practical way of sustainably increasing agricultural productivity and stabilising the food supply.

In the current study, apples, citrus, tomato, mango, peach, grapes, strawberry, banana, sweet cherries, and lettuce were identified as the most researched fresh produce products. This can be attributed to the fact that these products are amongst the most produced, locally consumed, and exported hence, their significance in postharvest research to reduce losses

(FAO, 2021). World statistics (Table1) shows that most of these crops are the most traded globally and all reported an increase in production from 2017-2021 due to their economic contribution (Agriculture and Agri-Food Canada, 2023). The apple industry, for instance, is regarded as the global economic powerhouse with a record increase of approximately three million tonnes in production per year between the years 2017 and 2021 (Agriculture and Agri-Food Canada, 2023). This highlights the need for research to improve its shelf-life and retain the postharvest quality of the fruit (O'Rourke, 2021). The tomato industry is another important economic pillar globally with its current fresh tomato production standing above 200 million tonnes per annum (Campos et al., 2020). Despite their economic importance, these fruits and vegetables are also categorised as highly perishable and record high postharvest losses between harvesting and consumption. For instance, the apple industry in the USA recently reported an annual loss of 8.6 % at the retail and 20 % loss at the consumer level due to microbial decay (Argenta et al., 2021). These trends reflect industry-specific prioritisation of research areas and funding. In our study, it was shown that most of the fresh produce postharvest research were targeting innovation technologies to mitigate postharvest losses linked to postharvest rots and quality deterioration.

Botrytis, *Penicillium*, *Colletotrichum*, *Alternaria*, *Rhizopus*, and *Aspergillus* species were identified as the most researched pathogens that affect the postharvest quality of fresh produce. This corroborates with the findings by Udoh et al. (2015) which showed that fungal pathogens are increasingly becoming quality deterioration agents of economically important fruit and vegetables hence, they are becoming a priority with regards to postharvest research.

Botrytis cinerea, a common cause of gray mould disease in many fruits and vegetables (Kahramanoğlu et al., 2022), was shown as the most researched pathogen. This could be associated with its economic importance in the fresh produce sector. For instance, *B. cinerea*

has previously been reported to cause significant economic losses in the horticultural industry accounting for annual losses of up to USD 100 million globally (Brito et al., 2021). The pathogen's high postharvest research interest can also be attributed to the fact that it continues to cause significant postharvest rots reported on most horticultural crops of global economic importance such as tomato, citrus, strawberries, raspberries, grapes, and apples (Agriculture and Agri-Food Canada, 2023). The study findings also showed *Penicillium* and *Alternaria* species as the other most researched postharvest pathogens. This could also be attributed to the global economic importance of the crops they affect and the resultant economic losses hence, their significance in terms of research. *Alternaria alternata* and *P. expansum* in particular are major postharvest pathogens of apples and have been reported to cause approximately 30-40 % of the total production globally (Patriarca, 2019). Other pathogens that have been associated with high losses in the apple industry include, *Colletotrichum*, *Fusarium*, *Monilinia*, and *Rhizopus* species (Patriarca, 2019). Apart from the deterioration of apples, most of these pathogens affect other fruits and vegetables causing significant economic losses. For instance, *Botrytis*, *Alternaria*, *Penicillium*, *Fusarium*, and *Rhizopus* have also been reported to cause postharvest losses in the citrus, grapes, and berry families (Tournas & Katsoudas, 2005). *Alternaria alternata* and *A. soliani* are also closely linked with major losses in the tomato industry at both preharvest and postharvest stages (Adhikari et al., 2017).

Alongside the pathogens of interest was the research dynamics on postharvest disease control strategies. A logical trend in the control of postharvest fungal pathogens was observed with research in the 1990s primarily focusing on chemical control methods and introduction of biological control. However, the research interest has since shifted towards chemical-free alternatives. For instance, during the last decade (2010-2020), postharvest research has been mainly focused on the use of plant extracts and more recently, physical technologies such as ozone-based treatments, ultrasound treatments, and ultraviolet (UV) irradiation amongst many

others. The surge in interest in most of these alternative treatments could be due to their ability to extend the shelf-life of fresh produce (Sipho & Tilahun, 2020). This could also be attributed to the banning of some fungicides and global campaigns calling for reduction of overreliance on chemical fungicides for fresh produce postharvest disease control (Damos et al., 2015). Other issues associated with the slow phasing out of some of the chemical fungicides include the development of fungicide resistance by some pathogenic strains rendering them less effective (Schneider et al., 2003). Researchers, funders, and regulation bodies are also shifting their focus from the use of synthetic chemicals to search for alternative protectants with less negative effects on human health and the environment hence the seen increase of research on alternative control strategies (Singh et al., 2022).

Despite the increased research interests and efforts towards the development of various health-safe and eco-friendly postharvest innovations, it is interesting to observe that postharvest losses of fresh produce are still high. This could be attributed to the lack of simple, cost-effective, and well-defined practical postharvest management technologies hence their low adoption (Danbaba et al., 2019). The application of some of the new innovations are also limited to the laboratory level mainly due to the gap between the idea or proof of concept to a product as well as their high scale-up costs rendering them unfeasible for commercial application (Sugri et al., 2021). Moreover, some of these technologies, for instance, essential oils are regarded to be effective only for a short duration (Yin et al., 2019) and their practicability in commercial setup is yet to be explored.

Collective responsibility to reduce postharvest losses and to ensure sustainable food production and supply chains globally has resulted in the growth of inter and intra-continental postharvest research collaborations among researchers. China, USA, Italy, Brazil, and Spain emerged as the leading collaborator countries in PHLR-related research in the world as

indicated by the collaboration links related to postharvest research based on the documents retrieved from the Web of Science Collection. Meanwhile, South Africa was observed as the main player in PHLR collaboration research in Africa followed by Egypt. China and USA emerging as the top countries involved in postharvest research is linked to high government investment in agricultural research and food security. China for instance, is regarded as the largest funder of agricultural research in the world with an investment of about USD 10 billion in agricultural research annually (Nelson & Fuglie, 2022a). The US federal government also heavily invest in agricultural research and development with approximately USD 5.2 billion being directed towards agricultural research annually (Nelson & Fuglie, 2022b). The two countries have also had long-term collaborations with other organizations e.g., Food and Agriculture Organization (FAO) to ensure food security and global trade stability (FAO, 2022).

The high postharvest research collaboration for countries like USA and China could also be associated with the benefits accrued when they invest in other countries more so in the LMICs. According to Kraybill and Mercier (2019), the USA's commitment to offering agricultural financial aid to foreign countries is rooted in the dual benefits accrued both to LMICs and to American farmers, companies, workers, and consumers. The benefits come in that through USA-funded collaborative research, agricultural production, and postharvest loss reduction in LMICs, raise household incomes, thereby boosting their purchasing power for USA agricultural, manufactured and technology exports (Kraybill & Mercier, 2019). The high USA collaboration on postharvest research especially with LMICs e.g., South Africa and Egypt is also to ensure the safety and steady supply of off-season high-quality fresh produce to the United States (Lynam et al., 2016).

The nature of the fresh produce industry in these two countries (China and USA) is much developed and vibrant hence, the need to invest in PHLR-related research as this sector

holds the country's economy. China is a world leader in fruit and vegetable production. In 2020 China's fruit and vegetable production was around 711 million tonnes accounting for 38 % of the total world fresh produce that year (Fepex, 2022). Likewise, the United States of America (USA) is not only a producer of fresh produce but also a major importer and exporter of fruits and vegetables in the world. According to USDA Agricultural Census report, the annual fruit and vegetable production for the USA was valued at USD 48.2 billion in 2017, accounting for 12.4 % of total agricultural output (Huang et al., 2022). The vibrant fresh produce industry in these countries also translates to more postharvest losses hence the investment in PHLR research to resolve the problem experienced (Negri et al., 2020).

South Africa is one of the countries in Africa that has invested significantly in postharvest research as indicated by the data of the study. This can be attributed to the growth in the South African fresh produce industry and its role in the country's economy as fresh fruits alone account for approximately 35 % of the total exports translating to over USD 3.3 billion annually (Fpef, 2022). Currently, South Africa is one of the major exporters of apples, citrus, litchis, pears, avocados, grapes, mangoes, pomes, blueberries, onions, and tomatoes (Fpef, 2022). Hence, postharvest research for the country is a huge priority to ensure extended shelf-life and the retention of fruit quality at both the local and export markets. This has resulted in a significant investment in postharvest research through public and private entities with the aim of boosting postharvest quality retention and shelf-life extension, especially for the export market. South Africa's government through the Department of Science and Innovations (DSI) is funding the Post-Harvest Innovation (PHI) programme which is at the forefront of driving technological innovation in the postharvest fresh fruit value chain and uplifting the global competitiveness of the South African fresh fruit industry (PHI, 2018). Other departments such as the National Research Fund and the Department of Agriculture, Land Reforms and Rural Development are also playing a major role in funding research related to pre-and postharvest

management of fresh produce in South Africa. Fresh produce grower associations such as Citrus Research International (CRI), South African Table Grape Industry, Subtrop and Hortgro among others have also extensively funded fresh produce postharvest research in South Africa.

On the other hand, the majority of the LMICs lag in postharvest research, and this can be associated with the undeveloped fresh produce industry and the lack of commitment to invest in PHLR research (Sibomana et al., 2016). Apart from funding from international bodies such as the FAO, low funding towards PHLR-related research in most LMICs is also a contributing factor to low postharvest research as the little available funds are channelled towards other basic needs such as healthcare (Fuglie & Rada, 2013). In addition, the inadequate information on the exact magnitude of postharvest losses experienced per produce in most LMICs also contribute to the lack of commitment and emphasis on postharvest loss research (Affognon et al., 2015).

To further elaborate on the PHLR and platforms used by researchers to disseminate their research work, an analysis of journals was undertaken. Several factors have been listed as criteria for selecting a journal to publish one's research work and this includes the high impact factor (IF), wide journal scope, strong journal scientific rigour, high editorial quality and peer-review process, good journal reputation amongst others (Suiter & Sarli, 2019). The IF gives the frequency with which the "average article" in a journal has been cited in a specified time and it is also used to measure the relative importance of a journal about its field (Sharma et al., 2014). According to Malathi and Thappa (2012), a journal with a comparatively high IF is rated as a good quality journal with the ability to attract more publications a criterion met by all the top five listed journals having an impact factor above 2.5.

The journal of Postharvest Biology and Technology was ranked top as it met the listed criteria ranging from a high impact factor of 6.751, a citation score of 9.8, a quick peer-review

process, and a shorter publishing time, which is approximately two months from submission of a paper to publication (Postharvest Biology and Technology, 2022). The journal also has a rigorous review process and is under Elsevier publishing house which is a well-known and trusted publisher. The journal also has been in existence for 18 years having a wide scope that is directly or indirectly linked to PHLR. The journal's wide scope covers several fields of research which makes it possible to publish many articles per year as compared to other journals in postharvest research with a narrow scope. For instance, the International Journal of Food Microbiology (IF:5.4) was ranked fifth below the Journal of Crop Protection (IF: 2.8). This could be directly associated with the journal's scope which is more inclined towards food safety while most of the documents used for the current study were more related to postharvest diseases of fresh produce and handling strategies to reduce the losses.

5. Conclusion

The last three decades have seen a drastic growth in PHLR-related research on fresh produce with much of it being reported in the last 10 years. The focus of research has since shifted from chemical disease control to alternatives such as plant extracts, edible coatings, ozone-based treatments, ultrasound treatments, ultraviolet (UV) irradiation, and more recently active packaging which have the added benefit of extending shelf-life of the fresh produce. Increased collaborations between different countries (continental and intercontinental) as well as between different researchers in a country have resulted in increased growth of postharvest research globally. Low-and middle-income countries (LMICs) mainly in Africa and other regions of the world are still lagging in postharvest research possibly due to the lack of adequate funding support and global connectedness with leading research teams. The study, therefore, recommends the need to strengthen PHLR-related research collaborations between researchers and industries, especially in LMICs to alleviate the huge burden of postharvest losses. There is

also a growing need, to fund projects that reflect strategically important focus areas, well-planned programmes with a proper upscaling matrix to ensure the adoption of these innovations and technologies at operational and commercial level. Finally, there is also a need to undertake a follow-up study to assess the specific research innovations and their impact on reducing postharvest losses for informed policy making regarding specific innovations and adoption. Future research investment should also emphasize on finding lasting solutions to postharvest loss of fresh produce caused by *Botrytis cinerea*, *Penicillium* species, and *Colletotrichum* species for they were shown to be the most persistent postharvest pathogens of fruits and vegetables.

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