Environment and food safety: a novel integrative review

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Abstract
Environment protection and food safety are two critical issues in the world. In this review, a novel approach which integrates statistical study and subjective discussion was adopted to review recent advances on environment and food safety. Firstly, a scientometric-based statistical study was conducted based on 4904 publications collected from the Web of Science Core Collection database. It was found that the research on environment and food safety was growing steadily from 2001 to 2020. Interestingly, the statistical analysis of most-cited papers, titles, abstracts, keywords, and research areas revealed that the research on environment and food safety was diverse and multidisciplinary. In addition to the scientometric study, strategies to protect environment and ensure food safety were critically discussed, followed by a discussion on the emerging research topics, including emerging contaminants (e.g., microplastics), rapid detection of contaminants (e.g., biosensors), and environment friendly food packaging materials (e.g., biodegradable polymers). Finally, current challenges and future research directions were proposed.

Keywords Food safety · Environmental pollution · Food packaging · Biodegradable polymers · Biosensors · Microplastics · Soil pollution

Introduction
Environment and food safety have been two important topics in the world (Zhang et al. 2015; Bilal and Iqbal 2020; Liu et al. 2020b; Song et al. 2020; Ye et al. 2020; Qin et al. 2021). Human activities have posed great threats on environment and food safety. For example, due to the intensive use of disposable masks which are mainly made of non-biodegradable polymers, massive amount of waste is produced. In fact, environment and food safety are closely intercorrelated (He et al. 2016; Sagbara et al. 2020). As shown in Figure 1, on the one hand, food safety is strongly affected by environment (Lu et al. 2015). Contaminants from polluted soil, water, and air could migrate into crops, vegetables, fish, animals, and so on (Lu et al. 2015; Sun et al. 2017; Lie et al. 2020a). On the other hand, in order to ensure food safety and quality, various processing procedures are carried out, which increase the burden on the environment and even cause environmental pollution (Yao et al. 2020). For example, food processing industry produces a huge amount of wastewater (Li et al. 2019; Ahmad et al. 2020; Akansha et al. 2020; Boguniewicz-Zablocka et al. 2020). If the wastewater is discharged into rivers directly, the rivers will be polluted. As food industry wastewater typically contains high concentrations of organic matters, eutrophication can easily take place (Feng et al. 2021; Jiang et al. 2021). In addition, food packaging materials are widely used as food containers and to preserve food from decay (Vitale et al. 2018; Wohnre et al. 2020; Zeng et al. 2021). When the food is consumed, a mass of packaging waste is produced, which will cause environmental problems if not disposed properly (Poyatos-
Racionero et al. 2018; Bala et al. 2020; Brennan et al. 2020; Liu et al. 2020a). However, plastics, as one of the most commonly used packaging materials, cannot be disposed easily and can exist in the environment for hundreds of years (Barnes 2019; Chen et al. 2021b; Mulakkal et al. 2021; Patricio Silva et al. 2021).

Environment and food safety have strong impacts on human health (Fung et al. 2018; Gallo et al. 2020). Many studies are conducted to investigate the migration of contaminants from the environment to food, and finally to human beings. For example, it is reported that heavy metals in the aquatic environment can migrate into fishes via bioaccumulation and bioconcentration (Baki et al. 2018; Korkmaz et al. 2019; Arisekar et al. 2020). When these polluted fishes are consumed, the heavy metals will migrate into human bodies (Saha et al. 2016; Gholamhosseini et al. 2021). Although the concentrations of heavy metals in the fishes are usually below the maximum allowed level (Velusamy et al. 2014; Safiur Rahman et al. 2019), the fact that humans are at the top of the food chain cannot be ignored. In other words, as there are various food sources for human beings, the heavy metals in our bodies could accumulate and finally reach a level that causes serious health risks, such as cancer (Badamasi et al. 2019; Yu et al. 2020a). In addition to the common types of contaminants (e.g., heavy metals, pesticides, pathogen, particulate matter), there are also some emerging types of contaminants (e.g., microplastics, personal care products, pharmaceuticals), and more efforts are needed to study their effects on human health (Aghilinasrollahabadi et al. 2020; Li et al. 2020b; Zhang et al. 2020).

Given the importance of environment and food safety, it is not surprising that a lot of related studies have been published, including many review studies. For example, Qin et al. (2021) reviewed the effects of heavy metals in soil on food safety in China and discussed the sources (e.g., pesticides, fertilizers, vehicle emissions, coal combustion, sewage irrigation, mining) and remediation strategies (e.g., soil amendments, phytoremediation, foliar sprays). Suhani et al. (Suhani et al. 2021) reviewed the effects of cadmium pollution on food safety and human health with a focus on the mechanisms (e.g., cellular or molecular alterations). Deshwal et al. (Deshwal and Panjagari 2020) reviewed the effects of metal-based packaging materials on food safety and health issues (e.g., bisphenol A migration, metal migration, dissolution, blackening, and corrosion). Sun et al. (Sun et al. 2017) reviewed the relationship between air pollution and food security with a focus on the food system (e.g., the effect of agricultural policy on food security). However, most of these review studies only focus on certain subfields (Ayelign and De Saeger 2020; Endersen and Coffey 2020; Imathiu 2020; Nelis et al. 2020; Singh et al. 2020a). In addition, most of these reviews are based solely on the subjective experiences of the researchers in the related fields. In the age of big data, it is necessary to give a timely update on the research of environment and food safety through objective data analysis. The scientometric-based statistical method provides a powerful tool to disclose research trends and progress on certain research areas through data analysis of published documents. However, although there are already quite a few scientometric studies on other research areas (Jiang et al. 2018; Li et al. 2018; Kamali et al. 2020; Khalaj et al. 2020; Zakka et al. 2021; Zeb et al. 2021; Ni et al. 2021), the scientometric studies on environment and food safety are very limited. Therefore, the aim of this study is to provide an integrative review on environment and food safety via objective statistical analysis coupled with subjective review on strategies to protect the environment and ensure food safety, followed by a discussion on emerging research topics.

A scientometric review

As shown in Figure 2, during the past 20 years, there were nearly 5000 publications on the topic of environment and food

Fig. 1 Illustration of the relationship between environment and food safety and their impacts on human health
safety (detailed method was provided in the Supplementary Information). From 2001 to 2020, there was a steady increase in publications every year. Meanwhile, it was indicated that the increase in research output slowed down in 2020, possibly due to the terrible coronavirus pandemic which suspended researchers’ lab work. In terms of document types, the 4904 publications were categorized into 10 types, where research article, review, and proceedings paper were the top three, accounting for 73.23%, 16.54%, and 13.09% of the total publications, respectively (Supplementary Table 1). In terms of languages, most of the documents were published in English, accounting for 96.76% of the total publications (Supplementary Table 2). The following languages were German (0.67%), Chinese (0.57%), Portuguese (0.43%), Spanish (0.41%), French (0.39%), etc. The language analysis revealed that a SCIE journal is not necessarily an English journal. For example, among the journals included in the data, the SCIE journal Berliner und Munchener Tierarztliche Wochenschrift publishes research results in German, and the SCIE journal Progress in Chemistry publishes research results in Chinese. To be available to researchers from all over the world, an English version of the titles, keywords, and abstracts of these publications are also provided. However, as the main text is not written in English, the impact of these publications is usually limited to the local research community, i.e., the papers written in German is normally only read by German researchers while the papers written in Chinese is normally only read by Chinese researchers.

In terms of journals, about 165 journals published at least 5 papers, and the total papers published in these journals accounted to about half of the total publications (more details are provided in supplementary data). Furthermore, as shown in Figure 3, the total papers published in the top 20 most publishing journals accounted to about one-fourth of the total publications. These results revealed that the research on environment and food safety is of broad interest.

In terms of publishing countries/regions, more than 100 countries/regions contributed to these publications (more details are provided in supplementary data). Especially, more than 50 countries/regions contributed at least 20 publications to the research on environment and food safety during the past 20 years. These results again revealed that the research on environment and food safety is of global interest. As shown in Figure 4, in terms of research output, the USA and China were leading the research on environment and food safety. Specifically, among the countries/regions, the USA was undoubtedly the most publishing country, which accounted for nearly one-fourth of the total publications. The runner-up was China, which contributed to around 15% of the total publications. However, it does not mean that the USA and China have contributed to around 40% of the total publications because many papers are published as a result of collaborations among several countries.

Generally, over 400 research institutes had contributed at least 5 publications to the research on environment and food safety, and nearly 50 research institutes published at least 20 papers during the past 20 years (more details are provided in supplementary data). The top 20 most publishing research institutes were summarized in Table 1. Chinese Academy of Sciences (CAS), which ranked the first place based on number of publications, is the largest cluster of research institutes in China. The research conducted by CAS is quite diverse and multidisciplinary. Especially, the research on environment and food safety is loosely conducted by different CAS research institutes, including but are not limited to Research Center for Eco-Environmental Sciences (RCEES), Institute
of Urban Environment, and Institute of Soil Science. For example, researchers from RCEES found that water pollution and soil pollution had serious effect on food safety and human health (Lu et al. 2015). The next one, USDA ARS, short for United States Department of Agriculture Agricultural Research Service, is a leading research institute in the USA focusing on food safety and human health from the aspect of agriculture. Similarly, US FDA is short for United States Food and Drug Administration and is exclusively focusing on food and drug-related research so as to protect public health. INRA, short for French National Institute of Agronomic Research, is a very famous research institute in Europe focusing on agricultural research. Similarly, Istituto Superiore di Sanità is a leading research institute in Italy focusing on public health. In addition to the above 5 research institutes, the remaining 15 research institutes are all universities, and their research on environment and food safety is mainly conducted by the related departments or research centers of the universities. For examples, the Department of Food Technology, Food Safety and Health at Ghent University (located in Belgium) is renowned for its state-of-the-art research on food technology, food microbiology, food chemistry, food safety, etc. Similarly, Wageningen University (located in Netherlands) has a research institute named Wageningen Food Safety Research. Another two European universities were both from Denmark, namely University of Copenhagen and Technical University of Denmark. The Department of Food Science at University of Copenhagen and the National Food Institute at Technical University of Denmark are mainly responsible for food-related research. Besides, there were also two universities from China (i.e., China Agricultural University and Zhejiang University) and one university from Canada (i.e., University of Guelph). The remaining 8 universities all came from the USA, accounting for over half of the universities in the top 20 most publishing research institutes, which corresponded well with the above countries/regions analysis.
Table 1 The top 20 most publishing research institutes

| ID no. | Research Institute                                      |
|--------|--------------------------------------------------------|
| 1      | Chinese Academy of Sciences                           |
| 2      | USDA ARS                                               |
| 3      | Ghent University                                      |
| 4      | US FDA                                                 |
| 5      | Wageningen University                                 |
| 6      | China Agricultural University                         |
| 7      | Cornell University                                    |
| 8      | INRA                                                   |
| 9      | University of California, Davis                        |
| 10     | Zhejiang University                                   |
| 11     | Technical University of Denmark                       |
| 12     | Iowa State University                                 |
| 13     | University of Copenhagen                              |
| 14     | University of Florida                                 |
| 15     | University of Maryland                                |
| 16     | University of Guelph                                  |
| 17     | University of Georgia                                 |
| 18     | Texas A&M University                                  |
| 19     | Istituto Superiore di Sanità                           |
| 20     | University of Minnesota                               |

Table 2 summarized the top 20 most-cited articles on environment and food safety. As revealed by Table 2, the research on environment and food safety is diverse, and there are quite a few research directions which received a lot of attention. Generally, the research topics disclosed by the most cited papers included food inspection/detection technique, heavy metal pollution, food additives, food packaging, food allergy, food pesticide, foodborne pathogen and diseases, microplastics, food processing, and production. Various food inspection/detection techniques have been reported, including electrochemical strategies to detect gallic acid in food (Badea et al. 2019), thermal imaging technique coupled with chemometrics (Mohd Ali et al. 2020), paper-based analysis device for rapid food safety detection (Qi et al. 2020), line-scan spatially offset Raman spectroscopy technique for sub-surface inspection of food (Qin et al. 2017), surface-enhanced Raman spectroscopy for detection of mycotoxins in food (Wu et al. 2021b), chromatography, and mass spectrometry (Pauk et al. 2021; Suman et al. 2021). In addition, heavy metal pollution has posed great threats on food safety, and a lot of studies are conducted, including the soil heavy metal pollution and food safety (Qin et al. 2021) and the impacts of various heavy metals (e.g., cadmium, lead, arsenic) on food safety and human health (Corguinha et al. 2015; Suhani et al. 2021). Furthermore, there are a variety of food additives used in different situations. For example, feed additives such as antibiotics have been used in animal nutrition; however, the use of antibiotics can cause antimicrobial resistance which can further increase the morbidity and mortality of diseases (Silveira et al. 2021). Therefore, as will be discussed below, laws and regulations are needed to strictly control the use of food additives. Furthermore, foodborne pathogen also has strong impacts on food safety. As an effective way to kill or inhibit foodborne pathogen, antimicrobial food packaging is gaining growing research interest in recent years (Woraprayote et al. 2018; Motelica et al. 2020; Alizadeh-Sani et al. 2021).

TC, total citations; the TC data was collected based on Web of Science core collection; PY, publishing year

As shown in Supplementary Figure 1 and Supplementary Figure 2, food, safety, and environment were the top three most common words in titles. The following ones were assessment, health, risk, and environmental. It is well known that environmental pollution can pose risks on food safety and finally threatens human health. A further analysis revealed that a lot of studies were related to risk assessment, such as risk assessment of antimicrobial resistance (Likotrafiti et al. 2018; Pires et al. 2018), risk assessment of heavy metals (Yasotha et al. 2020), risk assessment of pesticide (Frische et al. 2014), risk assessment of veterinary drugs (Tsai et al. 2019), environmental risk assessment (More et al. 2020), and health risk assessment (Akharizadeh et al. 2020). The next one was efficacy, which was usually combined together with safety, such as safety and efficacy of feed additives (Bampidis et al. 2020). Besides, Listeria monocytogenes was intensively studied by researchers (Anast et al. 2020; Kawacka et al. 2020b). Another common word was analysis, such as analysis of herbicide (Pan et al. 2020), analysis of bacteria (Kang et al. 2020), and analysis of microplastics (Primpke et al. 2020). Other common research topics revealed by title analysis included but are not limited to food quality, food production, food additive, food contamination, detection of food contaminants, food microbiology, environmental impact, as well as water, soil, animal, fish, meat, and dairy.

The top 20 most used keywords were listed in Table 3 (more details are provided in supplementary data). It could be seen that microbiology was closely related to food safety, and a lot of studies were conducted on Listeria monocytogenes, biofilm, salmonella, and antibiotic resistance. In addition, additives, such as zootechnical additives and nutritional additives, were also intensively investigated by researchers. Other topics included aquaculture, poultry, and agriculture. Another keyword worth mentioning was food security. Food security is different with food safety. Briefly, food security is a more inclusive term and focuses more on the availability of food while food safety is about the quality of food. On the other hand, food security and food safety are closely related to each other (Vipham et al. 2020). For instance, if food security becomes a big issue, then usually food safety is not guaranteed, and vice versa.
Generally, the results revealed by keywords analysis were in consistent with the above title and keywords analysis.

The keywords network graph revealed some interesting results. As shown in Figure 5, the network had three centers, namely the “food safety”-centered network, the “safety”-centered network and the “efficacy”-centered network. Interestingly, the “safety”-centered network and the “efficacy”-centered network were closely related, while they were relatively unrelated with the “food safety”-centered network. Furthermore, the results again uncovered that food safety involved many aspects, many of which were already discussed above.

The publications in this study were divided into over 200 Web of Science categories (more details are provided in supplementary data). The top 20 Web of Science categories were shown in Figure 6. Undoubtedly, the Food Science & Technology category ranked the first place, followed by the Environment Sciences category. As revealed by Figure 6, food safety was closely related to microbiology, chemistry, and agriculture. Microorganisms such as foodborne pathogens pose great threats on food safety and a lot of studies are focusing on it. For instance, Lin et al (Lin et al. 2021) studied the role of Salmonella Hessarek, an emerging foodborne pathogen, in egg safety. Anyogu et al. (Anyogu et al. 2021) reviewed the microorganisms and indigenous fermented

| No. | Reference | TC   | PY   | Brief summary                                                                                                    |
|-----|-----------|------|------|-----------------------------------------------------------------------------------------------------------------|
| 1   | (Li et al. 2010) | 2236 | 2010 | This paper reported an improved spectroscopy technique which could be used for food safety inspection.        |
| 2   | (Nagajyoti et al. 2010) | 1452 | 2010 | This paper reviewed the occurrence of common heavy metals and their toxicity on plants.                        |
| 3   | (Järup and Åkesson 2009) | 1250 | 2009 | This paper reviewed the effects of cadmium on human health.                                                       |
| 4   | (Weir et al. 2012) | 1102 | 2012 | This paper studied the amount of titanium dioxide additive in common food and personal care products and discussed its effects. |
| 5   | (Kenawy et al. 2007) | 1016 | 2007 | This paper did a review on antimicrobial polymers which might be useful in food packaging and storage.          |
| 6   | (Friedman 2003) | 759  | 2003 | This paper reviewed acrylamide which could be present in food products and could have negative effects on human health. |
| 7   | (Sicherer and Sampson 2014) | 699 | 2014 | This paper reviewed food allergy.                                                                                  |
| 8   | (Damalas and Eleftherohorinos 2011) | 651 | 2011 | This paper reviewed food pesticide.                                                                               |
| 9   | (Gandhi and Chikindas 2007) | 582 | 2007 | This paper reviewed foodborne pathogen: Listeria.                                                                  |
| 10  | (Van Cauwenbergh and Janssen 2014) | 574 | 2014 | This paper revealed the existence of microplastics in bivalves.                                                     |
| 11  | (Newell et al. 2010) | 548 | 2010 | This paper reviewed foodborne diseases.                                                                           |
| 12  | (Hong et al. 2005) | 513 | 2005 | This paper reviewed bacillus probiotics.                                                                         |
| 13  | (Humphrey et al. 2007) | 479 | 2007 | This paper reviewed campylobacters from the perspective of food production.                                       |
| 14  | (Koopmans and Duizer 2004) | 479 | 2004 | This paper studied foodborne viruses.                                                                            |
| 15  | (Kathariou 2002) | 476 | 2002 | This paper reviewed Listeria monocytogenes from the perspective of food safety.                                  |
| 16  | (Su and Liu 2007) | 445 | 2007 | This paper reviewed vibrio parahaemolyticus from the perspective of seafood safety.                             |
| 17  | (Lacey et al. 2001) | 432 | 2001 | This paper reviewed insect pathogens as biological control agents.                                                |
| 18  | (Tompkin 2002) | 423 | 2002 | This paper was about Listeria monocytogenes control during food processing.                                       |
| 19  | (Silvestre et al. 2011) | 414 | 2011 | This paper reviewed food packaging using polymer nanotechnology.                                                  |
| 20  | (Frederiksen et al. 2009) | 414 | 2009 | This paper reviewed human exposure to PBDEs.                                                                        |
foods with a focus on microbial food safety hazards. Van Boxstael et al. (2013) studied the impacts of bacterial pathogens and viruses on food safety in the fresh produce chain. Also, a lot of studies are focusing on food safety and chemistry, such as untargeted food chemical safety assessment (Delaporte et al. 2019), chemical safety of recycled food packaging (Geueke et al. 2018), and chemical food safety hazards of sausages (Halagarda et al. 2018). Furthermore, studies on food safety and agriculture include but are not limited to chemical and biological risks in urban agriculture (Buscaroli et al. 2021), biosensors for sustainable agriculture and food safety (Griesche and Baeumner 2020), agricultural soil contamination, and the impact on food safety (Wang et al. 2019b). In addition, the Materials Science category was also on the top list, which indicated that materials are also important research directions in environment and food safety. A further analysis revealed the common materials studied by researchers, including biomaterials, food packaging materials, biodegradable materials, coating materials, sensors and biosensors for food detection, and nanoparticles. The research area analysis showed similar results with Web of Science categories (Supplementary Table 3).

### Strategies to protect environment and ensure food safety

The above scientometric analysis revealed that the studies on environment and food safety were diversified and multidisciplinary. Further analysis of the above results disclosed the challenges and strategies to protect environment and ensure food safety. As discussed earlier, environment and food safety are closely related to each other. It should be noted that the environment here is not limited to the broad environment (e.g., air, water, soil) which the public are familiar with. In other words, in addition to the broad environment, there are also food-related environments which exist in various processes, including but are not limited to food processing, food packaging, food transportation, food storage, and food consumption. In order to ensure food safety, contaminants/pollutants from the environmental side should be prevented from reaching the food side. An example of food chain pollution control is presented in Figure 7. It can be seen that from growing wheat to making bread, there are a variety of processes which could cause pollution and control strategies are needed, which are summarized as follows. Firstly, from wheat growing to wheat harvesting: the pollutants/contaminants could be taken in or migrate into the wheat via contaminated soil, water, and air, and therefore strategies are needed to prevent soil, water, and air from being contaminated, such as reducing the use of pesticides and fertilizers. Secondly, initial processing of wheat: after the wheat is harvested, traditionally

| Keyword                  | Number of publications | Rank |
|--------------------------|------------------------|------|
| Food safety              | 710                    | 1    |
| Safety                   | 262                    | 2    |
| Efficacy                 | 170                    | 3    |
| Environment              | 157                    | 4    |
| Listeria monocytogenes   | 129                    | 5    |
| Risk assessment          | 108                    | 6    |
| Salmonella               | 92                     | 7    |
| Food                     | 91                     | 8    |
| Food security            | 57                     | 9    |
| Zootechnical additive    | 57                     | 9    |
| Sustainability           | 52                     | 11   |
| Heavy metals             | 49                     | 12   |
| Agriculture              | 46                     | 13   |
| Biofilm                  | 45                     | 14   |
| Antibiotic resistance    | 43                     | 15   |
| Aquaculture              | 43                     | 15   |
| Poultry                  | 42                     | 17   |
| Nutrition                | 41                     | 18   |
| Zootechnical additives   | 41                     | 18   |
| Nutritional additive     | 40                     | 20   |
it needs to be dried by the farmers before it is sold. During this process, contamination can easily occur if the wheat is dried directly on the road which is common in rural China. In addition, the containers of the harvested wheat are also sources of pollution which should be carefully controlled. Alternatively, the pollution can be avoided if the wheat is directly sold and transported to the flour mill from the farm without being dried by the farmers. Thirdly, during the transportation processes (e.g., from farm to flour mill, from flour mill to bread bakery, from bread bakery to supermarkets), contamination can also take place and control strategies are needed. Fourthly, during the wheat processing at the mill and bread baking at the bakery, contamination can take place due to environment exposure, insufficient frequency and quality of facility washing and cleaning, use of additives, etc. Fifthly, during the bread packaging process, the workers can be an important source of bread contamination if the bread is packed manually. Finally, when the consumers buy the bread and do not consume the bread timely, the bread can decay. Based on the above discussion, the food chain pollution control can be generally categorized into the following sections: source pollution (i.e., soil, water, air) control, pollution control during food processing, pollution control during food packaging, pollution control during transportation, pollution control during storage, and pollution control during consumption.

Especially, based on the type of chemicals, the contaminants/pollutants can be categorized into pesticides and herbicides, heavy metals, food additives, pathogens, microplastics, antibiotics, and so on (Van Boxstael et al. 2013; Tóth et al. 2016; He et al. 2019b; Rajmohan et al. 2019; Bonerba et al. 2021). Therefore, the corresponding strategies are to control the use of chemicals and materials which can produce these contaminates. For example, as will be discussed in the following section, microplastics come from the wide use of plastics and are receiving growing concern. In order to reduce the amount of microplastics, the use of plastics should be controlled or restricted. Based on the media of migration, these contaminants can reach at the food side via air, water, and soil. Therefore, the corresponding strategies are to remove contaminants from air, water and soil. Alternatively, strategies can be deployed to prevent these contaminants from contacting the food. For example, as will be discussed later, food packaging is a common strategy to protect food from being contaminated by the environment (Risyon et al. 2020). To sum up, by controlling the sources and migration routes of food contaminants, food safety can be improved. Furthermore, in order to ensure food safety, whole process monitoring techniques and platforms are necessary. A lot of studied have been conducted on food safety monitoring. For example, De Oliveira et al. (2021) proposed that environmental monitoring programs (EMPs) are necessary to ensure food safety and quality. The EMPs are used to prevent environmental contamination of the finished product, via checking the cleaning-sanitation procedures, and other environmental pathogen control programs with a range of sampling analysis. Medina et al. (Medina et al. 2019) proposed food fingerprints as an effective tool to monitor food safety. Weng et al. (Weng and Neethirajan 2017) reviewed microfluidics as an effective method to realize rapid, cost-effective, and sensitive detection of food contaminants such as foodborne pathogens, heavy metals, additives, and pesticide residues. Other monitoring methods/techniques/devices include but are not limited to pH-sensitive smart packaging films (Alizadeh-Sani et al. 2020), point-of-care detection devices (Wu et al. 2017), and real-time pathogen monitoring via a nanotechnology-based method (Weidemaier et al. 2015). Food safety monitoring can be done by either government officials or the relative bodies (e.g., self-monitoring), or both. Furthermore, from the time the food raw materials are being cultivated in the farm-land, pasture, fishing ground or other places, to the time the
food is being consumed by customers, inspecting and detecting should be deployed. This can be done by the government officials and/or the stakeholders. Although the term “inspection” and “detection” are often used as the same, here, food safety inspection is regarded as an administrative strategy, which is carried out by governmental officials to check whether the relative workers/factories/bodies have followed the food safety requirements/regulations, while food safety detection is regarded as a technique-based strategy, which is used to detect food contaminants and check whether the quality of the food meets the relative standards. Meanwhile, food safety laws need to be enacted to discourage or prevent the relative workers/factories/bodies from affecting the food safety, whether purposely or not.

On the other hand, during the process of food production, the environment can be polluted as well. For example, in order to increase crop yield, a lot of fertilizers are used, which will migrate into the soil and water bodies, and cause soil and water pollution. Therefore, the use of fertilizers should be restricted, which can be realized through agricultural innovations (Liu et al. 2021), government policies (van Wesenbeeck et al. 2021), etc. Furthermore, during food processing, a large amount of solid waste or/and wastewater are produced which can cause environmental pollution. Therefore, techniques are...
needed to dispose the food waste properly. Especially, food waste usually contains high amount of organic compounds and therefore falls into the category of biomass, which can be used to produce useful biochemicals like biofuels (Wainaina et al. 2018; Chun et al. 2019). For example, agro-food waste is an important source of lignocellulosic biomass; the valorization of lignocellulosic biomass is regarded as a sustainable source of energy and has the potential to replace conventional fossil fuels (Ong and Wu 2020; Lee and Wu 2021; Lee et al. 2021; Mankar et al. 2021; Zhenquan et al. 2021). Furthermore, the concepts of recycling and sustainable development can be deployed. For example, food packaging materials can be recycled and used again. Another example is to use cloth bags to replace plastic bags when shopping. These strategies can reduce the burden on the environment as the amount of food-related waste can be reduced. In addition, novel environment-friendly materials (e.g., biodegradable polymers) can be developed and used in food industries (Stoica et al. 2020; Cheng et al. 2021). To summarize, the above strategies to protect environment and ensure food safety are presented in Figure 8.

Emerging studies on environment and food safety

Scientometric analysis is powerful in disclosing the research trend and is relatively subjective compared to conventional type of review. However, as it is essentially a statistical study which relies on a huge amount of data, it is less effective to reveal the emerging research directions which could be ignored in the scientometric study. Therefore, it is necessary and important to carry out a subjective discussion on emerging studies on environment and food safety as an indispensable supplement (Figure 9).

Emerging contaminants

There are various contaminants affecting environment and food safety. Among the various types of contaminants, emerging contaminants, such as microplastics, are receiving growing concern due to their potential effects on human health (Sarker et al. 2020). Because of the wide application of plastics, microplastics are found almost everywhere in the environment, including soil, water, and air (Álvarez-Lopez et al. 2020; Chen et al. 2020; Wang et al. 2021e). For example, microplastics are reported to exist in bottled water (Zhou et al. 2021) and take-out food plastic containers (Du et al. 2020). Furthermore, researchers have found that microplastics could serve as the carrier for many other contaminants such as heavy metals and antibiotics (Zhou et al. 2019; Purwiyanto et al. 2020; Yue et al. 2020b). Studies reveal that the ability to absorb heavy metals increase as the microplastics age (Lang et al. 2020). As a result, the risks of microplastics on environment, food safety, and human health could be significantly increased. However, the research on microplastics is still at an early stage, and more efforts are needed to uncover the world of microplastics. For example, there is no standard procedures to extract, identify, and quantify microplastics so results by different methods could be different and uncomparable (Kumar et al. 2020; Zhou et al. 2020). Meanwhile, due to the various sizes, shapes, forms, sources, and types of microplastics, it is difficult and time-consuming to characterize microplastics (Wu et al. 2020a). Therefore, it is important to develop new methods for rapid and effective detection of microplastics (Li et al. 2020c).

In addition to microplastics, there are other emerging contaminants which can have negative effects on the environment, food safety, and human health. These emerging contaminants include but are not limited to persistent organic pollutants (Titchou et al. 2021), antibiotics (Koch et al. 2021), personal care products (Scaria et al. 2021), pharmaceuticals (Chaturvedi et al. 2021), endocrine-disrupting compounds

![Fig. 8 Strategies to protect environment and ensure food safety](image-url)
Kasonga et al. 2021), and non-nutritive artificial sweeteners (Praveena et al. 2019). More research efforts are needed to gain a better understanding of the migration, degradation, accumulation characteristics, as well as the potential risks of these contaminants.

**Rapid detection of contaminants**

Not limited to the detection of microplastics, it is also necessary to develop rapid detection methods for common contaminants. For example, due to the widespread application of pesticides in agriculture, pesticide residue is becoming a serious environment and food safety issue (Farahy et al. 2021). Traditionally, food contaminants are detected by instrumental analysis, such as chromatography and mass spectrometry (Ye et al. 2019). However, the instrumental analysis process is expensive, complicated, and time-consuming (Zhang et al. 2019). Furthermore, the contaminants are usually in low concentration, but can accumulate gradually in human bodies via bioconcentration. Therefore, it is important to develop rapid method to detect trace-level concentration of food contaminants. Biosensor is an emerging and promising technology in detecting food contaminants such as pesticides, and a variety of biosensors have been developed in recent years (Majdinasab et al. 2018, 2019). For example, Ouyang et al. (Ouyang et al. 2021) developed a sensitive biosensor to detect carbendazim pesticide residues based on luminescent resonance energy transfer from aptamer-labelled upconversion nanoparticles to manganese dioxide nanosheets. Capobianco et al. (Capobianco et al. 2021) developed an enzyme-linked immunoelectrochemical biosensor to detect pathogenic bacteria in large volume food samples without subsampling. Wang

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**Fig. 9** Emerging studies on environment and food safety

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Emerging contaminants

- Microplastics
- Antibiotics
- Personal care products
- Pharmaceuticals
- Endocrine disrupting compounds
- Non-nutritive artificial sweeteners

Rapid detection of contaminants

- Surface enhanced Raman scattering (SERS)
- Optical sensors based on nanomaterials
- Hyperspectral imaging technology
- Perfluorinated compounds (PFCs)

Environment friendly food packaging materials (biodegradable polymers)

- Polylactic acid (PLA)
- Polybutylene adipate terephthalate (PBAT)
- Polysaccharides
- Cellulose
- Pectin
- Starch
- Chitosan
- Polyhydroxyalkanoates (PHAs)
- Cellulose acetate
et al. (Wang et al. 2019a) developed a magnetic quantum dot-based lateral flow biosensor to detect protein toxins in food samples. Kaushal et al. (Kaushal et al. 2019) developed a novel biosensor using gold nanorods capped by glycoconjugates which demonstrated potential in optical detection and ablation of foodborne bacteria. Generally, a biosensor is mainly composed of a biological sensing element (also known as bioreceptor), a transducer, and an electrical output system (Santana Oliveira et al. 2019; Majdinasab et al. 2021). The bioreceptor will interact with the analyte, and the transducer will convert the interaction into a detectable signal, which is then processed and displayed on the output system. Common materials used in the biological element include antibodies, enzymes, nucleic acids, antigens, aptamers, whole cells, and bacteriophage (Arora et al. 2011; Rotaru et al. 2016; Griesche and Baeumner 2020; Singh et al. 2020). Biosensor technology has obvious advantages compared to traditional detection technologies. It is rapid, highly sensitive and selective, accurate, relatively compact, and easy to operate (Dominguez et al. 2017). However, there are still some challenges to widely commercialize biosensors, such as limited lifetime of the biological sensing elements and limited range of analytes that can be detected (Di Nardo and Anfossi 2020). Furthermore, as a specific type of biosensor is only effective in detecting a specific type of contaminant, more efforts are needed to develop integrated biosensors which can detect different types of containments simultaneously (Majdinasab et al. 2020). In addition to biosensors, there are also a variety of other reported methods for rapid detection of food contaminants, such as surface-enhanced Raman scattering (SERS) (Yao et al. 2021), optical sensors based on nanomaterials (Chen et al. 2021a), hyperspectral imaging technology (He and Sun 2015), and perflourinated compounds (PFCs) (Cai et al. 2021).

**Environment friendly food packaging materials**

As revealed above, food packaging is closely related to food safety. Although there are different kinds of food packaging materials, the non-biodegradable plastic materials (e.g., polyethylene, polypropylene, polyvinyl chloride, polystyrene, polyethylene terephthalate) are the most common ones and are widely used in our daily life (Cazón and Vázquez 2021). However, the non-biodegradable plastic materials have caused serious environmental problems, commonly known as white pollution. Especially, because of the coronavirus pandemic, take-out food becomes more popular. As plastic materials are the most common packaging materials for take-out food, the demand for plastic materials increases dramatically. Meanwhile, plastic materials also have food safety issues. It is found that the monomer residues used to make plastic polymers could migrate into food, which could cause health problems (Pilevar et al. 2019). Especially, the migration rate is not only affected by the quality of these materials, but also affected by the food properties. In addition to monomer residues, additives in these plastic materials could also migrate into food, causing health risks (Hahladakis et al. 2018). For example, bisphenol A, a common additive used in plastics, can adversely affect human endocrine system, block normal cell function, affect thyroid hormone, affect testosterone levels, and could also possibly induce cancer (Huang et al. 2019; Vilarinho et al. 2019). Another very common additive in plastics is phthalates, which is used as plasticizer to soften the plastics. It is reported that phthalates in plastic bottles could migrate into water, and the amount of migration increases as the storage time increases (Luo et al. 2018). Similar to bisphenol A, phthalates can also disrupt human endocrine system and cause bad effects on human health (Wang et al. 2018). Not limited to bisphenol A and phthalates, there are many types of plastic additives which could migrate into food and cause food safety issues.

As the conventional non-biodegradable plastics can cause both environmental problems and food safety issues, a lot of studies are carried out to find alternatives to non-biodegradable plastics for food packaging. Biodegradable polymers are regarded as the one of the most promising alternatives for food packaging (Othman 2014). As its name indicates, biodegradable polymers can be decomposed by microorganisms. Common biodegradable polymers studied as food packaging materials include but are not limited to polyactic acid (PLA) (Swaroop and Shukla 2018, 2019; Mohamad et al. 2020), polybutylene adipate terephthalate (PBAT) (Pattanayaiying et al. 2019), polysaccharides (such as starch (Osorio et al. 2019; Menzel 2020; Saraiva Rodrigues et al. 2020), cellulose (Balasubramaniam et al. 2020; Riaz et al. 2020), pectin (Nešić et al. 2018), chitosan (Haghighi et al. 2020; Priyadarshi and Rhiim 2020)), polyhydroxalkanoates (PHAs) such as polyhydroxybutyrate (PHB) (Adelye et al. 2020; Fernandes et al. 2020; Shahid et al. 2020), polycapro lactone (PCL) (Khalid et al. 2018; Mugwagwa and Chimpango 2020), and cellulose acetate (Xie and Hung 2018; Rajeswari et al. 2020).

However, in addition to high production cost, there are some critical technical challenges which must be solved so as to widely commercialize biodegradable polymers and replace conventional plastics (Pérez-Arauz et al. 2019). Generally, biodegradable polymers have low thermal stability, low mechanical stability, and poor barrier properties (Risyon et al. 2020). One way to improve its performance is to add additives during production. For example, Risyon et al. (Risyon et al. 2020) prepared PLA-based film using different concentrations of halloysite nanotubes as additives. They found that the PLA film with 3.0 wt.% of halloysite nanotubes demonstrated optimal properties. Dash et al. (Dash et al. 2019) prepared starch and pectin-based film using different concentrations of titanium dioxide nanoparticles. They found that
addition of the nanoparticles could effectively improve the mechanical properties and moisture barrier properties of the films. However, similarly to conventional plastics, these additives might also migrate into food (He et al. 2019a). Another strategy being intensively studied is polymer blending, which integrates the merits of different polymers (de Oliveira et al. 2020). For example, Rajeswari et al. (Rajeswari et al. 2020) blended polysaccharides and cellulose acetate together, and the resulting film showed improved thermal stability and tensile strength. The prepared films also demonstrated antimicrobial properties towards certain types of microorganisms. Sangroniz et al. (Sangroniz et al. 2018) blended poly(butylene adipate-co-terephthalate) with poly(hydroxyl amino ether), and the resulting film showed great improvement of barrier properties. However, polymer blending could also have its drawback. For example, if the blending polymers are immiscible with each other, the mechanical strength and barrier properties of the resulting materials will be affected (Corres et al. 2020).

Conclusions, challenges, and future research directions

In this review, a scientometric-based statistical study was firstly conducted on the research of environment and food safety, which revealed that the research on environment and food safety was growing steadily from 2001 to 2020. Interestingly, statistical analysis of the most-cited papers, titles, abstracts, keywords, and research areas revealed that the research on environment and food safety is diverse and multidisciplinary. Furthermore, strategies to protect the environment and ensure food safety are discussed, such as controlling the use of chemicals and materials which can produce environment and food contaminants, preventing these contaminants from contacting the food, developing whole process monitoring techniques and platforms, and utilizing the food waste properly. In addition, emerging research topics are discussed, such as emerging contaminants, rapid detection of contaminants, and environment friendly food packaging materials.

Although environment and food safety are receiving growing concern, there are still some very challenging issues. These challenges can be categorized into four parts. Firstly, it is challenging to eliminate environmental pollutions (Hao et al. 2018; Christy et al. 2021). Air pollution, water pollution, and soil pollution are still serious environmental problems in many parts of the world (Wu et al. 2016, 2021a; Rajeswari et al. 2019; Shen et al. 2021b). Although a lot of studies have been carried out, the mechanisms of some pollutions (e.g., haze weather) are still unclear (Shen et al. 2020; Wang et al. 2021a). Secondly, it is challenging to dispose food waste effectively and efficiently. It is reported that a substantial amount of food waste is produced along the food supply chain (Aschemann-Witzel 2016; Li et al. 2019). Especially, food wastewater typically contains very complex components, and the treatment process is very energy intensive and costly. Thirdly, it is challenging to realize whole-process monitoring of contaminants, due to the diverse contaminants during food cultivation, processing, packaging, transportation, and retailing. Fourthly, the accurate effects of environmental pollution on human health are still unclear, and it is challenging to establish procedures to accurately assess the risks of environmental pollution on human health. For example, it is well reported that ozone pollution and PM2.5 pollution can cause negative effects on human health (Guan et al. 2021; Shen et al. 2021a; Wang et al. 2021b). However, the underlying mechanisms, accurate assessment procedures, and quantitative studies are still lacking. In order to address these challenges, more research efforts are needed to (1) uncover the underlying mechanisms of contaminant formation, migration and fate; (2) develop more cost-effective and sustainable food waste treatment and utilization technologies, targeting net zero emissions; (3) develop rapid detection methods and in situ monitoring technologies for environment and food safety; and (4) establish health risk assessment models and procedures.

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