The World Trends and Patterns of Grain Loss and Waste Research and Their Implications

ACS Agricultural Science and Technology

Zhao, Yilin; Zhang, Di; Guo, Songhao; Wang, Yaxuan; Wei, Xun

https://doi.org/10.1021/acsagscitech.3c00421

ACS AGRICULTURAL SCIENCE & TECHNOLOGY

pubs.acs.org/acsagscitech

Article

The World Trends and Patterns of Grain Loss and Waste Research and Their Implications

Published as part of ACS Agricultural Science & Technology virtual special issue "Plant Biotechnology, Molecular Breeding, and Food Security".

Yilin Zhao,† Di Zhang,† Songhao Guo, Yaxuan Wang, and Xun Wei*

Cite This: *ACS Agric. Sci. Technol.* 2024, 4, 82−91

Read Online

ACCESS | Metrics & More | Article Recommendations | Supporting Information

ABSTRACT: Grain loss and waste (GLW) presents formidable challenges to global food security, sustainability, and efforts to combat climate change. This study delves into the evolution of GLW research themes spanning from 1996 to 2022, employing bibliographic couplings, keyword co-occurrence, and keyphrase analysis to examine 1,570 articles sourced from the Web of Science (WOS) database. Our investigation encompasses bibliometric indicators, the temporal progression of publications and citations, the impact of international collaborations among countries and institutions, influential publications, and the leading contributors on the global stage. By harnessing data from scholarly publications, this study offers a comprehensive exploration of GLW's multifaceted dimensions, scrutinizing thematic shifts, regional variations, and the key stages of GLW from production to consumption within the food value chain. Our findings underscore the pivotal roles of technological innovations, dietary awareness, and the principles of a circular economy in curtailing GLW. As governments worldwide commit to sustainability objectives, addressing GLW emerges as a momentous opportunity for climate mitigation, enhanced food security, and the advancement of circular economy practices. This research contributes valuable insights for guiding future endeavors aimed at minimizing GLW within the food value chain.

KEYWORDS: *grain loss and waste, bibliometric analysis, food security*

1. INTRODUCTION

Food security stands as a fundamental issue at the heart of human survival, and mitigating food loss and waste emerges as a pivotal strategy in ensuring it. On one hand, it is imperative to guarantee ample agricultural production to satiate the ever-increasing demand. On the other hand, concerted efforts must be directed toward curbing losses and waste along the entire value chain.[1] Recent years have witnessed food loss and waste gaining global attention, recognized as a formidable impediment to global sustainability.[2] According to the Food and Agriculture Organization (FAO), approximately one-third of the world's yearly food production, amounting to a staggering 1.3 billion tons, is lost or squandered.[3] In China alone, the food wasted by the catering industry in a single year could nourish 200 million people.[4] Numerous other assessments echo the magnitude of this issue.[5,6] Addressing the challenge of grain loss and waste (GLW) offers a triple-win opportunity, benefiting climate, food security, and the sustainability of agricultural food systems.[7] Reducing grain loss and food waste holds the potential to increase the consumption of agricultural products for food, feed, or valuable byproducts, all while providing opportunities to mitigate various environmental impacts. However, harnessing these opportunities and enabling policymakers to develop relevant regulatory frameworks require a comprehensive understanding of the nuances, scope, and cutting-edge research surrounding GLW across the entire supply chain.[8]

Food loss and waste permeate the entirety of the journey from farm to table. Figure 1 illustrates the occurrence of food losses and food waste at various stages of the food value chain. The quantification and characterization of these losses can vary significantly. The definitions and measurements of food loss and food waste exhibit substantial variability based on geographical location and research perspective, lacking a universal consensus on their precise delineations.[1] In line with the FAO report (2019), we designate losses occurring before the consumer stage as "grain loss" The substitution of "food" with "grain" underscores our emphasis on food security within the context of food crops. Meanwhile, losses at the consumer stage are referred to as "food waste." It differentiates three main life cycle stages: the agricultural production stage (on-farm loss before harvesting begins), the postharvest stage (between harvesting and human consumption, including harvesting, storage, processing, and distribution), and the consumer stage (at the household and out-of-home).

In recent years, grain-saving impairment has been a widespread concern by many countries and international institutions around the world. In 2019, the Food and

Received: September 29, 2023
Revised: November 16, 2023
Accepted: December 8, 2023
Published: January 3, 2024

https://doi.org/10.1021/acsagscitech.3c00421
ACS Agric. Sci. Technol. 2024, 4, 82−91

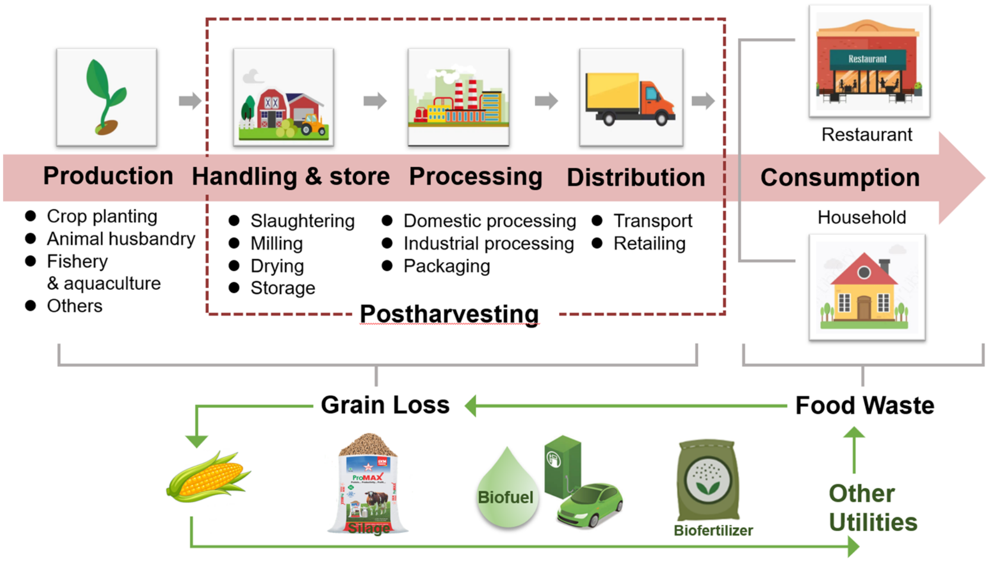

Figure 1. Concept model of grain loss and waste along the food value chain and its utilities.

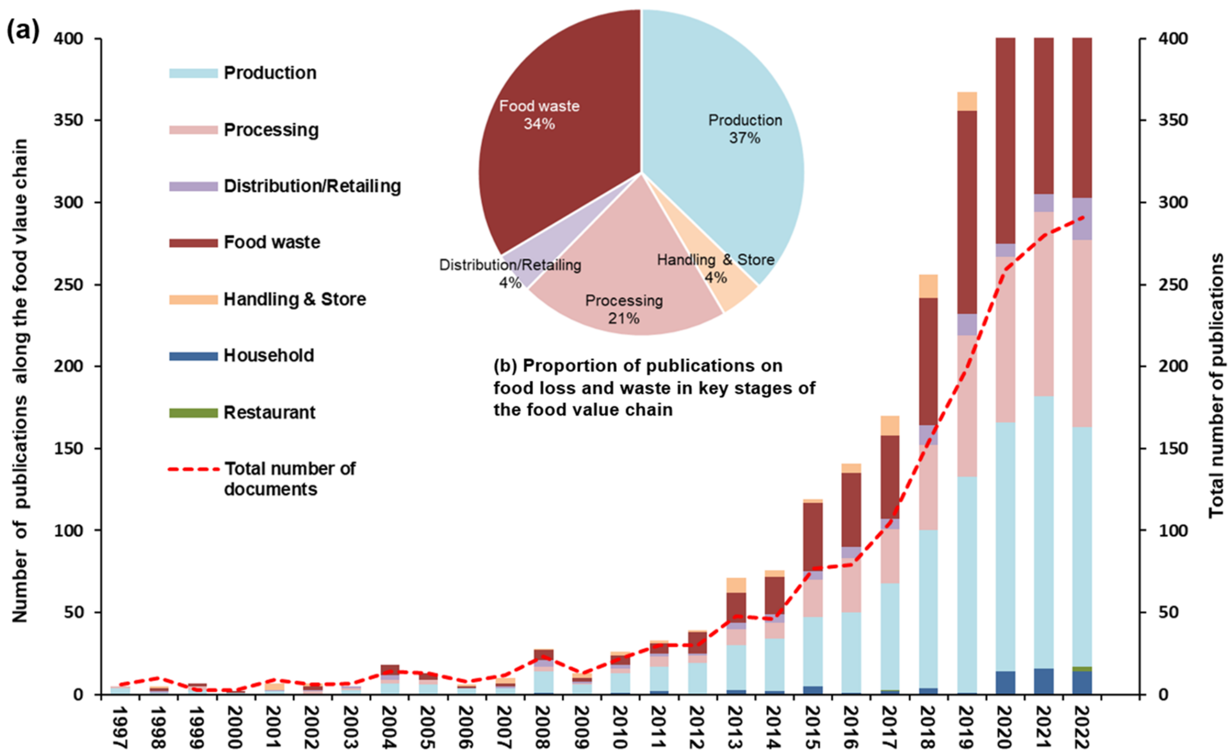

Figure 2. Number of publications related to grain loss and waste and in the subsubjects along the food value chain. (a) Annual specific publication variations; (b) Proportion of publications on food loss and waste in key stages of the food value chain.

Agriculture Organization of the United Nations (FAO) released "The State Of Food and Agriculture: Moving Forward On Food Loss And Waste Reduction".[9] In 2021, the United Nations Environment Programme[10] published the "Food Waste Index Report", which studied food loss and waste in major countries and explored measures to reduce food consumption. As we strive to make progress in reducing food loss and waste, our efforts can only be truly effective if we have a deep understanding of the problem. Here, we adopt a bibliometric method to comprehensively analyze the evolving landscape of research on GLW and its profound relationship with food security.

The significance of this research lies in its potential to inform policy, drive innovation, and guide future research endeavors based on the analysis of the laws and conclusions of existing research. By shedding light on the evolving priorities within the realm of GLW, we provide valuable insights for policymakers, agricultural experts, and stakeholders aiming to enhance food security. Understanding the key areas of research focus, international collaboration patterns, and historical development can help in the formulation of targeted strategies to reduce GLW, ultimately contributing to a more resilient and sustainable global food value chain.

https://doi.org/10.1021/acsagscitech.3c00421
ACS Agric. Sci. Technol. 2024, 4, 82−91

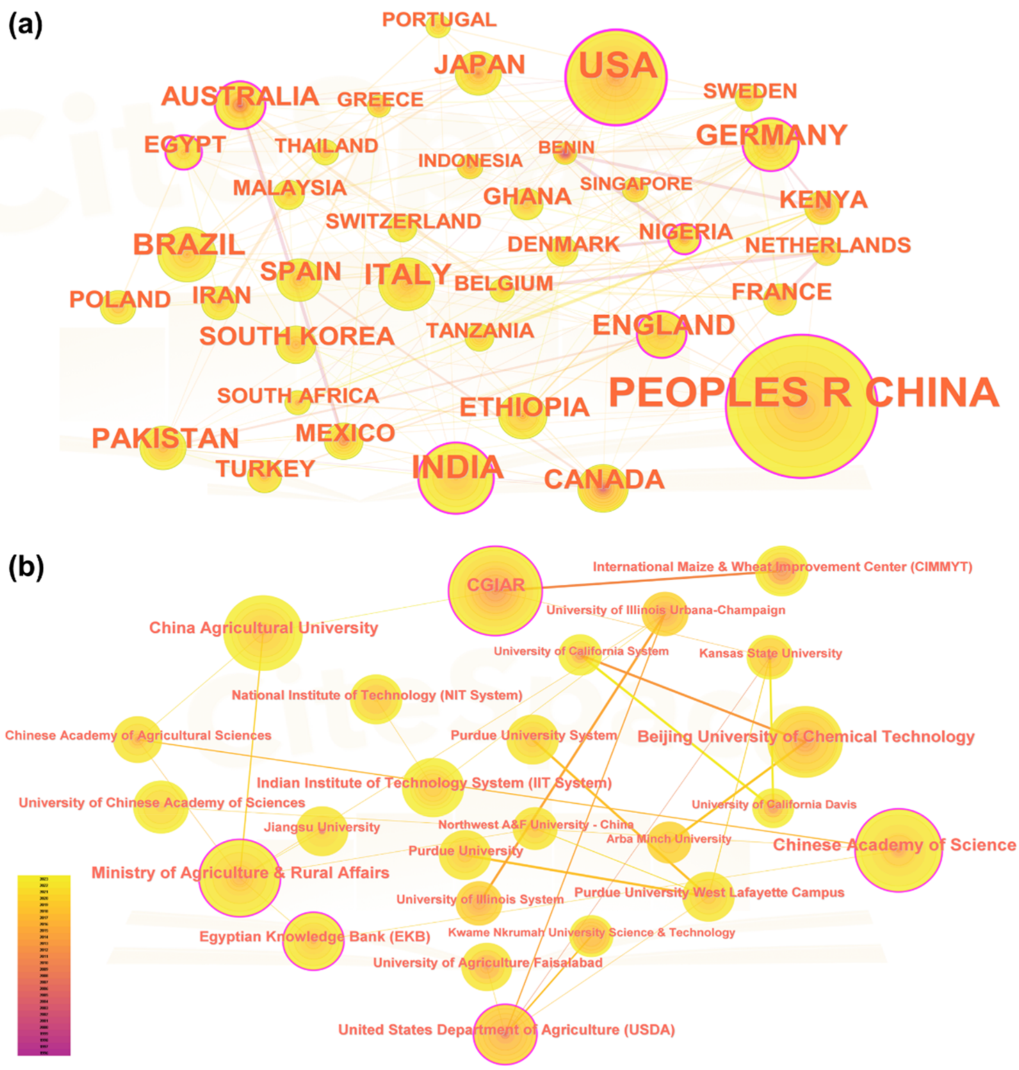

Figure 3. Academic performance across the world (a) national cooperation network. (b) The cooperative network between the top 20 productive institutes. The annual ring-shaped country node represents the year of publication with a gradient color, and the annual number of documents is expressed in different widths. Therefore, countries with larger nodes have more total publications. The colors of the links between countries, from purple to yellow, indicate the evolution of cooperation time, and the width represents the closeness of the relationship.

2. METHODS

Bibliometrics, an interdisciplinary approach that utilizes mathematical and statistical methods for the quantitative analysis of knowledge dissemination within various domains, can capture the development of research fields.[11] This methodology has been increasingly embraced across a wide range of professional fields. This paper leverages bibliometric techniques to scrutinize GLW along the food value chain.

2.1. Data Sources. To compile the data set for this bibliometric analysis, we retrieved articles from the Web of Science (WoS) database. The WOS Core Collection - Citation Database provides a unique feature of citation counting, allowing the determination of the relative importance of a large number of articles through the use of objective impact measurement methods,[12] and is renowned for encompassing a significant array of top-tier journals and high-quality peer-reviewed articles.[13−15] This methodological approach aligns with the practices employed in prior studies.[16]

Our data source is the Core Collection of WoS (https://webofknowledge.com), including SCI-EXPANDED (1985-present), SSCI (1970-present), A & HCI (1975-present), CPCI-S (1990-present), CPCI-SSH (1990-present), ESCI (2018-present), CCR-EXPANDED (1993-present), and IC (1993-present) provided by the University of Science and Technology Beijing.

2.2. Data Collection Process. Focusing on research related to GLW (as detailed in Table S1), we examined scholarly publications from 1996 to 2022. This analysis exclusively considers English-language literature and includes reviews and articles. A total of 1570 publications were yielded for content analysis on January 23rd, 2021 (the data up to September 12nd, 2023). The database was created including all bibliographic information (author, titles, abstract, source, volume, page, publication year, and cited reference) of all publications. All important bibliographic data are downloaded in plain text format as it is a common format that VOSViewer and Citespace can handle.

2.3. Analytical Tools. In this study, we use two essential analytical tools—Citespace and VOSViewer—due to their reliability in handling large data sets. Furthermore, these tools provide a diverse array of creative visualization analysis options and investigative possibilities, leveraging existing network and visualization analytics software.[17] We conducted keyword co-occurrence analysis by VOSViewer, generating keyword clustering maps to identify established and emerging research topics.[18] Citespace, a Java-based application, facilitates visualization of international and institutional competition and collaboration. We us it to analyze the evolution of keyword trends over time to track research patterns.[11]

Table 1. Top 10 Most Cited Articles in the GLW Research

	Title	Journal	Issue	Citations	Year
1	Recovery of high added-value components from food wastes: Conventional, emerging technologies and commercialized applications Galanakis	*Trends in Food Science & Technology*	Recovery of valuable components from food waste using both conventional and emerging technologies.	761	2012
2	Solid-state anaerobic digestion for methane production from organic waste	*Renewable & Sustainable Energy Reviews*	Research on treatment options for food waste: solid state anaerobic digestion (SS-AD)	638	2011
3	Corn growth and nitrogen nutrition after additions of biochars with varying properties to a temperate soil	*Biology and Fertility of Soils*	This study examines the effects of using food waste (biochars) as a fertilizer on corn growth and nitrogen nutrition.	526	2012
4	Anaerobic codigestion process for biogas production: Progress, challenges and perspectives	*Renewable & Sustainable Energy Reviews*	This article discusses the conversion of complex organic matter from food residues into renewable energy through anaerobic codigestion.	431	2017
5	Biorational Approaches to Managing Stored-Product Insects	*Annual Review of Entomology*	This research explores methods to reduce postharvest losses caused by stored-product insects.	402	2010
6	Reducing Postharvest Losses during Storage of Grain Crops to Strengthen Food Security in Developing Countries	*Foods*	A comprehensive literature review of the grain postharvest losses in developing countries, the status and causes of storage losses and discusses the technological interventions to reduce these losses.	345	2017
7	Exploitation of Food Industry Waste for High-Value Products	*Trends in Biotechnology*	Strategies and measures for managing food industry waste and transforming it into high-value products.	283	2016
8	Unpacking Postharvest Losses in Sub-Saharan Africa: A Meta-Analysis	*World Development*	A meta-analysis to expose nature and magnitude of reducing postharvest losses, and the kinds of interventions that have been attempted to mitigate the losses.	250	2015
9	Acidophilic biohydrogen production from rice slurry	*International Journal of Hydrogen Energy*	Hydrogen production from food waste (rice slurry).	237	2006
10	Characterizing distributions of surface ozone and its impact on grain production in China, Japan and South Korea: 1990 and 2020	*Atmospheric Environment*	Evaluate the impact that surface O-3 in East Asia had on agricultural yield losses in 1990.	218	2004

https://doi.org/10.1021/acsagscitech.3c00421
ACS Agric. Sci. Technol. 2024, 4, 82−91

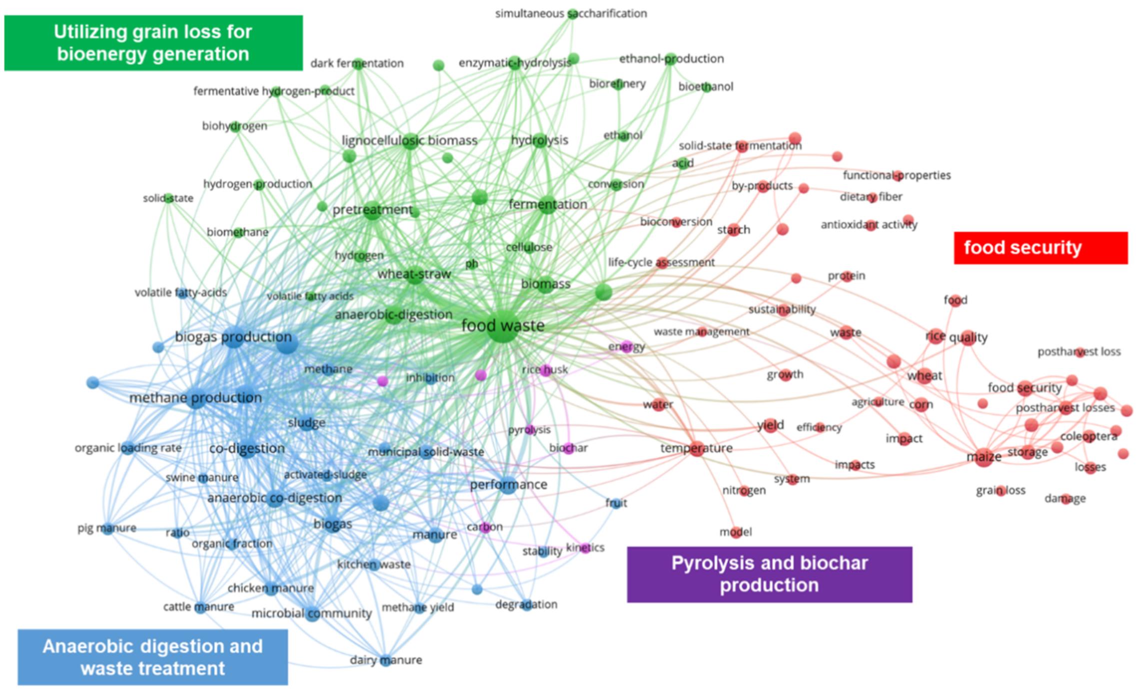

Figure 4. Keyword co-occurrence network. Each node corresponds to a keyword, with the node's size reflecting the keyword's frequency. Larger nodes signify more frequent keyword occurrences. The connections between nodes denote co-occurrences of keywords, and the thickness of these links indicates the frequency of such co-occurrences. Network density serves as a measure of network cohesion, with lower density values indicating poorer network integrity.

3. RESULTS

3.1. Evolution of Publications and Fields Distribution.

Regarding academic production, studies on GLW remained relatively low and stable from 1996 to 2007. However, a significant surge is evident in 2008, potentially influenced by the repercussions of the global economic recession on food supply chains. Following a minor dip in 2009, the field has experienced a notable upswing, underscoring the international focus on the food crisis (Figure 2a). Taking the entire period into account, publications on GLW grew at an annual rate of 17.2%.

We can see that food loss in the production stage has been a hot research issue in recent decades (related articles accounted for the largest proportion, reaching 37%). Researchers and policymakers have been increasingly concerned with reducing preharvest grain losses by implementing better agricultural techniques, such as improved crop management, pest control, and postharvest technologies. Innovations in processing methods and technologies can play a vital role in mitigating grain loss. Reducing loss during this stage not only saves resources but also ensures that more food reaches consumers. In contrast, the handling and storage and distribution/retailing stages, despite their importance, have not received consistent attention over the years (Figure 2b).

3.2. Collaboration and Competition in Research.

Figure 3 shows that at least 114 countries/regions and 230 institutions contributed to the GLW research. China and the United States have emerged as leaders in the field, with 499 and 219 publications, respectively (Figure 3, Supplementary Table S2). Countries with lower publication frequencies, notably, several African and Southeast Asian nations, may be in the nascent stages of developing expertise in this field. China, the United States, India, Australia, Germany, and Egypt, as indicated by the purple ring in the figure (Figure 3), display greater centrality and extensive collaborations with other countries. This highlights their pivotal role within the global collaboration network, serving as central nodes connecting researchers and institutions from various nations. Many countries with lower collaboration frequencies and degrees suggest untapped potential for enhanced global cooperation.

In terms of the absolute number of publications of institutions, Consortium of International Agricultural Research Centres (CGIAR) ranks first, followed by the Chinese Academy of Sciences, Ministry of Agriculture & Rural Affairs, China Agricultural University and Beijing University of Chemical Technology (Figure 3, Supplementary Table S3). Three of the institutions are from China. Notably, CGIAR, with a degree of 13 and a centrality of 0.15, emerges as a pivotal connector among institutions. Similarly, the Chinese Academy of Sciences and the Ministry of Agriculture & Rural Affairs demonstrate considerable centrality, reflecting their pivotal roles in fostering collaboration. The International Maize & Wheat Improvement Center (CIMMYT), with a higher Sigma value of 1.04, suggests its involvement in a more specialized collaboration network within the field. Furthermore, it is evident that certain institutions are experiencing substantial growth in recent years. The University of Chinese Academy of Sciences, for instance, embarked on a significant research expansion in 2021, signaling a growing interest and commitment to addressing GLW.

3.3. Distribution of Research Hotspots.

The examination of the top 10 most cited articles in the field of GLW research highlights a predominant focus on food waste and its resource recycling (Table 1). Six of the 10 articles specifically delve into the recovery of valuable components or energy from food waste. For example, the top-ranked article discusses the recovery of high-added-value components from food waste, showcasing a strong research focus on maximizing resource

https://doi.org/10.1021/acsagscitech.3c00421
ACS Agric. Sci. Technol. 2024, 4, 82−91

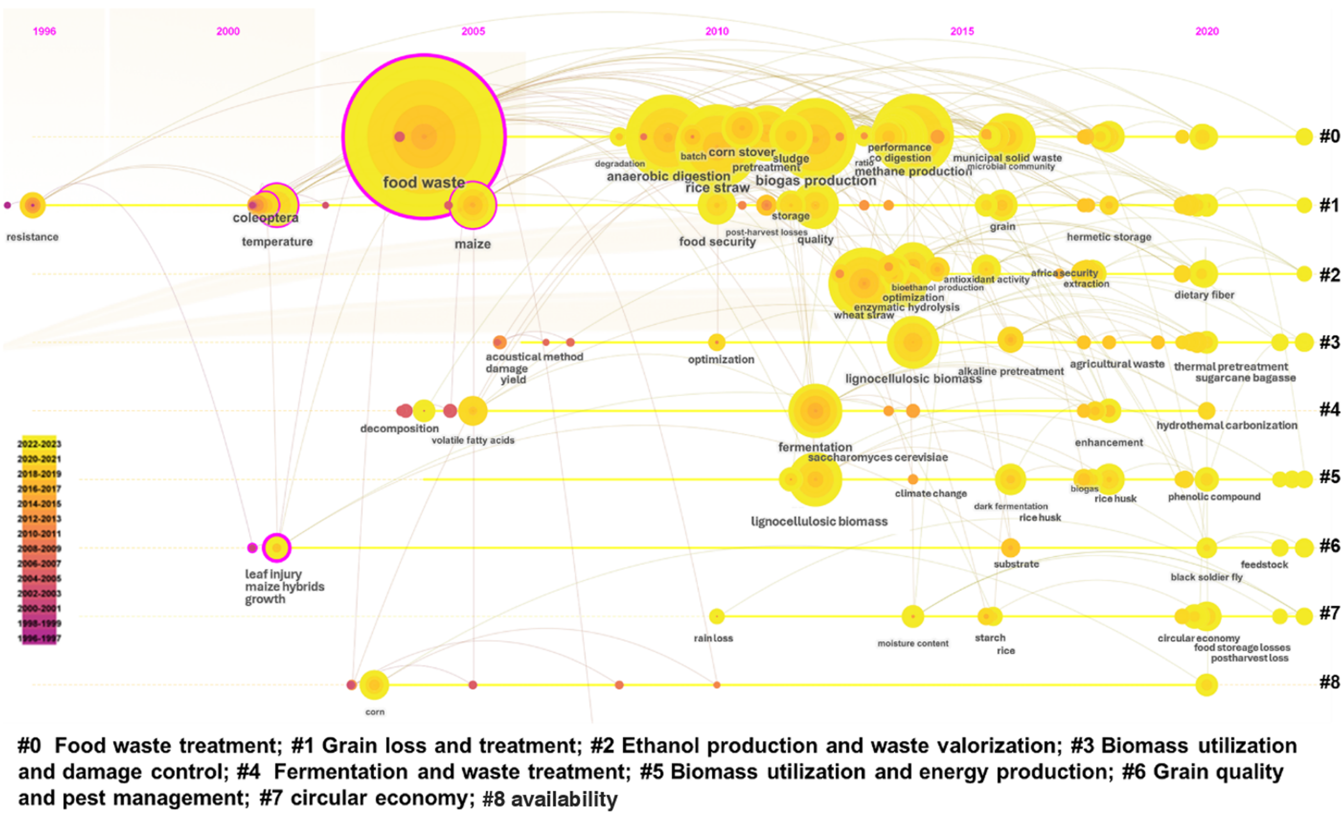

Figure 5. Sequence diagram of eight clusters of keywords, showing the emergence and alternation of research hotspots.

utilization and reducing waste. A significant portion of the articles explores waste management strategies, particularly through anaerobic digestion, to produce renewable energy such as methane (biogas), aligning with sustainability goals by addressing waste problems while generating clean energy. Furthermore, we found that the topic of food loss and waste appears to be highly interdisciplinary, involving fields such as food science, agriculture, environmental science, and energy production. This interdisciplinary approach is essential for addressing critical issues related to sustainability, food security, and environmental impact.

We further explored the main research branches of GLW through cluster analysis (Figure 4) and found that it is currently mainly concentrated in the following categories: **Cluster 1 (red)** focuses on the topic of food security. This cluster suggests a connection among efforts to reduce grain loss, improve food security, and enhance the nutritional quality of grains through dietary fiber. **Cluster 2 (green) and Cluster 3 (purple)** both focus on agricultural production waste treatment and energy production, but they have different core issues and areas of emphasis. **Cluster 2** includes terms like "ethanol production" and "sugar cane bagasse", indicating a cluster related to biofuel production from agricultural loss materials. This cluster highlights research into utilizing grain loss for bioenergy generation. **Cluster 3**, on the other hand, is centered on pyrolysis and biochar production. The core issue in this cluster is the conversion of biomass materials into biochar, a type of carbon-rich material. Researchers in this cluster are interested in pyrolysis, a thermal decomposition process, to produce biochar from materials, such as rice husk and wheat straw. The focus here is on energy-related aspects, including the energy potential of biochar and the kinetics of the pyrolysis process. **Cluster 4 (blue)** primarily revolves around anaerobic digestion and waste treatment. The core issue in this cluster is the treatment of organic waste materials, especially kitchen waste. Researchers in this cluster are interested in the processes of anaerobic digestion, biogas production, methane yield, and microbial communities involved in waste degradation. The primary goal here is to efficiently manage and convert organic waste into biogas while also studying factors such as inhibition, performance, and stability in the process.

3.4. Evolution of Research Trends. Figure 5 reveals a dynamic evolution of research trends over time, reflecting the changing priorities and concerns in the field, representing 2 stages in the development of research related to grain loss, waste reduction, and its impact on food security:

In the early 2000s, the focus was primarily on understanding the factors contributing to GLW reduction. Researchers emphasized postharvest loss, pest management, and waste reduction practices. This period was marked by keywords like "food waste", "rice straw", and "biogas production," reflecting efforts to address the significant loss occurring after the harvest. The aim was to minimize waste and improve the overall crop yield to enhance food security. A noticeable shift occurred **from 2011 to 2021** when research began to concentrate on sustainable biomass utilization. The focus moved toward converting agricultural waste, such as corn stover, into biofuels like biohydrogen, bioethanol, and biogas. This transition marked a pivotal moment in harnessing agricultural waste for energy production and sustainable agriculture. Keywords like "bioethanol production" and "hydrolysis" indicated this shift toward utilizing waste as a valuable resource. In parallel, there is a growing emphasis on fermentation processes and biogas production. Researchers delved into the possibilities of converting organic food waste

https://doi.org/10.1021/acsagscitech.3c00421
ACS Agric. Sci. Technol. 2024, 4, 82−91

materials into biogas, offering the dual benefit of waste reduction and energy generation. Fermentation-related keywords took center stage, illustrating a commitment to sustainable waste management practices.

In conclusion, the evolution of GLW research has seen a progressive shift from understanding the factors contributing to loss toward sustainable waste utilization and improving grain quality. These trends reflect a collective effort to address food security challenges while promoting environmentally friendly practices in agriculture. Future research should continue to prioritize sustainability and innovative approaches to ensure a more resilient and secure food value chain.

4. DISCUSSION

4.1. Reducing GLW Is Shifting from an Academic Hotspot to a Policy Emphasis. Based on the data from the WOS database, this study reveals a significant trend in the field of GLW research. Between 1996 and 2012, the volume of published papers in this area remained relatively stable. Starting from 2012 and continuing through 2022, there has been a remarkable and exponential increase in publications. This surge in research activity underscores the growing significance of food security in the academic community's agenda. Reflecting on the past, we observe a consistent rise in grain yields per hectare over recent decades, thanks to advancements in agricultural technologies.[19−21] Nevertheless, as the global population continues to expand, the pressure to sustain and further increase agricultural production intensifies. Consequently, while the agricultural sector focuses on "source development," it is equally vital to prioritize "resource conservation."[22,23] This entails minimizing GLW while making optimal use of the resources that underpin the food system. Embracing this approach has become an imperative choice for society as a whole. International attention on the issue of food loss and waste is firmly reflected in the 2030 Agenda for Sustainable Development. Specifically, Target 12.3 of the Sustainable Development Goals (SDGs), which embody this agenda, calls for the halving by 2030 of per capita global food waste at the consumption levels and the reduction of food losses. Many countries are already taking steps to reduce food loss and waste. Taking China as an example, in September 2021, China proposed hosting the first Global Food Loss and Waste Conference under the G20 framework. In October of the same year, the General Office of the Communist Party of China Central Committee and the General Office of the State Council issued the "Food Conservation Action Plan" (2021). The reduction of GLW has received significant attention from the Chinese government and various sectors of society.

4.2. The Problem of GLW in Production and Storage Phases Is More Serious in Economically Disadvantaged Regions. In general, throughout the entire food value chain, the global average food loss rate is alarmingly high, at 13.8%. Across different countries, this rate varies considerably, ranging from 5 to 6% in Australia and New Zealand to as high as 20−21% in Central and South Asia.[24] In economically disadvantaged regions, grain losses tend to be more severe throughout the entire process, from harvest to processing. In the context of developing countries, a substantial portion of these losses, up to 40%, unfolds during the production phase[25,26] such as wind-induced dispersion and backward mechanical level. In sub-Saharan Africa, the median level of grain losses is approximately 7%, with the maximum losses reaching up to 22.5%. The prevalence of technological and production constraints in these regions has led to the persistence of elevated rates of postharvest grain losses.[27] Our evolution analysis (Figure 5) underscores an escalating scholarly interest in related topics such as grain quality, pest management, and the integration of circular economy concepts into this field. Researchers have embarked on explorations of strategies aimed at curtailing postharvest losses, extending the storage life of grains, and infusing circular economy principles into agricultural practices. These advancements underscore the paramount significance of loss reduction while simultaneously enhancing the quality and accessibility of food resources.

Compared to the production stage, which has consistently been a focal point of research, issues related to handling and storage as well as distribution/retailing may not be as visibly apparent to researchers, decision-makers, or the general public. The processes involved in handling and storage as well as distribution/retailing are complex and diverse, influenced by various stakeholders, which can pose challenges for researchers in developing standardized methodologies or assessment metrics. However, food retailers tend to have a relatively large influence on GLW throughout the supply chain. Because of their dominant buying power, retailers can influence GLW further upstream.[28] Additionally, unsafe transportation and storage conditions lead to foodborne illnesses for 600 million people globally each year, resulting in 420,000 deaths.[29] Therefore, we advocate for further study of GLW in the handling and storage and distribution/retailing stages, which is crucial for gaining deeper insights into controlling grain losses and enhancing food safety and security.

4.3. Promoting Whole Grain Foods Can Largely Reduce the GLW during the Process. The food losses caused during processing are also quite alarming.[30] In the context of rice processing, approximately 31% of the raw material is discarded as waste, with a predominant share comprising 20% rice husks and 11% rice bran.[31] Subsequent polishing procedures further contributed to these losses. Therefore, addressing losses during the grain processing phase remains an urgent matter, often stemming from the pursuit of excessively refined grain products by consumers. The processing phase encompasses primary operations such as drying, dehusking, and deshelling, typically conducted at the farm level, as well as secondary processing involving product transformation.[32] For instance, in the case of rice, the process involves 16 distinct steps, including initial cleaning, vibrating sieving, gravity grain grading, white rice grading, and polishing, among others.[33] On average, with each additional polishing step, the milling yield decreases by approximately 1%. Presently, due to the excessive and rudimentary processing of rice, the annual grain losses exceed a staggering 13 billion pounds.[34] Thus, promoting the consumption of whole grains emerges as a pivotal measure for reducing grain processing losses.[35]

4.4. First-Hand Data on Food Waste at the Consumption Level Requires in-Depth Exploration and Research. Compared to upstream grain losses, food waste at the consumption level imposes a more significant environmental burden,[9] with a notable food waste rate reaching 17%, globally.[36] An estimated 8−10% of global greenhouse gas emissions are attributed to unconsumed food.[10] In the United States alone, retailers and consumers annually waste a staggering 133 billion pounds of food.[37] High-income countries have exhibited heightened concern regarding food waste issues and have conducted extensive research,

https://doi.org/10.1021/acsagscitech.3c00421
ACS Agric. Sci. Technol. 2024, 4, 82−91

particularly in North America and Europe. Notably, the United Kingdom has seen active engagement from nongovernmental organizations (NGOs) such as the Waste and Resources Action Programme (WRAP). Nonetheless, a comprehensive understanding of food waste remains notably lacking on a global scale.[1,38] At present, firsthand data on food waste beyond Europe and North America remains scarce.[39] Crucial questions persist, including the quantity of wasted or lost food, which sectors within the value chain contribute the most to waste, and which food categories are most affected. In the absence of such data, governments, businesses, and other organizations encounter challenges in justifying action and establishing priority areas for their efforts.

4.5. Reducing GLW within the Food Value Chain Is a Complex Interdisciplinary Challenge. Numerous investigations have explored GLW issue, predominantly adopting sociological or economic viewpoints, but potentially overlooking contributions from fields of chemical, energy-related studies etc., such as subjects of digestion composting, valorization, and anaerobic treatment.[40] However, these domains provide indispensable solutions for mitigating existing GLW, as is evident from our summarized evolution chart. It is crucial to recognize that GLW along the food chain is unlikely to be completely eradicated, despite efforts to minimize them through technological advancements and increased public awareness. Therefore, the question of how food that has already been lost or wasted can be transformed into resources with minimal energy loss becomes paramount. The principles of a circular economy offer a comprehensive framework for addressing food loss and waste. By minimizing inefficiencies, promoting resource efficiency, and encouraging responsible consumer behavior, a circular economy can significantly contribute to achieving global food security goals while reducing the environmental and economic impacts of food waste.[41] It requires collaboration among all stakeholders, spanning from producers to consumers, and from socio-economists to energy-environmental scientists, to transition toward a more sustainable and circular food system.

5. POLICY IMPLICATIONS

GLW results from a complex interplay of various factors. The upstream stages of the food value chain, encompassing production, harvesting, processing, and storage, are primarily influenced by technical proficiency and production management practices. Conversely, the downstream stage, which involves consumption, is predominantly shaped by human-related factors, such as awareness, institutional policies, consumer habits, and traditions.[42]

Therefore, government policies and initiatives can play a pivotal role in (i) promoting technological advancements in upstream processes, including breeding crop varieties with attributes like high yield, efficiency, resistance, and low-loss harvesting;[43] (ii) strengthening the integration of agricultural machinery, agronomy, and variety-specific practices. Equally important is the optimization of management paradigms, which entails formulating and refining technical guidelines for minimizing losses during grain crop harvesting. It also involves enhancing scientific grain storage training and services for farmers, as well as improving grain processing standards to enhance processing efficiency and reduce losses; (iii) fostering changes in consumption habits: Encouraging responsible consumption, promoting whole-grain foods, and educating the public about nutrition and dietary practices are key strategies. Collectively, these government-led actions may significantly reduce GLW over the entire food value chain.

Governments worldwide are currently taking both legislative and nonlegislative measures, coupled with consumer awareness campaigns, to facilitate the transition toward sustainable agri-food systems and value chains. This transition aligns with the goal of ensuring food security within the framework of green and circular economies.[44] For instance, European Union member states have pledged to halve per capita food waste at the retail and consumer levels by 2030 while also reducing grain losses in food production and value chains, in line with sustainable development objectives. To fulfill these objectives, since 2015, the European Commission has undertaken actions to prevent GLW based on the principles of reduction, reuse, and recycling within the Circular Economy Action Plan.[45] Meanwhile, in China, the Chinese Communist Party (CCP) has taken measures to combat official extravagance and curtail waste associated with government banquets. These initiatives, such as the "Eight-point Regulations", were first introduced in 2012. Additionally, the "Clean Plate Campaign," initiated in 2020, has demonstrated encouraging outcomes in the battle against food waste.[46] Furthermore, in April 2021, China officially implemented the "Anti-Food Waste Law", underscoring the importance of waste reduction. However, further intervention measures through regulations or policies are still urgently needed. For instance, it is crucial at the national level to establish specific targets and roadmaps for reducing GLW, aligning with the Sustainable Development Goal 12.3.

Moreover, the application of innovative technologies and big data monitoring platforms emerges as a key strategy for addressing food loss and waste, especially in economically backward areas. For example, Twiga Foods in Kenya links 3,000 food outlets daily with fresh produce from a network of 17,000 farmers and 8,000 vendors. The platform has reduced typical postharvest losses in Kenya from 30% to 4% for produce brought to markets.[47] Another example is Tata Consultancy Services (TCS), which developed a food freshness platform that monitors food quality throughout the supply chain. Connected sensors collect real-time data from farm to fork, assessing freshness. This information feeds into a digital twin, simulating environmental conditions affecting food lifespan (e.g., temperature, humidity, air quality).[48] By predicting the shelf life, this technology helps prevent premature spoilage and waste.

In summary, the establishment of comprehensive bioregional monitoring and assessment systems for the bioeconomy is essential for countries and regional actors to support sustainable and circular economies comprehensively.[41,49,50] Simultaneously, a comprehensive approach involving policy interventions, technological innovations, and global collaboration is essential to effectively combat GLW and contribute to sustainable and resilient food systems.

6. CONCLUSION AND LIMITATIONS

The primary objective of this study is to utilize a bibliometric approach to map the entire field of Grain Loss and Waste (GLW), examining and defining crucial literary works based on past, current, and future trends. The analysis is rooted in a visual overview of GLW growth patterns and subfields, highlighting core research institutions, key researchers, and key themes and focal points. More than 300 institutions in more than 200 countries around the world participate in research in this field, contributing an annual scientific research output rate of 15.2%, showing the broad prospects of this research topic. Moreover, metadata diagrams show the main research content and core themes of GLW, including 3 crucial topics: food security, agricultural production waste treatment and energy production, and anaerobic digestion and waste treatment. We conclude that the critical roles of technological innovations, dietary awareness, and the principles of a circular economy in mitigating GLW. As governments globally commit to sustainability objectives, addressing GLW emerges as a pivotal opportunity for climate mitigation, improved food security, and the promotion of circular economy practices. The research contributes valuable insights to guide future endeavors aimed at minimizing GLW throughout the food value chain. Overall, this study enhances our understanding of the complex challenges posed by GLW and provides a foundation for informed strategies and policies to create a more sustainable and resilient global food system.

However, there are limitations of the study, primarily stemming from the singular reliance on the Web of Science (WoS) database without encompassing other significant databases, such as Scopus. This choice may result in limitations in data comprehensiveness, as WoS cannot cover all relevant academic literature, potentially leading to an incomplete understanding of the field. Additionally, there may be biases in regional and disciplinary representation, since different databases have varying standards for the inclusion of literature from different geographic regions and academic disciplines. Potential limitations also include differences in the study's time frame and the assessment of impact factors and disparities in data quality and timeliness that could impact the study's comprehensiveness and accuracy.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsagscitech.3c00421.

(PDF)

■ AUTHOR INFORMATION

Corresponding Author

Xun Wei – *Research Institute of Biology and Agriculture, Zhongzhi International Institute of Agricultural Biosciences, Shunde Innovation School, University of Science and Technology Beijing, Beijing 100083, China; Environmental Economics and Natural Resources Group, Wageningen University & Research, Wageningen 6706KN, the Netherlands;* orcid.org/0000-0001-9828-6796; Email: weixun@ustb.edu.cn

Authors

Yilin Zhao – *Research Institute of Biology and Agriculture, Zhongzhi International Institute of Agricultural Biosciences, Shunde Innovation School, University of Science and Technology Beijing, Beijing 100083, China*

Di Zhang – *Research Institute of Biology and Agriculture, Zhongzhi International Institute of Agricultural Biosciences, Shunde Innovation School, University of Science and Technology Beijing, Beijing 100083, China*

Songhao Guo – *Research Institute of Biology and Agriculture, Zhongzhi International Institute of Agricultural Biosciences, Shunde Innovation School, University of Science and Technology Beijing, Beijing 100083, China*

Yaxuan Wang – *Research Institute of Biology and Agriculture, Zhongzhi International Institute of Agricultural Biosciences, Shunde Innovation School, University of Science and Technology Beijing, Beijing 100083, China*

Complete contact information is available at: https://pubs.acs.org/10.1021/acsagscitech.3c00421

Author Contributions

Y.Z.: Methodology, Writing–original draft. D.Z.: Data curation, Formal analysis, Writing–original draft. Y.W.: Data curation, Formal analysis. Z.J.: Investigation, Validation. W.Z.: Conceptualization, Investigation. X.W.: Conceptualization, Supervision, Funding acquisition, Project administration, Writing–review and editing.

Author Contributions

[†]Y.Z. and D.Z. contributed equally.

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This research was funded by the National Key Research and Development Program of China, grant number (2022YFF1100501; 2022YFF1003500), Beijing Nova Program (20220484114), and Foshan Municipal People's Government Special fund project for scientific and technological innovation (BK22BE013).

■ REFERENCES

(1) Liu, G. Food Losses and Food Waste in China: A First Estimate. *OECD Food, Agriculture and Fisheries Papers* **2014**. DOI: 10.1787/18156797.

(2) Searchinger, T.; Waite, R.; Hanson, C.; Ranganathan, J.; Dumas, P.; Matthews, E.; Klirs, C. *Creating a Sustainable Food Future: A Menu of Solutions to Feed Nearly 10 Billion People by 2050. Final Report*; World Resources Institute, 2019.

(3) Xue, L.; Liu, G. Introduction to Global Food Losses and Food Waste. *Saving Food*; Elsevier, 2019; pp 1–31.

(4) Wu, L. Grain Loss and Waste in China: Current Situation, Reduction Potential, and Counter-measures. *Journal of Agricultural Economics* **2022**, No. 11, 34–41.

(5) Dong, W.; Armstrong, K.; Jin, M.; Nimbalkar, S.; Guo, W.; Zhuang, J.; Cresko, J. A Framework to Quantify Mass Flow and Assess Food Loss and Waste in the US Food Supply Chain. *Commun. Earth Environ* **2022**, *3* (1), 1–11.

(6) Łaba, S.; Cacak-Pietrzak, G.; Łaba, R.; Sułek, A.; Szczepański, K. Food Losses in Consumer Cereal Production in Poland in the Context of Food Security and Environmental Impact. *Agriculture* **2022**, *12* (5), 665.

(7) Flanagan, K.; Robertson, K.; Hanson, C. *Reducing Food Loss and Waste: Setting a Global Action Agenda*. World Resources Institute, 2019. DOI: 10.46830/wrirpt.18.00130

(8) Allen, R. *Waste Not Want Not*; Routledge: London, 2013. DOI: 10.4324/9781315066721

(9) Bélanger, J.; Pilling, D. *The State of the World's Biodiversity for Food and Agriculture*; Food and Agriculture Organization of the United Nations (FAO), 2019.

(10) UNEP. *Food Waste Index Report 2021*; United Nations Environment Programme (UNEP): Nairobi, 2021.

(11) Basílio, M. P.; Pereira, V.; Costa, H. G.; Santos, M.; Ghosh, A. A Systematic Review of the Applications of Multi-Criteria Decision Aid Methods (1977–2022). *Electronics* **2022**, *11* (11), 1720.

(12) Dzikowski, P. A Bibliometric Analysis of Born Global Firms. *Journal of business research* **2018**, *85*, 281–294.

(13) Merigó, J. M.; Gil-Lafuente, A. M.; Yager, R. R. An Overview of Fuzzy Research with Bibliometric Indicators. *Applied Soft Computing* **2015**, *27*, 420−433.
(14) Gaviria-Marin, M.; Merigó, J. M.; Baier-Fuentes, H. Knowledge Management: A Global Examination Based on Bibliometric Analysis. *Technological Forecasting and Social Change* **2019**, *140*, 194−220.
(15) Basilio, M. P.; Pereira, V.; de Oliveira, M. W. C. M.; da Costa Neto, A. F.; Moraes, O. C. R. de; Siqueira, S. C. B. Knowledge Discovery in Research on Domestic Violence: An Overview of the Last Fifty Years. *Data Technologies and Applications* **2021**, *55* (4), 480−510.
(16) Xie, H.; Wen, Y.; Choi, Y.; Zhang, X. Global Trends on Food Security Research: A Bibliometric Analysis. *Land* **2021**, *10* (2), 119.
(17) Sarkar, A.; Wang, H.; Rahman, A.; Memon, W. H.; Qian, L. A Bibliometric Analysis of Sustainable Agriculture: Based on the Web of Science (WOS) Platform. *Environ. Sci. Pollut Res.* **2022**, *29* (26), 38928−38949.
(18) Basilio, M. P.; Pereira, V.; Oliveira, M. W. C. M. de. Knowledge Discovery in Research on Policing Strategies: An Overview of the Past Fifty Years. *Journal of Modelling in Management* **2022**, *17* (4), 1372−1409.
(19) An, X.; Ma, B.; Duan, M.; Dong, Z.; Liu, R.; Yuan, D.; Hou, Q.; Wu, S.; Zhang, D.; Liu, D.; et al. Molecular Regulation of ZmMs7 Required for Maize Male Fertility and Development of a Dominant Male-Sterility System in Multiple Species. *Proc. Natl. Acad. Sci. U. S. A.* **2020**, *117* (38), 23499−23509.
(20) Hou, Q.; An, X.; Ma, B.; Wu, S.; Wei, X.; Yan, T.; Zhou, Y.; Zhu, T.; Xie, K.; Zhang, D.; et al. ZmMS1/ZmLBD30-Orchestrated Transcriptional Regulatory Networks Precisely Control Pollen Exine Development. *Molecular Plant* **2023**, *16* (8), 1321−1338.
(21) Wan, X.; Wu, S.; Li, Z.; An, X.; Tian, Y. Lipid Metabolism: Critical Roles in Male Fertility and Other Aspects of Reproductive Development in Plants. *Molecular plant* **2020**, *13* (7), 955−983.
(22) Liu, X.; Jiang, Y.; Wu, S.; Wang, J.; Fang, C.; Zhang, S.; Xie, R.; Zhao, L.; An, X.; Wan, X. The ZmMYB84-ZmPKSB Regulatory Module Controls Male Fertility through Modulating Anther Cuticle—Pollen Exine Trade-off in Maize Anthers. *Plant Biotechnology Journal* **2022**, *20* (12), 2342−2356.
(23) Wan, X.; Wu, S.; Li, X. Breeding with Dominant Genic Male-Sterility Genes to Boost Crop Grain Yield in the Post-Heterosis Utilization Era. *Molecular Plant* **2021**, *14* (4), 531−534.
(24) Scott, P. *Global Panel on Agriculture and Food Systems for Nutrition: Food Systems and Diets: Facing the Challenges of the 21st Century: London, UK, 2016*; http://glopan.org/sites/default/files/ForesightReport.pdf; Springer, 2017.
(25) Gustavsson, J.; Cederberg, C.; Sonesson, U.; Van Otterdijk, R.; Meybeck, A. *Global Food Losses and Food Waste*; FAO Rome, 2011.
(26) Wunderlich, S. M.; Martinez, N. M. Conserving Natural Resources through Food Loss Reduction: Production and Consumption Stages of the Food Supply Chain. *International Soil and Water Conservation Research* **2018**, *6* (4), 331−339.
(27) Gustavsson, J.; Cederberg, C.; Sonesson, U.; van Otterdijk, R.; Meybeck, A. *Global Food Losses and Food Waste: Extent, Causes and Prevention*; Food and Agricultural Organization of the United Nations, 2011.
(28) *The "Why and How to Measure Food Loss and Waste" Practical Guide*. http://www.cec.org/flwm (accessed Nov. 12, 2023).
(29) Rudra, S. G.; Basu, S.; Chanda, A. Editorial: Food Storage, Spoilage and Shelf Life: Recent Developments and Insights. *Frontiers in Sustainable Food Systems* **2022**, *6*, 01−04.
(30) Szulecka, J.; Strøm-Andersen, N.; Scordato, L.; Skrivervik, E. Multi-Level Governance of Food Waste: Comparing Norway, Denmark and Sweden. *From Waste to Value*; Routledge, 2019.
(31) Bodie, A. R.; Micciche, A. C.; Atungulu, G. G.; Rothrock, M. J.; Ricke, S. C. Current Trends of Rice Milling Byproducts for Agricultural Applications and Alternative Food Production Systems. *Frontiers in Sustainable Food Systems* **2019**, *3*, 47.
(32) Food and Agriculture Organization of the United Nations (FAO). *State of Food and Agriculture 2019. Moving forward on food loss and waste reduction*; FAO: Rome, 2019.
(33) Liu, H. Grain processing results in significant food waste. *Wealth and Prosperity* **2014**, No. 7, 68.
(34) Fan, Q.; Liu, M.; Qi, H. Research on loss in rice processing and governance measures. *Science and Technology of Cereals, Oils and Foods* **2015**, *23* (5), 117−120.
(35) Wei, X.; Yang, W.; Wang, J.; Zhang, Y.; Wang, Y.; Long, Y.; Tan, B.; Wan, X. Health Effects of Whole Grains: A Bibliometric Analysis. *Foods* **2022**, *11* (24), 4094.
(36) Xue, L.; Liu, X.; Lu, S.; Cheng, G.; Hu, Y.; Liu, J.; Dou, Z.; Cheng, S.; Liu, G. China's Food Loss and Waste Embodies Increasing Environmental Impacts. *Nat. Food* **2021**, *2* (7), 519−528.
(37) Buzby, J. C.; Farah-Wells, H.; Hyman, J. The Estimated Amount, Value, and Calories of Postharvest Food Losses at the Retail and Consumer Levels in the United States. *USDA-ERS Economic Information Bulletin* **2014**, No. 121. DOI: 10.2139/ssrn.2501659
(38) Min, S.; Wang, X.; Yu, X. Does Dietary Knowledge Affect Household Food Waste in the Developing Economy of China? *Food Policy* **2021**, *98*, 101896.
(39) Gustafsson, J.; Cederberg, C.; Sonesson, U.; Emanuelsson, A. *The Methodology of the FAO Study: Global Food Losses and Food Waste-Extent, Causes and Prevention"-FAO, 2011*; SIK Institutet för livsmedel och bioteknik, 2013.
(40) Chauhan, C.; Dhir, A.; Akram, M. U.; Salo, J. Food Loss and Waste in Food Supply Chains. A Systematic Literature Review and Framework Development Approach. *Journal of Cleaner Production* **2021**, *295*, 126438.
(41) Wei, X.; Liu, Q.; Pu, A.; Wang, S.; Chen, F.; Zhang, L.; Zhang, Y.; Dong, Z.; Wan, X. Knowledge Mapping of Bioeconomy: A Bibliometric Analysis. *Journal of Cleaner Production* **2022**, *373*, 133824.
(42) Luo, Y.; Wu, L.; Huang, D.; Zhu, J. Household Food Waste in Rural China: A Noteworthy Reality and a Systematic Analysis. *Waste Management & Research* **2021**, *39* (11), 1389−1395.
(43) Wei, X.; Long, Y.; Yi, C.; Pu, A.; Hou, Q.; Liu, C.; Jiang, Y.; Wu, S.; Wan, X. Bibliometric Analysis of Functional Crops and Nutritional Quality: Identification of Gene Resources to Improve Crop Nutritional Quality through Gene Editing Technology. *Nutrients* **2023**, *15* (2), 373.
(44) Schuster, M.; Torero, M.Toward a sustainable food system: Reducing food loss and waste. *Global Food Policy Report*; International Food Policy Research Institute (IFPRI), 2016. DOI: 10.2499/9780896295827_03
(45) Santeramo, F. G. Exploring the Link among Food Loss, Waste and Food Security: What the Research Should Focus On? *Agriculture & Food Security* **2021**, *10* (1), 26.
(46) Feng, Y.; Marek, C.; Tosun, J. Fighting Food Waste by Law: Making Sense of the Chinese Approach. *J. Consum Policy* **2022**, *45* (3), 457−479.
(47) Kim, J.; Shah, P.; Gaskell, J. C.; Prasann, A. *Scaling up Disruptive Agricultural Technologies in Africa*; World Bank Publications, 2020.
(48) Saeidi, H.; Prasad, B. Impact of Accounting Information Systems (AIS) on Organizational Performance: A Case Study of TATA Consultancy Services (TCS)-India. *Journal of Management and Accounting Studies* **2014**, *2* (03), 54−60.
(49) Linser, S.; Lier, M. The Contribution of Sustainable Development Goals and Forest-Related Indicators to National Bioeconomy Progress Monitoring. *Sustainability* **2020**, *12* (7), 2898.
(50) Wei, X.; Luo, J.; Pu, A.; Liu, Q.; Zhang, L.; Wu, S.; Long, Y.; Leng, Y.; Dong, Z.; Wan, X. From Biotechnology to Bioeconomy: A Review of Development Dynamics and Pathways. *Sustainability* **2022**, *14* (16), 10413.