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Review

Reviewing chemical and biological risks in urban agriculture: A comprehensive framework for a food safety assessment of city region food systems

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ABSTRACT

Attention to urban agriculture (UA) has recently grown among practitioners, scientists, and the public, resulting in several initiatives worldwide. Despite the positive perception of modern UA and locally grown, fresh produce, the potential food safety risks connected to these practices may be underestimated, leading to regulatory gaps. Thus, there is a need for assessment tools to evaluate the food safety risks connected to specific UA initiatives, to assist practitioners in self-evaluation and control, and to provide policy makers and scholars a means to pursue and assess food safety in city regions, avoiding either a lack or an excess of regulation that could ultimately hinder the sector. To address this aim, this paper reviews the most recent and relevant literature on UA food safety assessments. Food safety indicators were identified first. Then, a food safety assessment framework for UA initiatives was developed. The framework uses business surveys and food analyses (if available) as a data source for calculating a food safety index for single UA businesses and the whole UA landscape of a given city region. The proposed framework was designed to allow its integration into the CRFS (City Region Food System) toolkit developed by FAO (Food and Agriculture Organization of the United Nations), RUAF foundation (Resource Centres on Urban Agriculture and Food Security) and Wilfrid Laurier University.

1. Urban agriculture: goals, benefits and perception

Urban agriculture (UA) is a strategic tool for food security in cities of the global south, as well as a powerful asset for urban sustainability and climate change adaptation in the global north (Orsini et al., 2020). In recent years, the importance of UA has largely increased, with the flourishing of many diverse initiatives and pilots, such as urban orchards, vertical farms, aquaponics or even more complex "green industry" plants (e.g., water treatment plants integrating hydroponics and heat generation). UA initiatives have great potential for positive social and economic impacts (Hallett et al., 2016; Horst et al., 2017; Kunpeuk et al., 2020) as well as resilient food provision processes or contributions that shorten the municipal food supply chain (European Commission, 2015) in both the global north and south (De Zeeuw et al., 2011; Hallett et al., 2016). Moreover, technologically advanced UA projects, provided that they are economically sustainable, can have a positive impact on employment, food carbon footprint reduction, efficient land management and food market diversification (Gómez et al., 2019; Rothwell et al., 2016; Sanyé-Mengual et al., 2019; Savvas & Gruda, 2018). Such initiatives integrate well with municipal networks of food producers, distributors, processors, and consumers. Therefore, UA may contribute to global food policy objectives (Local Governments for Sustainability [ICLEI], 2015; Food and Agriculture Organization of United Nations [FAO] & Resource Centres for Urban Agriculture and Food Security [RUAF], 2015), ultimately enabling sustainable and resilient urban or regional food supply chains, as recently defined within the framework

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for City Region Food System (CRFS) (FAO & RUAF, 2015; RUAF, 2015). The CRFS approach promotes sustainable and resilient food systems among urban centres, peri-urban areas and rural territories, forming a city region by strengthening their connections. Following this approach, the FAO and RUAF CRFS toolkit evaluates the status of a food system through specific indicators for different policy areas, helping decision-makers pursue desired goals (Blay-Palmer et al., 2018; FAO & RUAF, 2015). The strengthening of a CRFS through modern and intersectional UA production initiatives is recognized as an extremely valuable tool for policy challenges and the creation of social and economic value (Maye, 2019).

UA initiatives are diverse; more traditional initiatives, such as farmers' markets or community gardens, are usually well accepted by consumers and residents, especially with regard to locally produced food (Feldmann & Hamm, 2015). The same is not necessarily true for more technologically advanced systems, such as aquaponics, insect farming, algae and indoor vegetable production, for which there is a different degree of consumer acceptance (Specht et al., 2019). Undeniably, the literature reveals that consumers tend to overestimate the food safety level of locally grown food compared to large-scale retail trade produce, as they perceive locally grown food as more "genuine" (Khouryieh et al., 2019; Mohammad et al., 2019; Yu et al., 2017). However, shortening the distance from farm to fork may result in the avoidance of safety and/or quality controls and an oversimplification of safety-assuring procedures. Moreover, peri-urban agriculture and, especially, urban allotment gardens may suffer significantly from urban-related environmental pollution (Säumel et al., 2012). On the other hand, modern and innovative cultivation techniques (such as plant factories with artificial lighting [PFALs], recirculating systems, soilless systems, or vertical farms in general) are not necessarily considered appealing to consumers. This could be a consequence of a lack of awareness (Ercilla-Montserrat et al., 2019) or of the common narrative for which traditionally grown food is better and more "natural". However, while advanced UA production systems are generally well accepted (Jürkenbeck et al., 2019; Miličić et al., 2017; Pollard et al., 2017; Sanyé-Mengual et al., 2018; Specht et al., 2016), studies on consumers' safety perception of their produce are scarce and locally based (Kaiser et al., 2015). Apart from their perception, short food supply chains, farmers' markets, directly sold produce, and modern cultivation techniques do not intrinsically guarantee high levels of food safety and have potential biological and chemical risks (Antisari et al., 2015; Riggio et al., 2019; Säumel et al., 2012).

1.1. Food safety regulations and CRFS assessment approaches

Within the European Union (EU), food and feed sanitization rules for all supply-chain operators ("from farm to fork") were adopted in 2004 through Regulations (EC) 852/2004, 853/2004, and 854/2004 that came into force on January 1, 2006. A certain degree of flexibility was also considered for microenterprises and some food producers. These exceptions allowed small local businesses to stay in the market without being overwhelmed by unaffordable costs required to comply with sanitization regulations, provided some conditions were satisfied. For example, EU member states can grant derogations to some animal-based "traditional foods" recognized within the EU. Additionally, farm shops or micro-producers selling their own products directly to consumers in small quantities can be subject to simplified regulations, although more stringent member state regulations can still be in force. Nevertheless, the risk for avoiding food control still exists due to intrinsic traceability difficulties justified by small lots and an extremely large number of micro-food businesses, accounting for over two hundred thousand food and drinking micro-enterprises (European Executive Agency for Small-and Medium-sized Enterprises [EASME], 2019).

In many Western countries, locally and traditionally grown food from small businesses has a better reputation to consumers, despite being, in many cases, less regulated and less systematically controlled than larger scale retail and imported food (Herman et al., 2012; Pussemier et al., 2012). Short supply-chain food (including produce from UA initiatives) should not meet a lower food safety standard than traditional large-scale retail trade produce (for which regulations and controls are broadly in place). Adequate quality controls should also be adopted for short supply-chain food whenever they do not already exist. A simplified and adaptable company structure, in addition to low distribution costs, should allow the competitiveness of short supply-chain businesses rather than safety control avoidance.

The contribution of UA to local food system performance and to the improvement of urban resilience and sustainability can be effectively assessed through the CRFS methodological approach (Blay-Palmer et al., 2018). Nevertheless, as the increase in the strength of UA initiatives is being considered, a fundamental investment in food policy becomes crucial (FAO, 2019; von der Leyen, 2019), especially regarding food safety risk assessments of UA initiatives and local food businesses. Specifically, there is a concurrent need to a) ensure that efficient control protocols are in place in small traditional businesses, b) prevent possible risks in UA practices of different natures/sources, and c) improve the public perception of food safety in technological systems.

Currently, with the CRFS assessment proposed by the FAO and RUAF (Carey & Dubbeling, 2017), the global food safety level of the CRFS can be generally assessed by surveys and secondary data, as some general food safety indicators are proposed (e.g., indicators 50 to 55). Carey and Dubbeling (2017) suggest, whenever possible, gathering disaggregated data. In this paper, a more detailed approach is proposed for UA, consisting of a) production of a UA initiatives inventory and b) assessment of their individual food safety risk level through specific risk-based scores. Public administrators and policy makers could rely on a more detailed assessment of local UA food businesses and producers to help them become empowered. Moreover, businesses themselves could benefit from these assessments. In fact, businesses would be able to improve their own food control programs, link analyses with proper risk management, and provide tools for good manufacturing or agricultural practices (GMP and GAP) and training.

This study detects the main food safety risks connected to UA vegetable production practices through an extensive scientific literature investigation, with the following aims:

- Identify the main food safety risks from the available literature;
- Develop an analytical framework to evaluate the food safety of single UA initiatives; and
- Propose an index that enables UA businesses to improve their own food safety control.

The proposed framework, even if aimed at evaluating single UA initiatives, was developed to be compatible with the CRFS assessment and monitoring approaches contained in the FAO/RUAF CRFS toolkit (Carey & Dubbeling, 2017; FAO, RUAF, & Wilfrid Laurier University 2018).

2. Literature research methodology

2.1. Background setting and protocol study definition

An initial literature overview of food safety and health risk assessments related to UA food production was performed in May 2020 to provide a basis to set up the search keywords for the subsequent systematic review. The following string was adopted when searching the PubMed, Scopus, and Web of Science databases:

("Urban Agriculture" OR "CRFS" OR "City Region Food Systems") AND "Food Safety"

No chronological constraints were set. The search produced a total of 73 results. The entries were hence screened by discarding textbook chapters (8), non-English texts (3), false positives completely unrelated to food safety (5), a duplicate entry (1) and a paper with no full text available (1).

The 55 resulting papers were diverse in scope and perspective, documenting UA initiatives from very different parts of the world (Figure SM1). Only 31 of them referred to specific food safety risks of UA initiatives (e.g., foodborne pathogens and potentially toxic elements), while the remaining 24 either addressed food safety in general without addressing any specific risks or did not present any risk at all (only 2 papers). Thirty-five papers considered the social, economic and sustainability impacts of UA, while only 19 were actual food safety assessments.

The geographical distribution of the 55 papers (Figure SM1A) confirmed that the issue of food safety connected to UA is not predominant in the world's global south, where possibly other issues associated with UA (e.g., its contribution to food security) prevail (Orsini et al., 2013). Thus, the risk of a geographic bias of the search results was deemed negligible.

Overall, this preliminary research suggested the following possible risks: a) difficulty in distinctively differentiating studies related to UA rather than to rural agriculture, mostly due to the generic definition of UA and b) a possible risk of a high number of false positives, in particular studies addressing food security and sustainability.

2.2. Systematic literature search protocol

A qualitative systematic literature review (SLR) assessing the main food safety issues connected to UA was performed from March to June 2020. General principles for a SLR were adopted (Gough et al., 2017), as well as most appliable PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) recommendations (Moher et al., 2009). Web of Science and Scopus database were chosen. The search was set with a total of 79 keywords related to UA techniques (e.g., hydroponics and vertical farming) and hazards (e.g., Salmonella, nitrates, and heavy metals). The query used for the literature search included all "context" and "assessment" keywords (x and y, respectively), as listed in Table 1, by the formula:

$$(x1 \text{ OR } x2 \text{ OR } x3 \text{ OR } \ldots \text{ xn}) \text{ AND } (y1 \text{ OR } y2 \text{ OR } y3 \text{ OR } \ldots \text{ yn}) \tag{1}$$

The search obtained more than a hundred thousand results, most of which were false positives. Hence, a further selection process was performed, as depicted in Fig. 1. Briefly, the first 500 results of each x:y combination were manually screened to keep the items relevant to UA and risk assessment only. Books and book chapters were discarded. The process resulted in 895 items selected. Furthermore, all duplicates were discarded, as well as unusable items (e.g., papers with unavailable full texts or non-English documents), resulting in 665 research products remaining. Ultimately, only actual UA risk assessment studies were considered suitable to the scope of the present SLR, and thus, the following were discarded: a) studies on non-food crops, b) field studies in contexts different from urban or peri-urban areas, and c) studies on animal husbandry, except for aquaculture and aquaponics. Papers addressed in the selected review papers were considered on a case-by-case basis. Eventually, 217 papers were selected and used for the qualitative analysis. The resulting entries spanned from 1962 to 2020, and approximately 60% of them were published from 2011 to 2020.

2.3. Data analysis for the development of a UA initiatives food safety assessment framework

Two key sets of information were extrapolated from the collected papers necessary for the development of the proposed framework. These were a) the identification of food safety hazards reported in UA practices and how they were assessed and b) the classification of UA types and identification of their inherent risk factors.

Table 1
List of X (context) and Y (assessment) keywords used in the literature search with the query (x1 OR x2 OR x3 OR … xn) AND (y1 OR y2 OR y3 OR … yn).

X (context) keywords	Y (assessment) keywords	
City Region Food Systems	Food quality	Good agricultural practices
CRFS	Food safety	GAP
Hydroponics	Pesticides	Agricultural practices
Soilless system	Plant protection products	Polycyclic aromatic hydrocarbons
Roof garden	PPP	PAH
Aquaponics	Pesticide residues	Persistent organic pollutants
Food production	Heavy metals	POP
Rooftop greenhouse	Potentially toxic elements	Postharvest handling
Controlled environment	PTE	Processing practices
Indoor farming	Dioxins	Consumer handling
Urban farming	Dibenzofurans	Washing and sanitizing
Leafy Vegetables	Polychlorobiphenyls	Risk management
Fresh produce	PCB	Risk assessment
Hydroponic produce	Nitrates	Benefits in nutrition
Nutrient Film Technique	*E. coli*	Nutrient
NFT	*E. coli* O157:H7	Additives
Recirculating nutrient solution	Salmonella	fortifica* OR biofortifica*
Recirculating aquaponic system	Listeria	Anti-nutrients
Irrigation water	Coliforms	Food chain
Urban soil	Foodborne illness	Food composition
Rural soil	Human health	Government food standards
zero km food	Community health	Bioactive non-nutrients
Urban horticulture	Health risk evaluation	Food contaminants
Urban agriculture	Quantitative microbial risk assessment	Shelf-life
Vertical Farming	QMRA	Nutraceuticals
	Ultraviolet treatment	Microplastics
	Water disinfection treatment	Plastics

2.3.1. Identification of food safety hazards reported in UA practices

In this investigation, both regular and review articles were considered. The papers were singly considered to collect data about what hazards were identified and how the risk was assessed (specifically, what parameters were analysed). Eight hazard categories were identified based on the preliminary examination of title, abstract and keywords (: a) foodborne pathogens and microorganisms, b) potentially toxic elements (PTEs), c) pesticide residues, d) nitrate and nitrite contents, e) microfauna and pluricellular parasites, f) persistent organic pollutants (POPs), g) organic xenobiotics and pharmaceuticals, and h) hazardous materials. These hazard categories are described in detail in section 3.1.

Since most papers addressed more than one hazard, the 217 research papers were broken down into risk assessments, defined as the analytical determination (laboratory analysis) of one hazard on a specific matrix (e.g., growing medium, irrigation water, and food products). The papers contained a total of 399 risk assessments based on gathered data or direct analyses. As a brief example, Christou et al. (2016) investigated the quality and safety outputs of strawberries cultivated in ground-based greenhouses that received wastewater. Here, PTEs and pathogens were assessed on two matrices (irrigation water and fruit); thus, the paper was counted as four (4) assessments.

2.3.2. Classification of UA types and identification of their inherent risk factors

Six different UA classes were identified among the 217 selected papers: a) soil-based urban and peri-urban green, b) soilless UA systems, c) aquaponic plants, d) waste assimilating and experimental UA plants, e) processing and food industries, and f) local markets and retail. The first four (a to d) classes were UA production system types. Categories a, b

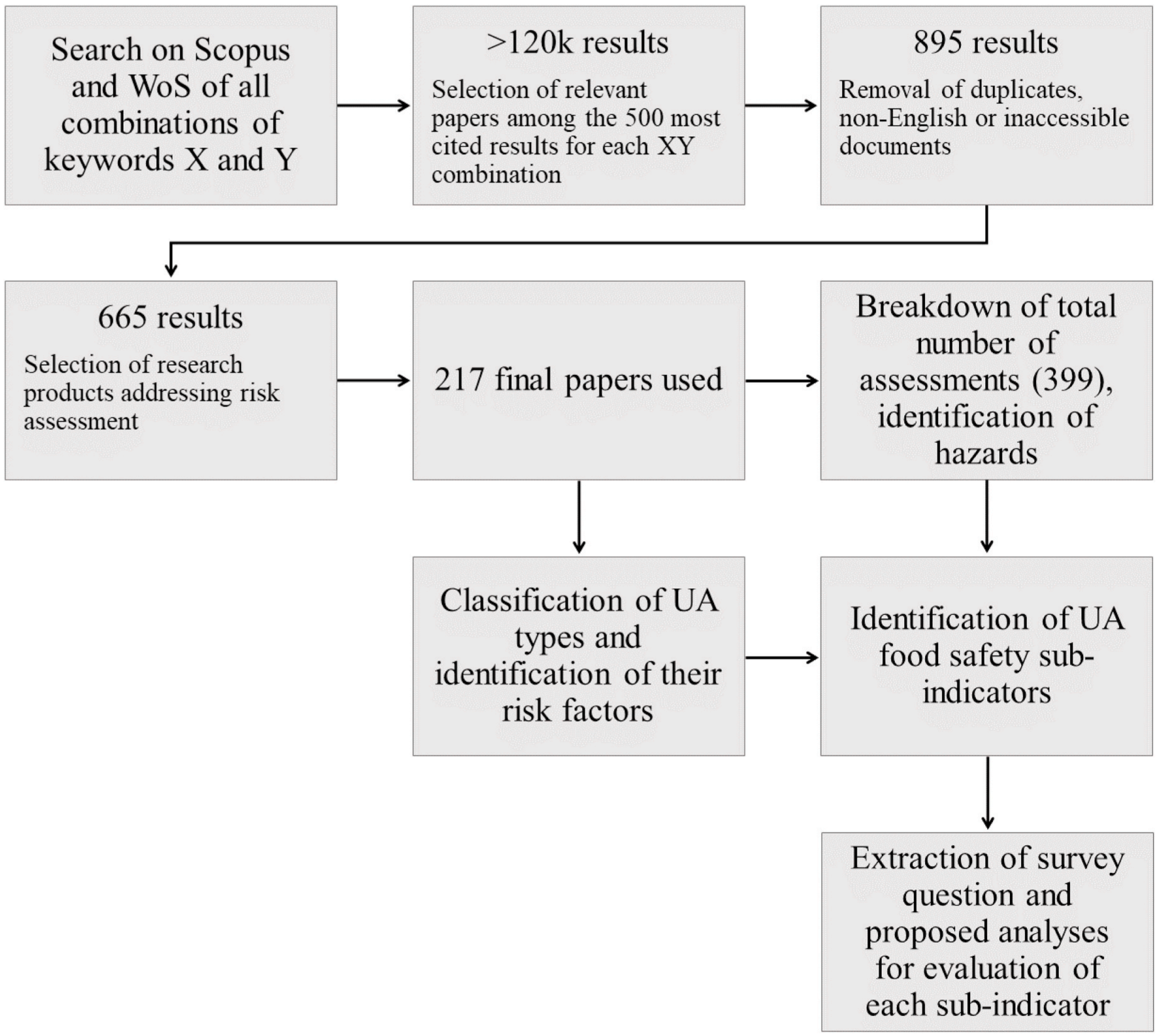

Fig. 1. Scheme for the systematic literature search.

and c were mutually exclusive. This simplified and generic classification was adopted to find similarities among different UA settings described in different papers. A more rigorous classification of UA production types is addressed in section 3.2.

The last two classes (e and f) were not UA production systems but destinations for UA production described or examined in the aforementioned papers. For example, Christou et al. (2016), previously described in section 2.3.1., accounted for the class categories “urban and peri-urban greens” and “waste assimilating and experimental UA plants”.

2.3.3. Identifying a framework for UA initiative food safety assessment: development of indicators, index of food safety for single initiatives, and global CRFS food safety index

Food safety risk indicators were developed to evaluate the food safety levels of single UA initiatives. The step-by-step procedure for their development was the following: a) indicators were defined as a measurement of risk, b) each indicator represented a defined risk factor connected to all possible UA production systems, c) each indicator had a different weight (or a different score range) reflecting the risk likelihood of the hazards represented, and d) each indicator fit a specific risk class (biological, chemical, and management).

The food safety index (FSI) of a specific UA initiative is calculated as the weighted average or algebraic sum of all its indicator scores. If an inventory of all UA initiatives within a CRFS is available, then a global FSI can also be calculated through a weighted average of the singular FSI (in this case, the weight is represented by the production volume of each initiative).

3. Results

3.1. Most common hazards connected to UA food production in scientific literature

Overall, the risk assessments consisted of biological or chemical direct analyses of hazards within fresh produce from UA production systems, small local processing plants and/or local retailers. A synopsis of the number of assessments obtained per hazard category per period is shown in Table 2. For additional details, Fig. 2 displays the number of papers per hazard category per year (2011–2020).

3.1.1. Foodborne pathogens and microorganisms

As shown in Table 2, approximately 50% of the risk assessments contained in the selected papers addressed human pathogens. Such biological assessments were mostly from a) urban or peri-urban farms irrigated with greywater, b) hydroponic or aquaponic farms, and c) processing and sanitizing treatments of fresh produce. Human pathogens, such as *Escherichia coli*, *Salmonella enterica*, *Listeria monocytogenes*, *Staphylococcus aureus,* and *Campylobacter* serovars, are ubiquitous in the environment, commonly associated with faecal matter, and capable of

Table 2
Number of hazard assessments by category and period.

Hazard category assessed	N° of assessments			
	Period			Total
	<2001	2001–2010	2011–2020	
Foodborne pathogens and microorganisms	39	39	123	201
PTEs and heavy metals	13	20	51	84
Pesticides residues	5	9	13	27
Nitrate and nitrite	7	4	27	38
Microfauna and pluricellular parasites	4	13	0	17
POPs	5	3	9	17
Xenobiotics (organic compounds) and pharmaceuticals	1	1	10	12
Toxins	1	0	1	2
Hazardous materials	0	0	1	1

PTEs: potentially toxic elements; PPP: plant protection products; POPs: persistent organic pollutants.

causing foodborne diseases (Newell et al., 2010; Nyachuba, 2010). These microorganisms can be found in the growing media of plants (soil, solid substrates, nutrient solutions, etc.), especially when biological wastes are used as a nutrient source (Bernstein et al., 2008; Rababah & Ashbolt, 2000). Pathogens may come in contact with edible parts of crops and even be internalized in vegetable organisms (Golberg et al., 2011; Riggio et al., 2019). The most frequently assessed bacterial pathogens were the Shiga toxin-producing *E. coli* (STEC) (Deering et al., 2012; Koseki et al., 2011; Lopez-Galvez et al., 2014; Moriarty et al., 2019; Settanni et al., 2013), *S. enterica* (Castro-Ibáñez et al., 2015; Nousiainen et al., 2016; Phungamngoen & Rittisak, 2020), and *L. monocytogenes* (Sant'Ana et al., 2014; Y. J.; Wang et al., 2020). Irrigation water treatments (Dandie et al., 2019), postharvest sanitation, and GMP are considered crucial in reducing such biological risks (Olaimat & Holley, 2012; Trinetta et al., 2012).

Antimicrobial resistant strains of such pathogens were also of concern (Aarestrup et al., 2008), especially in environments where continuous exposure to antimicrobials could induce resistance in microbiota (Checcucci et al., 2020; García et al., 2020; Xi et al., 2015). Among protozoa, the addressed pathogens were mainly *Cryptosporidium* (Eregno et al., 2017) and *Giardia* (Srikanth & Naik, 2004).

Many research papers have addressed human viruses as well, mostly norovirus (Carducci et al., 2015; DiCaprio et al., 2012; Wang & Kniel, 2016). In fact, even though viruses are generally inactivated outside of a host, infecting doses can survive in the environment in multiple ways until reaching a new host (van Boxstael et al., 2013).

3.1.2. *Potentially toxic elements*

Approximately 49% of the reviewed papers and 21% of the total assessments addressed heavy metal and PTE traces in UA production (Table 2). Plants can accumulate hazardous doses of PTEs from contaminated growing media due to their capacity to uptake nutrients (e.g., cobalt, molybdenum, and copper) and translocate them into plant tissues. This scenario is also the case for elements relatively abundant in urban environments such as lead, cadmium, and zinc, as well as less abundant arsenic and mercury (Antisari et al., 2015; Joimel et al., 2020; Khan et al., 2008; Pennisi et al., 2016, 2017). In addition to the uptake from soil or growing substrates, plants grown in urban environments and exposed to open air may be contaminated by dry (particulate) and wet (smog) deposition of metal-containing particles that originate from traffic and heating pollution (Ercilla-Montserrat et al., 2018; Mu et al., 2017).

3.1.3. *Pesticides residues*

Less than 11% of the examined literature (7% of the assessments, Table 2) addressed residues of plant protection products (PPPs) or pesticides in UA. Most intensive horticulture areas or peri-urban farms have been studied (Polder et al., 2016; Zhang et al., 2013). Soilless cultures were also addressed (Savvas & Gruda, 2018) but were mainly used for modelling studies and did not reflect real case risks (Ni et al., 2018; Yang et al., 2019).

Active substances of PPP (mainly insecticides, herbicides, and fungicides) may persist on edible parts of plants for several days after treatment. In urban environments, pesticide treatments are also performed for non-agricultural purposes, such as mosquito or roadside herbicidal treatments (Md Meftaul et al., 2020). Normally, permitted treatments have precautionary limitations, such as a minimum latency period before harvest or a minimum distance from roadsides and residential buildings. Hence, the presence of pesticide residues in food would most commonly be caused by a) disregard for precautionary limitations, b) misuse of authorized active substances, and c) use of unauthorized substances. Unfortunately, detailed assessments on the use of pesticides in allotment gardens were missing, yet it can be assumed that risk is present (Atkinson et al., 1979; Voigt et al., 2015).

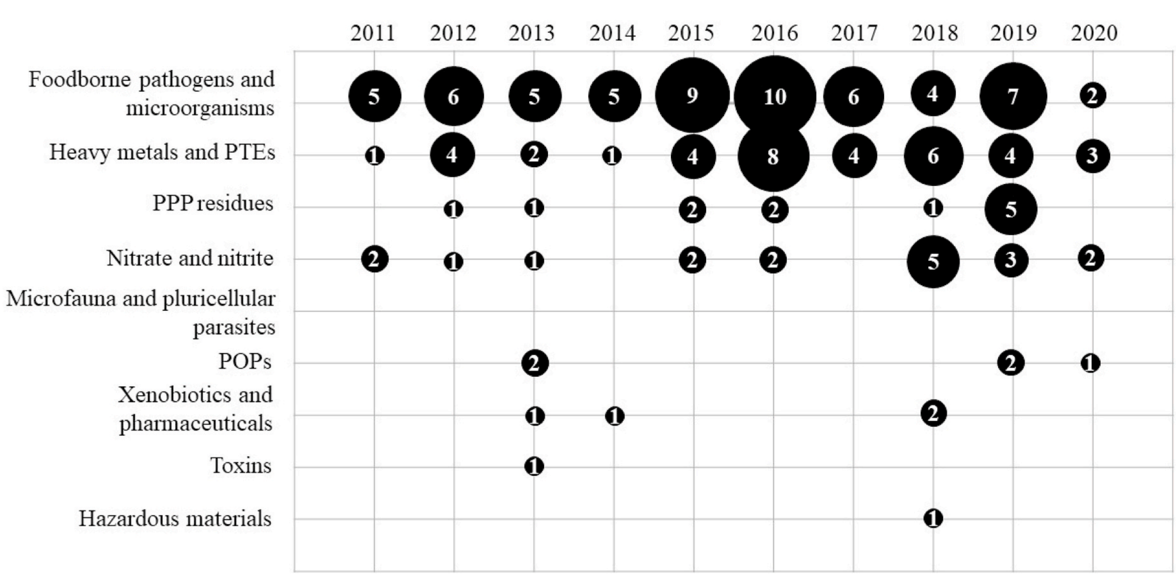

Fig. 2. Number of papers per hazard category per year (2011–2020).

3.1.4. Nitrate and nitrite

Even if nitrate does not have high acute toxicity *per se*, it may be implicated in human methemoglobinemia disease (Hegesh & Shiloah, 1982; Langlois & Calabrese, 1992; Manassaram et al., 2010). Most importantly, nitrate metabolites and reaction products from human digestion (e.g., nitrite, *N*-nitroso compounds, and nitrosamines) have high toxicity levels and have been connected to gastrointestinal cancer, as stated by the European Food Safety Authority (EFSA) in 2017 (Mortensen et al., 2017). Nitrate and nitrite are naturally present in plants, where nitric nitrogen can be stored as a salt in cell vacuoles when it exceeds plant requirements. Nitrite is formed by the reduction of nitrate as a first step of nitrogen assimilation processes.

Some leafy vegetables have the tendency to accumulate high concentrations of nitrate in edible tissues (leaves especially). Approximately 13% of reviewed papers (9.5% of the assessments, Table 2) addressed nitrate excess in UA-produced vegetables as a food safety risk. Nevertheless, in most cases, the general purpose of the assessment was related to plant nutrition optimization rather than to proper safety risk determination. Vegetables such as spinach, kale, and chard (Bosnir et al., 2017) may contain up to hundreds or even thousands of mg of nitric nitrogen per kg of plant tissue. Rocket is one of the most nitrate-accumulating leafy vegetables, often containing several thousands of mg kg^{-1} tissue (Cavaiuolo & Ferrante, 2014). In traditional agriculture and non-protected environments, the seasonality of nitrate content in many vegetables is strong, as the content of nitrate in autumn harvests is significantly higher than that in other periods (Bosnir et al., 2017). In protected environments, the risk could be even higher, as nitrate levels frequently exceed plant requirements in nutrient solutions. This is especially the case for hydroponics (Guadagnin et al., 2005) and aquaponics (Pérez-Urrestarazu et al., 2019). As a result, leafy vegetables from any cultivation typology may contain nitrate concentrations higher than those recommended by the European Commission in 2011 (600–2000 mg kg^{-1} of product, EU Commission Regulation No 1258/2011). For the sake of clarity, it should be considered that nitrate intake includes multiple dietary and non-dietary sources other than vegetables, such as food additives, processed meat (Honikel, 2008) and drinking water (van den Brand et al., 2020).

3.1.5. Microfauna and pluricellular parasites

For the remaining sections, as the number of papers decreases, the difference between the % of total papers and the % of total assessments loses meaning, and only the second will be provided. As reported in Table 2, approximately 4% of the assessments addressed pluricellular parasites. Most of these studies focused on the effect of untreated wastewater utilization in extensive UA in the global south (Amoah et al., 2005) but not exclusively (Forslund et al., 2010). Ova of pluricellular worms such as *Taenia, Fasciola* and *Ascaris* are common in faeces, cattle sludge, and urban wastewater (Newell et al., 2010). Untreated water and compost can harbour active ova, and if used in UA, this water and compost may result in vegetable contamination, hence causing parasitosis to consumers, as is commonly reported (Al-Megrin, 2010; Matini et al., 2016).

3.1.6. Persistent organic pollutants

Approximately 4% of the assessments focused on POPs (Table 2). These are particularly hazardous and recalcitrant chemicals listed by the World Health Organization for special surveillance. Many POPs were originally used as pesticides prior to their prohibition, as was the case for aldrin, dieldrin, chlordane, DDT, etc. Other POPs are polychlorinated biphenyls (PCBs) and dioxin-like compounds such as polychlorinated dibenzodioxins or polychlorinated dibenzofurans (PCDDs and PCDFs, respectively), both by-products of waste combustion under certain conditions. While PCB use and production are currently banned, dioxin-like compounds are still generated from unauthorized waste combustion. The latter spread through contaminated particulate matter suspended in air and then are deposited on land. Heavily contaminated sites are generally under surveillance by local authorities. Few papers have addressed these contaminants in UA initiatives, mostly in contaminated urban and peri-urban sites or experimental set-ups (Tozzi et al., 2020; Urban et al., 2014; Wu et al., 2012).

3.1.7. Organic xenobiotics and pharmaceuticals

Approximately 3% of the assessments addressed other potentially hazardous organic xenobiotics and active principles (Table 2), which were not PPPs. The most notable examples were assessments of multiple xenobiotics in vegetables irrigated with reclaimed water (Dodgen et al., 2013; Margenat et al., 2018). Moreover, Mathews et al. (2014) assessed plant uptake of two antimicrobials under hydroponic conditions.

3.1.8. Toxins

The presence of toxins such as patulin, cyanotoxin, ochratoxin and aflatoxin is generally associated with their respective microbial contamination, as well as processing and/or storage mismanagement. Only 2 assessments (Table 2) addressed this risk in UA: Hao et al. (1999) assessed the presence of botulin in packaged vegetables, while Hariprasad et al. (2013) investigated the presence of aflatoxin in green leafy vegetables. Additionally, Lee and colleagues studied the internalization of cyanobacteria and the presence of cyanotoxin in lettuce through simulated scenarios of contaminated water irrigation (Lee et al., 2021).

3.1.9. Hazardous materials

Theoretically, certain materials may cause adverse health effects to consumers and operators when coming into contact with food or food production. This scenario occurs for hazardous materials such as asbestos, engineered nanoparticles and plastic micro or nanoparticles. No studies involving the presence or risk of asbestos in the context of UA were found. The only paper dealing with hazardous materials (a single assessment, as reported in Table 2) was from Ma et al. who reviewed the assimilation risks of nanoparticles, as well as the environmental effects on soil and plants in several studies (Ma et al., 2018). Asbestos and nanoparticle risks, however, are not inherently connected to UA practices, and their presence may be situational yet not negligible. Similarly, apart from the results of the present literature analysis, it may be necessary to mention another potential emerging risk to consider: the ubiquity of micro- and nanoplastics capable of contaminating the trophic chain in various ways, such as biomagnification, packaging contamination and internalization in crops (Rai et al., 2021; Senathirajah et al., 2021; Wang et al., 2019).

3.2. UA production systems and technologies as food safety risk factors

As reported by various authors (Eigenbrod & Gruda, 2015; Lovell, 2010; Mok et al., 2014), UA initiatives in developed countries are greatly varied and diverse in scope, structure, and production means. Neighbourhood and community gardens, allotment gardens, peri-urban farms, aquaponics, PFALs and experimental plants can all be included among UA initiatives (O'Sullivan et al., 2019). For this reason, a clear definition of UA typologies would be of great importance for UA initiative assessments. In the scope of this work, the use of different UA technologies involved different grades of food safety risk. According to the findings of our literature review, the most critical environmental aspects for the categorization of UA production systems were a) the use of natural soil rather than artificial media, b) exposure to pests, air pollution and/or atmospheric fallout, and c) the use of waste or by-products harbouring biological and/or chemical risks. The first two criteria were consistent with those proposed in Goldstein's taxonomy (Goldstein et al., 2016). Goldstein and co-authors proposed a UA classification based on four different types defined by two functional and technological criteria: a) integration with other buildings (ground-based *vs* building integrated) and 2) condition of the space (conditioned or nonconditioned). As stated before, soil-exposed UA farms may be seen as ground-based UA types, while open-air initiatives are the equivalent of non-conditioned types.

Unfortunately, such specific cataloguing could not be systematically adopted in this study because of the heterogeneity and/or lack of information regarding the UA systems described in the selected papers. In addition, the use of wastes as growing media is not covered in Goldstein's taxonomy, according to which all four types have potential for liquid and solid waste assimilation. However, the use of risk-harbouring wastes is crucial for food safety assessments of UA. Since the authors consider Goldstein's taxonomy valuable, despite some limitations to the scope of the present work, in this paper the term "types" will refer to this taxonomy and used when possible; in addition, "productive system" or "system" will be used as a general term. In Table 3, the number of research papers per production system or context per hazard category and per time period are presented. In the following sections, the main food safety risks connected with specific aspects of UA production systems are presented.

3.2.1. Soil exposure: soil-based vs soilless systems

The most notable examples of soil-based UA systems or ground-based types (Goldstein et al., 2016) are allotment gardens, traditional peri-urban farms, community greens and urban orchards. They are generally found in city suburbs or peri-urban areas. Topsoil, in addition to possible irrigation techniques, is used to produce fresh vegetables and, less frequently, fruits. Small animal production (hens, rabbits, turkeys, honeybees, etc.) or fishing ponds may be present too. Soil-related pests are inevitable (such as moles, snails, nematodes and soil-borne plant pathogens), paving the way for possible utilization of PPPs (Zhang et al., 2013). Operators of these UA initiatives are gardening enthusiasts and amateurs (Teuber et al., 2019), workers enlisted through social programmes (Horst et al., 2017), and professional farmers. Many of these operators may not be specialized workers and have not received specific training, especially in allotments and community greens where the production is not meant for the market but for self-consumption.

Apart from their common traits, these UA initiative environments may be protected or unprotected (conditioned or nonconditioned ground-based types, according to Goldstein et al., 2016) and may receive solid and liquid waste (especially where freshwater is scarce). Their technological intensiveness may vary. For soil-based systems, the main risks are represented by the plant uptake of PTEs (Antisari et al., 2015; Bidar et al., 2020; Pennisi et al., 2016). As well documented in the literature, urban and peri-urban soil can be contaminated with several hazardous chemicals due to human activities (Yuan et al., 2021; Zheng et al., 2014). A full preliminary soil characterization would be advisable in soil-exposed UA, especially in areas where historical records of land use are not available from local authorities.

Soilless systems, on the other hand, are the norm for vertical farms and terrace gardens (which use inert substrates such as peat or perlite), hydroponics (which use a liquid nutrient solution), aeroponics (which use a vaporised nutrient solution) and PFALs in general. Most soilless UA systems are also enclosed in protected environments (conditioned types), but this is not always the case. As their technological level is generally higher with respect to soil-exposed systems, the control over production factors is higher, and their operators tend to be more specialized or better trained, resulting in reduced risks.

The chemical risks connected to the use of contaminated soil are negligible in soilless systems, provided that the artificial medium is controlled or comes from controlled sources (e.g., commercial peat). On the other hand, the risk for excessive nitrate uptake is higher in these systems with respect to uptake from soil-based ones, as reported in Table 3. In the papers reviewed, most nitrate assessments were conducted in soilless systems or aquaponics (Nozzi et al., 2018; Pérez-Urrestarazu et al., 2019).

3.2.2. Air exposure: unprotected vs protected environments

The addition of a physical shelter around crops allows for the modification of the growing environment, offering the advantage of enhancing crop productivity. Moreover, the presence of a physical barrier also has relevant implications for food safety. From the viewpoint of food risk assessment, there is a substantial difference between air-exposed, unprotected UA systems and protected environments (nonconditioned and conditioned types, respectively, according to Goldstein and colleagues).

Table 3

Number of research papers per different hazard category and time period, categorized by five UA production contexts and local market assessments.

Hazard category assessed	Period	Soil-based urban and peri-urban greens	Soilless UA systems	Aquaponic plants	Waste assimilating and experimental UA plants	Processing and food industry	Local market survey
Foodborne pathogens and microorganisms	<2001	4	1	0	5	18	3
	2001–2010	5	7	0	5	3	0
	2011–2020	2	29	6	7	24	1
Heavy metals and PTEs	<2001	11	5	1	2	0	5
	2001–2010	14	6	3	3	1	0
	2011–2020	23	9	2	7	2	0
PPP residues	<2001	3	2	0	0	0	0
	2001–2010	2	3	0	0	1	0
	2011–2020	3	5	0	0	2	2
Nitrate and nitrite	<2001	1	3	0	0	1	1
	2001–2010	1	3	0	1	0	0
	2011–2020	1	9	5	0	1	1
Microfauna and pluricellular parasites	<2001	1	0	0	1	1	0
	2001–2010	3	1	0	4	0	0
	2011–2020	0	0	0	0	0	0
POPs	<2001	3	1	0	0	0	0
	2001–2010	2	0	0	0	0	0
	2011–2020	2	2	0	1	0	0
Xenobiotics and pharmaceuticals	<2001	0	0	0	1	0	0
	2001–2010	0	0	0	0	0	0
	2011–2020	2	1	0	1	0	0
Toxins	<2001	0	0	0	0	1	0
	2001–2010	0	0	0	0	0	0
	2011–2020	1	0	0	0	0	0
Hazardous materials	<2001	0	0	0	0	0	0
	2001–2010	0	0	0	0	0	0
	2011–2020	0	0	0	1	0	0

PTEs: Potentially toxic elements: PPP: plant protection products; PoPs: persistent organic pollutants.

Rooftop and terrace gardens, allotment gardens and open-air sky farms are a few examples of unprotected UA systems (Germer et al., 2011; Orsini et al., 2014; Orsini et al., 2020). These systems may be part of municipal beautification or revaluation projects, as they can also improve the appearance of a neighbourhood (similar to rooftop terraces and gardens). Vegetables exposed to urban air can be contaminated by hazardous compounds through precipitation, wet deposition (fog and smog) and dry deposition (particulate matter). PTEs such as lead, cadmium, copper, zinc, and mercury (Amato-Lourenço et al., 2016; von Hoffen & Säumel, 2014; Säumel et al., 2012) and even more hazardous POPs in particularly contaminated areas (Amodio et al., 2009; Polder et al., 2016) can end up in edible parts of vegetables. Moreover, pests such as insects, volatiles and rodents can more easily endanger crops, incentivizing the use of PPPs.

In contrast, protected environment systems (conditioned types) are typically confined inside buildings, greenhouses, or opaque structures (Gould & Caplow, 2012). They can have different degrees of environmental control, starting from ground-based greenhouses to more advanced soilless PFALs with automated climate, irrigation, and nutrient controls (Gómez et al., 2019; Orsini et al., 2020). Thus, these systems are insulated from the urban environment to a certain degree and rarely experience the aforementioned risks. Other risks, as well as risks due to growing control failures or mismanagement, can still be present if not properly addressed with GAP (Ferentinos & Albright, 2003).

3.2.3. Waste assimilation: aquaponics and other experimental systems

The use of by-products and wastes (especially human or animal *excreta*) has always played a crucial role in agriculture, and this is also the case for UA. In fact, UA has great potential for the *in situ* assimilation of solid and liquid wastes, transforming them into nutrient-rich substrates through the action of microbiota and plant enzymes (Kawamura-Aoyama et al., 2014). This scenario is clearly the case for water-scarce countries in the global south, in which the use of greywater for crop fertigation in extensive peri-urban farms is crucial for water management and savings (Abubakari et al., 2011; Asafu-Adjaye, 2012; Keraita et al., 2007a; Menyuka et al., 2020). Modern UA techniques combine food production with waste transformation, such as aquaponics (Enduta et al., 2011; Magwaza et al., 2020; Rufí-Salís et al., 2020; Yep & Zheng, 2019).

Aquaponics and similar waste-assimilating UA systems exploit the joint ability of plants and microbiota to remove or degrade nutrients from growing media (Su et al., 2020). In the case of aquaponics, wastewater from an aquaculture system is used as a nutrient solution for plants. After nutrient abatement and other additional treatments, specifically, in the case of recirculating aquaponic systems (RAS), the water is generally recirculated into fish tanks multiple times, closing the cycle.

Waste material from faecal matter can harbour helminths and human pathogens (bacteria, viruses, and protozoa), potentially causing foodborne diseases and adverse health effects (Bartelme et al., 2019; Jeong et al., 2016). Moreover, human or animal excrement can contain several persistent pharmaceuticals if excreted unaltered from target organisms (Herklotz et al., 2010; Kinney et al., 2006). Several antibiotics commonly used in human therapy or animal husbandry have been shown to select antimicrobial resistant strains of bacteria in the environment (Finley et al., 2013; Manaia, 2017; Martinez, 2009), resulting in dangerous sanitary risks for UA operators and consumers, especially in recirculating systems (Li et al., 2019). Depending on the source of the waste administered in a UA system, many other contaminants could be present, such as PTEs or POPs (Chaney et al., 1996; Khan et al., 2008; Tremlová et al., 2013). Finally, excess nutrients should also be considered, as many leafy vegetables have the tendency to accumulate high concentrations of nitrate in edible parts (Hu et al., 2015; Nozzi et al., 2018).

Apart from compliance with pertinent regulatory systems (Joly et al., 2015), UA production systems using potentially hazardous inputs (e.g., aquaculture effluents, wastewater treatment plant sludge, contaminated soil, and by-products from the food industry) should continuously determine the potential health risks of their produce through food safety analyses and the adoption of advanced quality control systems. Water and nutrient solution quality parameters should continuously be monitored (e.g., implementing sensors for water quality parameters). The presence of pathogens or hazardous chemicals (contaminants and/or pharmaceuticals) should frequently be assessed and possibly reduced, implementing adequate techniques (e.g., stabilization of immature compost, water ozonation or UV treatment). Final products should be analysed as well.

3.2.4. Good practices and management of risk in UA initiatives

Compliance with GMP and GAP, considering the specifics of UA production systems through preliminary risk assessments, should guarantee that fresh produce in UA meets adequate quality and safety levels up to harvest. Presumably, respect for good practices and quality management systems would also ensure higher food quality levels in subsequent processes (harvest, sanitation, packaging, distribution, etc.) as is the case for traditional agricultural products. Food safety management practices, such as hazard analysis and critical control points (HACCP) (Wallace, 2014, pp. 226–239) in addition to related management standards such as the UNI EN ISO 22000 family (International Organization for Standardization [ISO], 2018)), remain valid for UA initiatives and businesses.

3.3. Focus on food safety: integration with CRFS assessment indicators

The official indicator framework proposed by the FAO, RUAF and Wilfrid Laurier University for the CRFS assessment and evaluation is a powerful tool for policymakers (Blay-Palmer et al., 2018; Carey & Dubbeling, 2017). Its holistic approach is useful for a first assessment of CRFS functionality and its adherence to given multilevel policy goals (e.g., environmental, social or economic sustainability). Here, the different food system components (namely, production, processing, distribution, retail, and consumption) were evaluated through six different sustainability macro-targets, consisting of different sets of indicators. These indicators were calculated using data collected through research (typically surveys) or existing databases. The 210 indicators proposed by the FAO, RUAF and Wilfrid Laurier University are clearly meant for evaluating multiple aspects of a local food system as a whole and generally address aggregated data. Food safety is not an objective *per se*, but it is an *impact area* among the macro-policy target "*Social sustainability and equity (improve of health and well-being)*". Thus, FAO/RUAF food safety indicators are limited, do not take into account single initiatives or businesses, and tend to have general character, such as *Presence of food safety legislation* […] or *Number of food safety incidents* […] (FAO, RUAF, and Wilfrid Laurier University 2018b, p 26).

Nevertheless, the official CRFS assessment would not be incompatible *per se* with more detailed investigations, such as business inventories or catalogues. A CRFS assessment could include a detailed assessment (relevant to research, policy or management) of the food safety performances of selected UA initiatives and businesses. Such detailed analysis or monitoring could be implemented based on the most pertinent risk assessment and rely on food analyses. Thus, in this section, an operational framework was proposed for the development of a safety assessment of UA initiatives compatible with the official CRFS framework and based on relevant research on hazards connected to UA.

Through the subsequent proposed framework, it is possible to evaluate the food safety risk of a specific UA initiative. Additionally, if an inventory of all UA initiatives is available and evaluations for all initiatives are performed, then this framework allows an estimation of the overall food safety level of the whole CRFS and, in addition to the ordinary CRFS assessment, paves the way for further analyses based on non-aggregated data.

3.3.1. Food safety indicators

In Table 4, fifteen detailed indicators for a food safety assessment of UA initiatives are proposed. These were divided into three risk groups: biological, chemical, and management risk. Consistent with the results on hazard frequency described in section 3.1., each indicator has a score range representing its weight. Biological risk indicators accounted for approximately 33% of the risk, while chemical risk and management risk indicators accounted for approximately 55% and 12% of the risk, respectively. These three values were obtained as a sum of score ranges from indicators of the same group divided by the total score range. The higher weight of chemical risk was simply due to the presence of many different hazards in the chemical risk category. Each indicator is calculated based on one or more questions posed to UA initiative directors and should be validated through data, documentation, analyses, and other possible valid information, as suggested in Table 4. The scoring of each indicator was designed to intuitively suggest being negative for high-risk circumstances. A benchmark indicator score value for specific classes of UA initiatives could possibly be established after adequate testing and data collection in further works.

3.3.2. Food safety index

A numerical score for each indicator is calculated following established guidelines such as those proposed in Table 4. Then, a safety index can be calculated as a sum of each indicator score by the following formula:

$$FSI_i = \sum_{j=1}^{M} I_{i,j} \tag{2}$$

where:

- i is a given UA initiative.
- j is the indicator.
- FSI_i is the safety index of initiative i.
- M is the number of indicators (15).
- $I_{i,j}$ is the score of indicator j for UA initiative i.

The FSI score, using the proposed indicators, spans from +130 to −115. The maximum value represents the highest food safety level or a very good risk management.

3.3.3. UA initiatives inventory and evaluation of CRFS global FSI for UA

In contrast to the CRFS framework approach, the proposed methodology aims to calculate (at least for all UA initiatives) a general food safety macro-indicator starting from a food safety evaluation and assessment of single initiatives (bottom-up approach). To implement this approach, it is necessary to build an inventory of UA food-producing initiatives in the CRFS, gathering data available in the territory. Some criteria needed for the inventory are suggested below.

The inventory should include any active initiative from allotment gardens to experimental vertical farms in a yearly timeframe. Thus, contiguous allotment gardens should be considered as a single UA initiative. For each initiative, data need to be gathered concerning a) identification, b) production types based on identifiable and well-recognized taxonomy systems for UA initiatives (Goldstein et al., 2016), c) production volumes (e.g., estimated gross production and value), d) destination of products (e.g., market segments or other destinations), and e) conductor, manager, or other representative of the initiative.

Since the food safety assessment for UA initiatives suggested in this review is meant for plant-producing initiatives, only these initiatives should be included. Animal urban farms, food processors, food distributors and hospitality/catering initiatives (HORECA) should be treated separately (optimally, with different dedicated indicators for their assessment). Ideally, each initiative in the inventory should be examined, but in case this is not feasible, a representative sample may be

Table 4
Synoptic table of possible indicators for food business safety assessment.

Risk area	Indicator (minimum and maximum score value)		Data source	Survey question examples (indicator score variation)
Biological risk **Chemical risk**	1	Implementation of biological control (−15; +35)	Business survey, periodic safety controls and analyses (pathogen analyses on final produce)	Are pathogens and other biological analyses performed on final products? Which one? (multiple selection, +3 per selection, up to +15, −5 if no options are selected) If so, how frequently? (from 0 to +10) How many non-compliances are found (by you or by external entities) per volume of production? (from +10 to −10)
	2	[Unlikelihood of] food exposed to uncontrolled fauna (e.g., rodents, pigeons) and/or zoonosis (−5; +5)	Business survey, periodic safety controls (traps)	Is the presence of pests and/or undesired animals controlled? (+5 if affirmative) How frequently pests and/or undesired animals are found in the growing environment? (from 0 to −5)
	3	[Unlikelihood of] food exposed, even occasionally, to growing media harbouring biological risk (−5; +5)	Business survey, periodic safety controls and analyses (raw material and supplies quality control)	Is any waste used in the production of biological origin, even occasionally? (−5 if affirmative) Is this material biologically controlled from an external provider or within your company? (from 0 to +5)
	4	[Unlikelihood of] food biologically altered during processing (spoilage or poor sanitization/ preservation) (−5; +5)	Client/ customer survey, periodic quality control (shelf life)	How are the products sanitized after harvest? (from 0 to +5) Is the shelf life satisfactory? (from −5 to 0)
	5	[Unlikelihood of] food exposed to waste harbouring chemical risk (−10; +10)	Business survey, periodic safety controls and analyses (PTEs and other hazardous substances)	Is any kind of non-biological waste used in production? (−5 if affirmative) Is natural soil used in

(continued on next page)

Table 4 (*continued*)

Risk area		Indicator (minimum and maximum score value)	Data source	Survey question examples (indicator score variation)
				production? (−5 if affirmative) Is the substrate material used for growing (natural or artificial) fully characterised? (from 0 to +10)
	6	[Unlikelihood of] food exposed to particulate, smog and/or atmospheric deposition (−10; 0)	Business survey, environmental service (air quality)	Is the growing environment isolated from the external atmosphere? (−5 if negative) If that is not the case (negative answer to previous question), is quality of air satisfactory in your area, according to environmental services? (+5 if affirmative, 0 if negative, −5 if answer is "no data available") If the answer from the previous question is "no data available", how clean would you judge the air to be in your area? (from 0 to +5)
	7	[Unlikelihood of] food exposed to PPP and other pharmaceuticals (−25; +10)	Business survey, periodic safety controls and analyses (PPP)	Are any PPP used during the production cycles? (−5 if affirmative) If so, which ones are regularly used? (−2 for each active principle indicated, up to −10) How frequently are PPP residues on final products controlled? (from 0 to +10) How many non-compliances are found (by you or by external entities) per volume of production? (from 0 to −10)
	8	[Unlikelihood of] food exposed to regulated chemicals such as additives, and disinfectants, fertilizers (−10; +5)	Business survey, periodic safety controls and analyses (GMP and GAP)	Which other chemicals are used in the production environment and how likely are they to be found in final products? (from −10 to +5)
	9	[Unlikelihood of] food accumulating (e.g., by phytoextraction or biomagnification) potentially hazardous elements or nutrients (such as PTEs or nitrate) (−10; +20)	Business survey, periodic safety controls and analyses (PTEs, nitrate)	Which chemical analyses on final products are periodically performed? (+2 per PTE, maximum +10; +5 for nitrate in addition) How frequently? (from +1 to +5) How many non-compliant actions are found (by you or by external entities) per volume of production? (from 0 to −10)
	10	[Unlikelihood of] food exposed to undesired or hazardous materials and substances such as micro-plastics and asbestos. (−10; +5)	Business survey, periodic safety controls and analyses (hazardous materials)	Are these compounds likely to be found in final products? (multiple selection, from −10 to +5)
	11	[Unlikelihood of] food contaminated by toxins (−5; +5)	Business survey, periodic safety controls and analyses (toxins)	Are toxins controlled in final products? How frequent are non-compliant actions per volume of production? (from +5 to −5, 0 if not controlled)
Management risk	12	[Prevention of] food adulteration, tampering and accidents (−5; 0)	Business survey	To your knowledge, have any adulteration or tampering episodes occurred? How frequently? (from 0 to −3) How frequently does equipment malfunction? (from 0 to −2)
	13	High food safety education level of business operators (0; +5)	Business survey (operators and conductor)	How would you judge the training of your collaborators and employees? (from 0 to +3) How much do you invest in training? (from 0 to +2)
	14	Implementation of food quality system, traceability,	Business survey	Have you adopted any quality management

(*continued on next page*)

Table 4 (*continued*)

Risk area	Indicator (minimum and maximum score value)	Data source	Survey question examples (indicator score variation)
	scheduled controls, and management of non-compliance (0; +15)		program other than those prescribed by law? Which one? (from 0 to +5) Have you obtained any quality certifications? Which ones? (from 0 to +5) Have you adopted any quality policy program other than those prescribed by law? Can you describe it? (from 0 to +5)
	15 [Rareness of] safety control and non-compliance (0; +5)	Periodic safety control (if present)	Could you describe your course of action in this particular scenario? (a scenario is illustrated, in which non-compliance is found) (discursive, from 0 to +5)

defined. In this study, a global FSI is calculated as a weighted mean of all the safety indexes (in this context, the weight factor would be represented by the estimated gross annual production of each initiative).

$$GFSI_{UA} = \frac{1}{P_T}\sum_{i=1}^{N} P_i \cdot FSI_i \qquad (3)$$

where:

- $GFSI_{ua}$ is the CRFS global food safety index for UA initiatives and businesses.
- P_T is the total production (or market) volume of all the considered UA initiatives within the CRFS.
- i is a given UA initiative.
- N is the number of all UA initiatives considered.
- P_i is the production (or market) share of initiative i.
- FSI_i is calculated by formula (2).

Many different data analyses can be performed with this approach (e.g., the relationship between UA types and their FSI in a given CRFS, the identification of specific risks through the global study of a single indicator in a CRFS, and the relationship between economic performances of UA initiatives and their FSI in a given CRFS).

For example, data analysis might be performed through a scatter plot. Each initiative i could be plotted as:

$$FSI_i - \overline{FSI}; P_i - \overline{P} \qquad (4)$$

where:

- FSI_i is calculated by formula (2).
- i is a given UA initiative.
- $\overline{FSI}$ is the sample mean of the food safety indexes for the N initiatives.
- P_i is the production (or market) share of initiative i.
- $\overline{P}$ is the sample mean of production or market shares for the N initiatives.

In this context, points (initiatives) in the upper-right quadrant would represent mature businesses with better-than-average risk control practices (as shown in Fig. 3). Bottom-right quadrant points would be initiatives with better-than-average risk with potential for market expansion. Upper-left quadrant points would be larger-than-average businesses with lower-than-average risk management. Finally, bottom-left points would represent smaller-than average initiatives with lower-than-average food safety indexes.

4. Conclusions

In this work, the most relevant scientific papers addressing food safety assessments for UA techniques were reviewed to establish a framework for the evaluation of food safety in UA initiatives.

Among the 217 selected research papers, 120 addressed human pathogens either exclusively or not exclusively. These results indicated the use of excreta-derived nutrient sources (implicit, as in the case of aquaponics, or facultative, as in the case of greywater fertigation) or fresh produce sanitation failures as a source of risk. Approximately 94 papers addressed PTEs, indicating air pollution exposure or contaminated substrates as risk sources. Less frequent, but not of lesser importance, other hazards considered in UA food safety assessments were nitrate excess (28 papers, mostly in recirculating systems) and pesticide residues (23 papers). The hazards connected with the use of solid or liquid wastes were POPs (11 papers), organic xenobiotics and pharmaceuticals (5 papers) and hazardous materials (1 paper). Toxins were rarely assessed (2 papers).

Three main criteria determining the risk level of UA initiatives were identified: a) use of soil rather than inert substrate/media, b) exposition of crops to atmospheric deposition, and 3) use of solid or liquid wastes in the growing cycle.

Therefore, an operational framework for a qualitative-quantitative assessment of food safety levels in UA initiatives was developed. The proposed approach is based on the CRFS assessment indicator framework and is meant to contribute to or benefit from it. The methodology integrates the use of business surveys and food analyses (where available) to evaluate food safety risks through specific indicators. A food safety index can then be calculated for each initiative by averaging the indicator scores. Moreover, a global UA food safety index may be derived within the CRFS by weighing each UA initiative index according

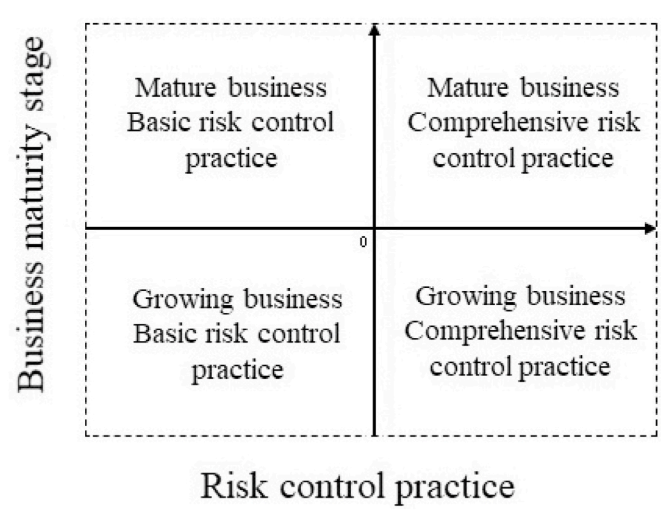

Fig. 3. Reference scatter plot for analysis between FSI and business maturity.

to their production share. Apart from data handling and simplicity of implementation, another advantage lies in the possibility of comparing risks among very different kinds of UA initiatives. Instead, some limits are due to the falsifiability of survey answers (which could be corrected by validating the answers with biological or chemical analyses); in addition, some limits occur because the definition of UA is not strict (sometimes even arbitrary), and thus. what is considered UA may vary in different CRFSs. This proposed framework supports decision-making and enables stakeholders from an initiative to the policy-making level to improve food safety control in a UA. This framework thereby contributes to protecting and improving the health and well-being of future consumers in a CRFS. A rigorous and homogeneous scoring system for each food safety indicator must still be implemented and validated in further and applied studies to fully utilize the potential of this framework, enabling it to benefit the public sector, policy makers and academia.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foodcont.2021.108085.

Author contribution statement

E. Buscaroli: conceptualization, investigation, data curation, writing – original draft, writing – review & editing, supervision.

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F. Orsini: conceptualization, writing – review & editing, supervision, project administration, funding acquisition.

Declaration of competing interest statement

Authors declare no conflicts of interest.

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