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Research Paper

Generic Food Safety Assessment: A Framework to Evaluate Food Safety Hazards Emerging from Change(s) in the Primary Production System – A Case Study Involving Intercropping

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ABSTRACT

Food safety is a shared responsibility of all actors along the food supply chain. Changes in the primary production system can affect food safety hazards along the supply chain. This highlights the need for a framework that enables primary producers (i.e., farmers) to assess the potential food safety hazards and, if needed, to apply control measures. This paper presents a generic food safety assessment (GFSA) framework that has been developed based on Hazard Analysis and Critical Control Point (HACCP). The proposed framework was applied to a case study, i.e., the transition from sole cropping of oats to intercropping of oats with lupins. The application of the GFSA framework enabled the evaluation of potential changes in food safety hazards from this transition and the establishment of appropriate control measures. In addition, GFSA users can employ the results to support decision-making process. Our case study showed that implementing GFSA can be challenging for smallholder or individual farmers and may need coordinated action. Finally, effective and transparent communication is critical for managing food safety along the food supply chain, including when changes are implemented in primary production.

Current food production systems are challenged by climate change and biodiversity loss; both hamper access of many populations to safe and nutritious food (FAO, 2021; Muluneh, 2021). A transition towards a more sustainable food production system is therefore urgently needed to feed the world's growing population (FAO, 2021). The European Union (EU) through its European Green Deal has laid down Farm to Fork strategy, a set of policy initiatives to achieve a healthy and sustainable food production system (European Commission, 2023). Both the EU Farm to Fork strategy and the General Food Law (Regulation (EC) No 178/2002) require the responsibility of every stakeholder along the food supply chain to guarantee that food is safe for consumption (European Commission, 2002). Therefore, it is necessary to assess the impacts on food safety when introducing a change at any point of the supply chain.

Certain food safety hazards may either be introduced, increased, decreased, or eliminated due to new or altered conditions during production. For example, the transition from conventional to organic farming may lower the concentration of pesticide residues; on the other hand, it may increase the risk of microbiological contamination from the use of animal manure (Ferelli & Micallef, 2019; Garcia & Teixeira, 2017). Although postharvest treatments and further food processing may decrease or eliminate these hazards, it is also important that farmers are aware of their obligation to ensure the safety of the raw materials they produce. The abovementioned example emphasizes the importance of assessing food safety hazards prior to implementing changes in the primary production system. This type of assessment is included in the common food safety management system (FSMS) in food processing, such as Hazard Analysis and Critical Control Points (HACCP) as food processors are required to review and update their HACCP plan following changes in the production process that may affect food safety hazards (e.g., new product, ingredient or equipment) (Codex Alimentarius, 2022). Meanwhile, FSMS at primary production, such as Good Agricultural Practices (GAP) and Good Hygiene Practice (GHP), is rather static and does not incorporate such an assessment (FAO, 2016).

The EU-funded Horizon 2020 project CROPDIVA helps to achieve the EU Green Deal goals by promoting underutilized crops in various

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cropping systems to create new value chains (CROPDIVA, 2023). Included in the proposal is to design a dynamic FSMS at farm level that enables farmers to identify, evaluate, and control hazards resulting from changes in their production system. The basis of this GFSA framework is HACCP, a systematic approach used in the food industry to evaluate and control food safety hazards. The essence of this approach, namely analysis and control of hazards throughout all processing steps, can be extended to the primary production to increase the assurance of safe food production (Codex Alimentarius, 2022; Gil et al., 2015). Considering limited resources at farm level (e.g., time, manpower, knowledge), the ideal approach would be simple and straightforward, but structured and able to capture any potential hazards that may emerge, be increased, decreased, or eliminated. As primary production systems vary greatly, the framework should be generic, to be easily used and applied by farmers in various production systems.

This study aimed (1) to design a generic food safety assessment framework based on HACCP principles to evaluate food safety hazards arising from any changes at the primary production band (2) to apply the designed framework in a case study, i.e., from growing oat as a sole crop to intercropping of oats with lupins.

Methodology

Designing Generic Food Safety Assessment (GFSA) framework for primary production

The GFSA framework was developed based on HACCP, a systematic approach commonly applied by the food industry to evaluate and control food safety hazards (i.e., biological, chemical, physical hazards, and allergens) that could threaten the production of safe food (Codex Alimentarius, 2022). In essence, the HACCP approach focuses on the analysis and control of hazards throughout the entire food processing steps. Therefore, similar principles can be applied in other parts of the food supply chain, including during primary production (e.g., crop, livestock production). Based on the HACCP principles, the GFSA was designed to identify and assess potential food safety hazards due to implementing changes in the primary production and to establish control measures thereof.

Case study GFSA: From sole cropping of oats to intercropping of oats with lupins

To evaluate the feasibility of the designed framework, it was applied to one case study, i.e. from sole cropping of oats to intercropping of oats with lupins. Intercropping involves growing two or multiple crops simultaneously in the same field (Francis & Porter, 2017). Although intercropping has been traditionally practiced by smallholder farmers in many regions of the world, its application on larger scales is still underutilized (Bybee-Finley & Ryan, 2018). In recent years, intercropping is gaining global interest as a sustainable agricultural practice (Mazzafera et al., 2021). Crops selected for intercropping typically have different abilities to access available resources for their growth. Legumes are often used for their ability to fix nitrogen, which will benefit the companion and the subsequent crop, as well as the ability to grow in marginal soils (Ayilara et al., 2022; Pueyo et al., 2021).

Within the CROPDIVA project, combinations of cereal and legume crop species have been investigated, including triticale with fava bean and oats with lupins. Legume crops such as lupin and fava bean are valued for their ability to fix nitrogen and for high-quality protein content, making them prospective alternatives for animal-based proteins (Lucas et al., 2015). Moreover, these legumes can replace soybean in human and animal diets, thus lowering EU's dependency on soybean import and contributing to the transition towards sustainable agricultural production in the EU as envisioned in the EU Green Deal policy (Ferreira et al., 2021). Studies on changing systems from sole cropping to intercropping mainly focused on the impacts on productivity, quality (e.g., higher yield, efficient use of resources) and environmental impacts (e.g., increase of in-field biodiversity, suppression of weeds, pathogens and insects) (Bybee-Finley & Ryan, 2018). Since the impacts of intercropping on food safety aspects are not yet well studied, this transition was selected as the case study for GFSA application.

Results

Generic Food Safety Assessment (GFSA) framework for primary production

The GFSA developed consists of five steps as depicted in Fig. 1. The step-to-step procedure is elaborated as follows.

Step 1: Identify changes from the current to the new system. The first step in the application of the GFSA is to identify changes that will be implemented to an established production system. Some examples of changes in primary production are new farming location, cultivation of new crops/cultivar, change in plant protection products (PPPs) and fertilizers, and change in cropping system (Table 1). To apply step 1, all activities from pre- to postharvest treatment that occur at farmers' facility are described by using a process flow diagram of which an example is presented in Fig. 2. If considered relevant, changes in the flow of people and equipment should be included as well. Next, change(s) needs to be identified for each activity described in the flow diagram.

Step 2: Identify changes in potential food safety hazards. The following step aims to identify and estimate the occurrence of any potential food safety hazards resulting from the changes described in step 1, including potential hazards from changes in the flow of people and equipment. Food safety hazards are defined as any substance or material that can potentially cause adverse effects to human health. These hazards are commonly grouped into microbiological, physical, and chemical hazards. Some examples of food safety hazards are foodborne pathogens, fragments from glass, thorns or stones, plant toxins, mycotoxins, pesticide residues, and allergens (Codex Alimentarius, 2020). A recently published FAO guideline can be used as a relevant source to identify factors that may impact food safety at the farm level (FAO, 2023). Moreover, users can use sources such as CODEX standard or legislation texts to identify relevant hazards in certain products. For example, CODEX standard for contaminants and toxins in food and feed (Codex Alimentarius, 1995), Regulation (EC) 2073/2005 on microbiological criteria for foodstuffs (European Commission, 2005a, 2005b), and Regulation (EC) 2023/915 on chemical contaminants for foodstuffs (European Commission, 2023). Various factors may affect the occurrence of the hazards and depend on a particular change as shown in some examples in Table 1.

The likelihood of occurrence of each identified hazard in the new system is compared to the current system. It is assumed that farmers are aware of the potential hazards in their current production system. For example, such an analysis is usually included in GAP. This is considered as the starting point to evaluate potential hazards in the changed situation, which can be expressed qualitatively as: new, eliminated, decreased, or increased. A new hazard is a hazard that is expected to occur in the new system, but not in the current system. In contrast, an eliminated hazard is a hazard that occurs in the current system but is not expected to occur in the new system. Likewise, increased and decreased hazards are hazards that are expected to occur at higher and lower levels in the new system, respectively. New and increased hazards are considered significant hazards and prioritized to receive control measures in step 3. A proper justification should be provided for eliminated and decreased hazards that are not considered significant and thus will not be prioritized.

Step 3: Establish control measures. A control measure is any action to prevent, eliminate or reduce food safety hazards to an accept-

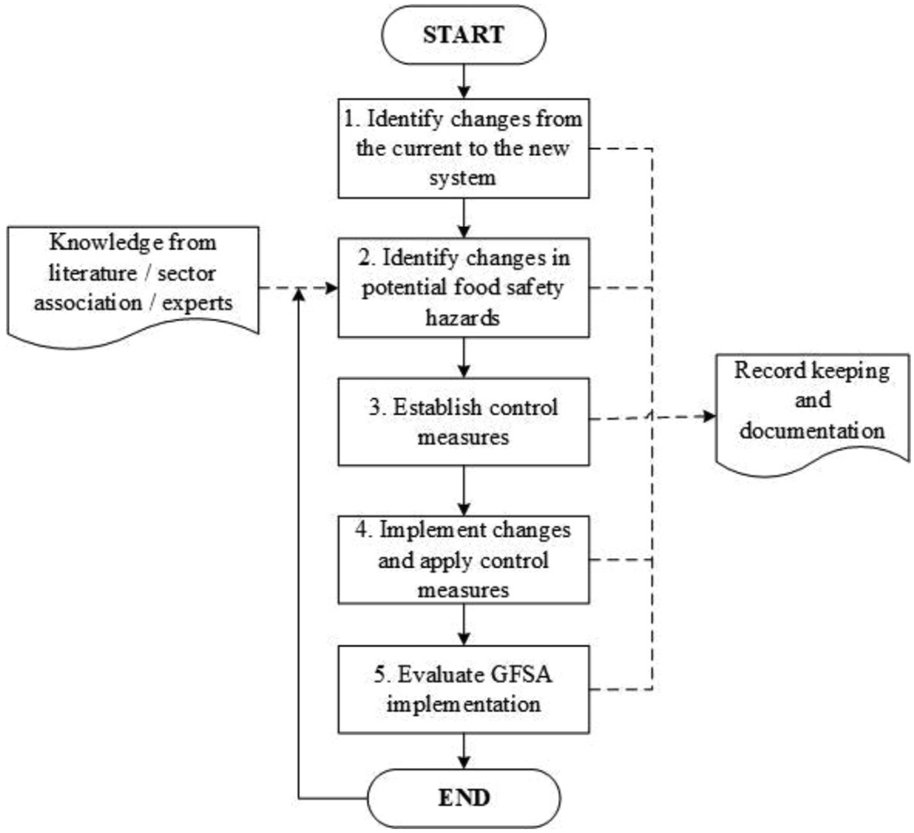

Figure 1. Flowchart of the Generic Food Safety Assessment (GFSA) framework. Solid lines indicate flow between activities, dashed lines indicate information flows.

Table 1
Examples of changes in primary production and possible consequences on food safety hazards (not an exhaustive list)

Changes	Possible hazard	Elaboration on sources/drivers of hazards	References
Farming location	Pathogens, stones, pesticide residues, heavy metals	Food safety hazards related to farming location can be associated with the historic use and geographic location of the land. For instance, prior application of pesticides and animal manure might lead to the presence of pesticide residues and pathogens in the soil, respectively. Soil type might also influence the occurrence of physical hazards like stones that can be found in the crops. The proximity to industrial areas such as wastewater facilities, mining, or waste disposal is considered as a major source of microbial and heavy metal contamination.	Alengebawy et al. (2021), FAO (2023)
Crop species/ cultivar	Mycotoxins, plant toxins, allergens	Growing new crop species or cultivars entails an evaluation on food safety hazards. For example, some crops like groundnuts and cereals are more susceptible to mycotoxin contamination. Introducing a totally new crop may eliminate or introduce intrinsic hazards, such as plant toxins (e.g., alkaloids in lupins, erucic acid in rapeseed) or allergens (e.g., gluten in wheat).	European Commission (2023)
Plant protection products (PPP)	Pesticide residues	Change in PPP needs to be assessed as each crop has different permitted PPP and corresponding maximum residue limits (MRLs). This evaluation is necessary to prevent the exceedance of residue limits and the presence of illegal substances in crops.	European Commission (2005a, 2005b)
Fertilizers	Pathogens	Animal manure may carry pathogens that can transfer to soil and environment as well as to fruit and vegetable crops. This change can pose a risk particularly for fruit and vegetables commonly consumed raw.	Black et al. (2021), Sharma and Reynnells (2016)
Cropping system	Allergen	Introducing intercropping with new crops that contain inherent allergens, may result in product impurity due to cross-contact and thus increases the food safety concern.	Kiær et al. (2022)

able level (Codex Alimentarius, 2008). Control measures are defined and applied for prioritized hazards identified in step 2, i.e., new hazards and hazards that are expected to increase. Establishing control measures also implies the effect of measures on the survival or persistence of a hazard that is to prevent or minimize it. Control measures are formulated for each specific hazard and at specific activities. Multiple measures can be necessary to control one single hazard (multihurdle approach), for example, mycotoxins control. Control measures for mycotoxin formation can vary depending on the crops and mycotoxins of concern. Extreme weather conditions have been associated with higher levels of aflatoxins in maize and in this case, control measures can include proper irrigation and selection of drought-tolerant cultivars (Guo et al., 2008; Herrera et al., 2023). Preharvest measures to control *Fusarium* head blight caused by *F. graminearum* and mycotoxin formation (e.g., deoxynivalenol and zearalenone) in wheat include the use of disease-tolerant varieties, avoiding wheat after maize in crop rotation, tillage of previous crops residues, use of biological, or chemical control (Drakopoulos et al., 2020; Torres et al., 2019). Predictive modelling may assist decision-making for farmers in mycotoxins control, for example regarding fungicide application and harvest timing (Liu et al., 2018). Favorable conditions for postharvest mycotoxin formation such as high temperature and high relative humidity should be avoided at all times (Sarmast et al., 2021). Here, control measures include proper cleaning, removal of contaminated crops and maintain-

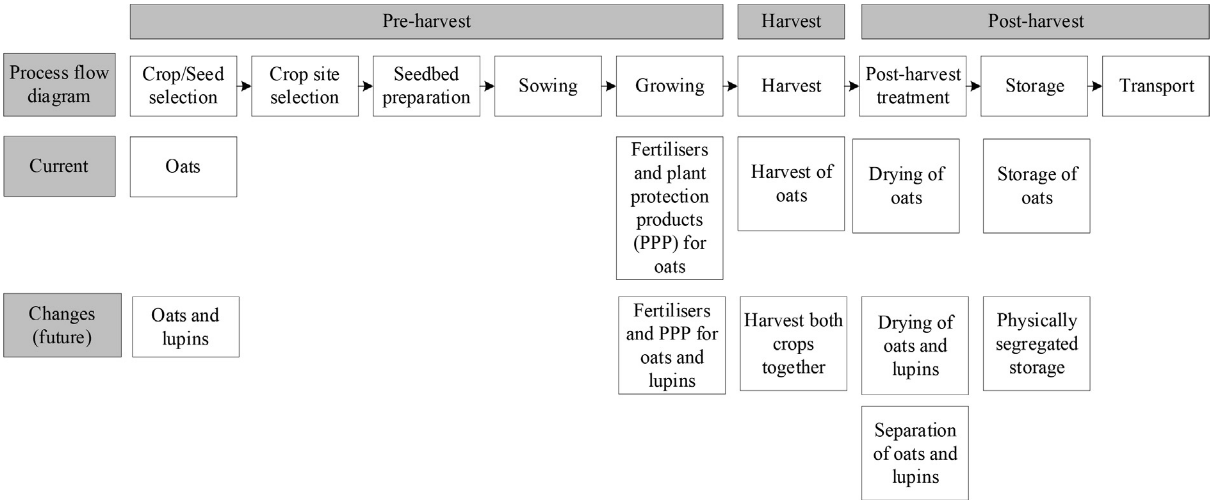

Figure 2. Process flow diagram of step 1 in the GSFA illustrating changes from sole cropping of oats to intercropping of oats with lupins.

ing a stable storage environment to inhibit fungal growth. Furthermore, multiple hazards can also be controlled by one control measure, for examples control measures in postharvest stage as shown in Table 2.

Step 4: Implement the changes and apply control measures. At this point, the GFSA user has a thorough understanding on the food safety risks that may arise from implementing certain changes and their potential control measures. When potential hazards emerge or increase due to changes, farmers must apply control measures that may require additional resources, such as time, labor, cost, or consumable inputs (e.g., fertilizer, irrigation, pesticides). Combined with other considerations, GFSA can support the decision-making process for farmers. Subsequently, when proceeding with any management changes during primary production that may introduce new or increase known food safety risks, it is vital to communicate this to all actors in the food supply chain.

Step 5: Evaluate the GFSA. After implementing the proposed changes and control measures to manage the hazards, it is important to verify that the system works effectively. It is also crucial that the entire procedure (steps 1–5) is properly documented to verify that appropriate control measures are in place to control food safety hazards continuously. Control measures should be regularly monitored. Furthermore, a corrective action plan should be established in the event of deviation (if applicable). This evaluation will serve as a starting point to facilitate improvements for the periodic evaluation (annually or after one cultivation cycle) and when introducing a change in the production system.

Case study GFSA: From sole cropping of oats to intercropping of oats with lupins

This case study assessed food safety hazards from sole cropping of oats to intercropping of oats with lupins. Steps 1–3 of the GFSA framework were followed and described in this paper. Steps 4 and 5 contain results from implementing changes in the production system and can only be explored in a follow-up study; therefore, these steps are out of scope of this study.

Step 1: Identify changes from sole cropping of oats to intercropping of oats with lupins. As shown in Fig. 2, the followings are the identified changes occurring at the pre- and postharvest stage:

Table 2
Control measures in pre- and postharvest stages of oats and lupins grown in an intercropping system

	Control measure	Hazard			
		QAs	Mycotoxins (Field)	Mycotoxins (Postharvest)	Allergens
Preharvest					
Crop/seed selection	Select low-alkaloid lupin varieties	X			
	Select oat varieties with lower susceptibility to *Fusarium* species		X		
	Use compatible lupin and oat varieties (e.g., similar maturity time)		X	X	
	Use appropriate seed proportions to prevent inter plant competition	X	X		
	Use high quality, certified seeds		X		
Growing	Prepare descriptive plans to prevent (a)biotic stress factors and incorporate them into Good Agricultural Practice (GAP)	X	X		
	Prepare descriptive plans on mycotoxin mitigation and incorporate them into GAP		X		
Postharvest					
Drying	Perform timely drying step			X	
Separation	Perform separation and cleaning	X		X	X
Storage	Ensure closed packaging and clear labelling	X		X	X
	Ensure sufficient physical separation and use clear signage	X		X	X
	Perform regular allergen testing				X
All postharvest steps	Clean and sanitize shared facilities	X		X	X
	Perform regular inspection on each postharvest step	X		X	X
	Maintain documentation and record keeping	X		X	X

the selection of the crops (oats and lupins), fertilizers, and plant protection products (PPPs), simultaneous harvest, drying step, separation of kernels, and segregated storage. The process flow diagram is presented in Fig. 2.

Step 2: Identify changes in potential food safety hazards. The effect of changes as identified in step 1 (Fig. 2) on potential food safety hazards were further evaluated in step 2 of the GFSA. Information was retrieved from expert opinions and literature. The results are summarized in Supplementary Materials Table S1. In this case study, four hazards were identified that are affected by the changes in crop production, i.e., quinolizidine alkaloids (QAs), mycotoxins, pesticide residues, and allergens. Below is the evaluation of the four potential hazards that may occur when changing from sole cropping of oats to intercropping of oats with lupins.

Lupins can be considered as a useful addition to food/feed supply particularly for their high protein content. On the other hand, lupins produce quinolizidine alkaloids (QAs) – toxic secondary metabolites acting as a defense mechanism against pest and disease (Gresta et al., 2017). QAs can cause health implications in humans when ingested in large quantities (EFSA Panel on Contaminants in the Food Chain, 2019). At present, no harmonized maximum limit (ML) on QAs in food is set in the EU, but Australia and New Zealand have established an ML of 200 mg QAs/kg lupin-derived food products (Australia New Zealand Food Authority, 2001). Some lupin species with low alkaloid contents have been selected and domesticated for food and feed production, for instance *Lupinus albus*, *L. luteus*, *L. angustifolius,* and *L. mutabilis*, as well as different varieties within the species (Gresta et al., 2017). The quantity and profile of QAs are influenced by multiple factors, i.e., genotype, biotic (e.g., insects, pathogens, weeds) and abiotic stress (e.g., salinity, flood, drought, extreme temperature) (Rodés-Bachs & Van der Fels-Klerx, 2023). While QAs are considered a specific hazard when growing lupins, growing oats and lupins together poses a risk that QAs might transfer to oats during postharvest stages, for instance, due to improper separation step, insufficient cleaning of shared equipment, and lack of physical segregation during storage. Therefore, QAs are considered new hazards for both lupins and oats grown in an intercropping system.

Studies suggest that intercropping of legumes and cereals reduces the overall fungal infection severity in the field, thus reducing the need for fungicides (Księżak et al., 2023; Zhang et al., 2019). However, if fungi infect crops and subsequently produce mycotoxins, health implication for consumers may occur. Oats are prone to contamination with T-2 and HT-2 toxins produced by *Fusarium* species, while lupins are the main host for *Diaporthe toxica*-producing phomopsins (Pitt, 2014; Tarazona et al., 2021). Data on the effects of intercropping of oats and lupins on mycotoxin contamination are still lacking. However, intercropping may lessen fungal pressure on host-specific pathogens such as *Fusarium poae*, *F. langsethiae* in oats and *Colletotrichum lupini* and *Diaporthe toxica* in lupins as there are many nonhost plants in the same field. Consequently, field-derived mycotoxin levels in oats and lupins could be expected to decrease. Intercropping requires the crops to be harvested at the same time which poses the risk that one of the crops may not have reached optimum maturity and is harvested with elevated moisture level. If not dried immediately after harvest, this can lead to postharvest mycotoxin formation, such as aflatoxins and ochratoxin A in oats (Neme & Mohammed, 2017) and phomopsin A and ochratoxin A in lupins (Kunz et al., 2022). Additionally, improper separation and lack of physical segregation during storage could contaminate lupin products with mycotoxins from oats, and vice versa.

Studies showed that growing legumes in an intercropping system lowered the prevalence of weeds and harmful insect species and disease (Kebede, 2017; Kumawat et al., 2022) and reduced fungal diseases (Księżak et al., 2023; Zhang et al., 2019). Altogether, it can be expected that intercropping lupins and oats will reduce pest and disease, leading to a lower amount of pesticide application and subsequently lower pesticide residue levels in crops. If intercropping is considered, legal requirements for the use of pesticides in crops should be assessed as each crop has permitted pesticides and their maximum residue limits (MRLs) (European Commission, 2005a, 2005b). In the case of pesticides that are only authorized for oats but not for lupins, and vice versa, these pesticides should not be used in an intercropping system to avoid the risk of illegal substances being present in the crops.

Growing lupins in an intercropping system has many benefits as elaborated above. However, lupins contain lupin allergens, which can be transferred to the accompanying crop during harvest and postharvest treatment. The ingestion of food containing allergen can trigger mild to severe allergic reactions in people with food allergy; therefore, allergens must be labelled sufficiently to prevent adverse health impacts (Codex Alimentarius, 2020). All actors in the food production chain using the accompanying crop grown together with lupins need to be informed of this practice so they can correctly label their product. Lupin allergen is, therefore, considered a new hazard for oats and lupins grown in an intercropping system. Oats are currently included as cereals containing gluten given the oats supply chain that are commonly produced and processed in the same facilities as other cereals containing gluten (European Commission, 2011). However, oats in itself do not contain gluten, but avenin and as such are gaining an interest as an alternative product for gluten-free diet (FAO and WHO, 2022). In the intercropping of oats and lupins, gluten is, thus, not considered a hazard that can be present in lupins.

Step 3: Establish control measures. Control measures were formulated to mitigate prioritized hazards, i.e., QAs, lupin allergens, and mycotoxins (field and postharvest). QAs and lupin allergens were new hazards for oats and lupins. Field mycotoxins are expected to decrease in crops grown in an intercropping system. However, as empirical data are limited and mycotoxins are highly toxic and difficult to remove once present in crops, it is therefore crucial to minimize their levels at the primary production stage. Examples of control measures in pre- and postharvest stages for the given case are summarized in Table 2.

At the preharvest stage, several measures are aimed at minimizing the formation of QAs and mycotoxins. An important measure is to start with selecting oat cultivars that are resistant or less susceptible to *Fusarium* species (if available) and lupin cultivars that produce low amounts of QAs. Moreover, it is also crucial to select compatible cultivars to grow in an intercropping system, for instance similar climate requirements and maturity time and less competition. Selecting crop cultivars that have similar maturity time can be beneficial in preventing postharvest mycotoxins. Furthermore, using appropriate seed proportions can prevent inter-plant competition, which might trigger QAs and mycotoxin production.

Next, it is also recommended to use good quality seeds that have low or are free of fungal infection. *Fusarium* species are common in small-grain cereals like wheat and oats; if the fungi survive in the soil and/or splash onto the plant during wet conditions, they can affect plant health and produce mycotoxins (Janssen et al., 2019). Likewise, phomopsin-producing fungi can survive in seeds (EFSA Panel on Contaminants in the Food Chain, 2012). Finally, both QA formation in lupin and mycotoxin formation are influenced by various biotic and abiotic stress factors in the field. Descriptive plans to mitigate these stress factors can be prepared and incorporated to GAP.

Postharvest measures mainly aim to prevent postharvest mycotoxins and the transfer of hazards between crops. The most critical point for mycotoxins accumulation is the drying step, which is already a widely accepted postharvest mycotoxin control measure. Next, the separation step is crucial to achieve product purity and to avoid unintended lupin allergens in oats. Care must be taken when separating the two crops to prevent that lupin seeds get broken and thus passing through to the oat kernels. A similar case was expected to be the cause of an incident in the Netherlands involving the presence of undeclared lupin allergens in rye bread whereby cultivation practice, harvesting, sorting, and cleaning steps were among the possible causes of the unintended lupin allergen (Verheijen et al., 2021). Even though allergen testing can be used to accurately determine the presence of unintentional allergens, this measure involves additional costs. Moreover, in this case, a precautionary allergen labelling (PAL) (e.g., "may contain traces of lupin") could be considered when it is difficult to ensure the presence of unintentional allergens; however, PAL should not be used to compensate a poor allergen management (Codex Alimentarius, 2020).

During storage, the following measures can be implemented to prevent cross-contact between crops: closed packaging must be ensured, clear labelling (e.g., with different colors), sufficient physical separation, and allergen warning signals in the storage area (Codex Alimentarius, 2020). In all postharvest steps, measures are required to prevent cross-contact: proper cleaning and sanitation of shared facilities and equipment, regular monitoring (e.g., visual inspection in the separation step, cleaning inspection, etc.). Finally, the implementation of these control measures must be well documented and regularly evaluated to assess their effectiveness.

Discussion

Design of the GFSA framework

The GFSA is based on HACCP principles and adapted to render it user-friendly and thus feasible to implement by the target users, i.e., the farmers. The complexity of HACCP often hinders its implementation and can easily be considered as a technical barrier, most notably hazard analysis (de Oliveira et al., 2016; Dzwolak, 2019; Wallace et al., 2014). In HACCP, hazard analysis is a key step in which the risk level of each potential hazard is assessed by evaluating both the likelihood of occurrence and severity to human health. However, as farmers are not expected to have all resources to perform a thorough hazard analysis in great depth like in a standard HACCP plan, step 2 of GFSA was simplified into estimating the likelihood of occurrence of a hazard in the new system compared to the current system. Meanwhile, the classification of the severity to human health was excluded from the step 2 GFSA. The underlying assumption is that food safety hazards may cause adverse effects on human health, especially regulated hazards such as mycotoxins, pesticide residues, and bacterial foodborne pathogens. Therefore, when a new potential hazard is identified or when the likelihood of occurrence of an existing hazard is expected to increase, a control measure must be in place. On the one hand, this may be seen as a limitation to this approach. On the other hand, it makes the approach more generic and can facilitate the practical application by farmers.

To our knowledge, quantitative data on the likelihood of occurrence of certain hazards due to changes during primary production are still lacking. Thus, the likelihood of occurrence of a hazard can be expressed qualitatively as new, eliminated, decreased, or increased. Information can be mainly obtained from literature and expert opinions. Altogether, this simplified approach is considered appropriate to pinpoint potential food safety hazards arising from changes in the production system using available resources.

Lessons learned from the case study and possible challenges for future applications

Results from our case study demonstrate the importance of applying a structured framework like GFSA as a dynamic and repeated process whenever changes in the production system are implemented. Intercropping of oats and lupins followed by postharvest treatment in the same facility might lead to three potential hazards (QAs, mycotoxins, and lupin allergens). Simultaneously, intercropping with legumes benefits soil health and fertility, consequently, reduce fertilizer and pesticide use and may lower chemical residues in crop. Knowing the significance of these hazards can help farmers to allocate their resources to control the respective hazards. The straightforward structure of the GFSA framework is useful to identify potential hazards which might otherwise be overlooked if no assessment is performed, for example, unintentional lupin allergens in oats due to cross-contact.

The occurrence of hazards along pre- and postharvest stages can be dynamic across the production stage. For example, QAs and lupin allergens are inherent hazards in lupins; however, postharvest stages can introduce these hazards to oats. At primary stage, it is also important to prevent or minimize the occurrence of certain contaminants that are difficult to remove, such as mycotoxins. In this case, preharvest measures play a crucial role in reducing the risk of infection by mycotoxin-producing fungal species. All measures must aim to prevent or minimize hazards occurrence. Unlike in the food industry, where desired conditions can be controlled, factors affecting field conditions (e.g., drought, heavy rainfall, and extreme temperature conditions), and thus the occurrence of certain hazards, cannot be controlled by farmers. Some control measures during primary production, therefore, depend on the field situation and farmers should determine possible scenarios affecting hazard occurrence before applying appropriate control measures. This is especially relevant for hazards such as plant toxins and mycotoxins.

Transparency along the food chain is pivotal in safeguarding food safety, as was demonstrated by a food safety incident involving an undeclared allergen in the Netherlands that was linked to the cultivation and processing practice (Verheijen et al., 2021). This point also substantiates the need for effective and transparent communication between farmers and the next supply chain actors. This is also encouraged through the ISO 22000 food safety management (FSSC 22000, 2019). FSMS developed for food processors, such as HACCP and Brand Reputation through Compliance Global Standard (BRCGS), require an update to the risk assessment for raw materials, for instance when there is a change in a raw material, its processing, supplier or when a new risk emerges (BRCGS, 2022). The outcome of the GFSA application can provide valuable input for this assessment for food processors to update their food safety plan and to adjust control measures. For instance, raw material suppliers should provide information on the possible unintentional presence of allergens to improve transparency along the food supply chain (Linders et al., 2023). Food processors should also be proactive in asking for this type of information, for example, by performing a raw materials supplier's risk assessment (BRCGS, 2022). By establishing effective communication, both farmers and food processors are prepared to manage hazards, consequently increasing food safety and quality, preventing complaints, improving trustworthiness, and finally maintaining business sustainability (Astill et al., 2019; Liu, 2018).

As elaborated in previous sections, applying the GFSA framework requires knowledge on food safety hazards from both current and future systems to fully analyze whether a hazard will be introduced (new), increased, decreased, or eliminated. It is assumed that farmers are aware of hazards in their current production system, and they are already included in their GAP. However, it can be expected that hazards in future systems are not known by farmers. In the presented case study, information on potential hazards were elicited from literature studies and expert opinions. Both sources are not easily accessible for farmers. Making these data available is, therefore, considered a prerequisite for a practical implementation of this GFSA framework. Collaboration among stakeholders, such as researchers, farmers, farmers' associations/cooperatives, and food processors, is strongly encouraged. Furthermore, GSFA requires resources (e.g., time, people, knowledge) from the user, making it more challenging for small-scale farmers. As an alternative, farmers' associations/cooperatives could apply GFSA for their sector commodities (e.g., cereals, pulses, fruits, and vegetables) and disseminate the knowledge to their members. In this way, these organizations can also raise awareness to their members that food safety aspects should be considered when changing their production system.

Conclusion

A generic food safety assessment (GFSA) framework has been developed to help farmers evaluate and control food safety hazards resulting from changes in their production system. The overall goal is to raise awareness that decisions made by farmers could have a significant impact on food safety on the whole food supply chain, either positive or negative. Applying the GFSA is a dynamic process that is carried out before any changes are implemented in the primary production system. In this sense, farmers can use the GFSA as part of their decision-making process. Effective and transparent communication is crucial for managing food safety hazards along the food supply chain, including when changes are made at the farm level.

Our case study showed that there is a lack of quantitative data on food safety hazards associated with certain changes in the primary production, like in crops grown in an intercropping system. Collaboration among all stakeholders along the food chain is, therefore, strongly advised to provide these data as a prerequisite for the future application of GFSA. Further studies are recommended to assess the robustness of the framework, for instance by applying GFSA to other case studies and through implementation by farmers. Having a real implementation by farmers is useful to obtain a comprehensive evaluation of the framework.

CRediT authorship contribution statement

Rosa A. Safitri: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Esther D. van Asselt:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization. **Judith Müller-Maatsch:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Susanne Vogelgsang:** Writing – review & editing, Investigation, Funding acquisition. **Tamara Dapcevic-Hadnadev:** Writing – review & editing, Investigation. **Monique de Nijs:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

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References

Alengebawy, A., Abdelkhalek, S. T., Qureshi, S. R., & Wang, M. Q. (2021). Heavy metals and pesticides toxicity in agricultural soil and plants: Ecological risks and human health implications. *Toxics, 9*(3). https://doi.org/10.3390/toxics9030042.

Astill, J., Dara, R. A., Campbell, M., Farber, J. M., Fraser, E. D. G., Sharif, S., & Yada, R. Y. (2019). Transparency in food supply chains: a review of enabling technology solutions. *Trends in Food Science & Technology, 91*, 240–247. https://doi.org/10.1016/j.tifs.2019.07.024.

Australia New Zealand Food Authority (2001). *Lupin alkaloids in food: a toxicological review and risk assesment*. Retrieved from https://www.foodstandards.gov.au/publications/documents/TR3.pdf. Accessed March 1, 2024.

Ayilara, M. S., Abberton, M., Oyatomi, O. A., Odeyemi, O., & Babalola, O. O. (2022). Potentials of underutilized legumes in food security. *Frontiers in Soil Science, 2*, 1020193. https://doi.org/10.3389/fsoil.2022.1020193.

Black, Z., Balta, I., Black, L., Naughton, P. J., Dooley, J. S. G., & Corcionivoschi, N. (2021). The fate of foodborne pathogens in manure treated soil. *Frontiers Microbiology, 12*, 781357. https://doi.org/10.3389/fmicb.2021.781357.

BRCGS (2022). *Global standard food safety: Issue 9*. In (pp. 31). London: BRCGS. Retrieved from https://www.brcgs.com/product/global-standard-food-safety-issue-9/p-13279/. Accessed March 1, 2024.

Bybee-Finley, K. A., & Ryan, M. R. (2018). Advancing intercropping research and practices in industrialized agricultural landscapes. *Agriculture, 8*(6), 80. https://doi.org/10.3390/agriculture8060080.

Codex Alimentarius (1995). *General standard for contaminants and toxins in food and feed CXS 193 – 1995*. Retrieved from https://www.fao.org/fao-who-codexalimentarius/sh-proxy/en/?lnk=1&url=https%253A%252F%252Fworkspace.fao.org%252Fsites%252Fcodex%252FStandards%252FCXS%2B193-1995%252FCXS_193e.pdf. Accessed March 1, 2024.

Codex Alimentarius (2008). *Guidelines for the validation of food safety control measures CAC/GL69-2008*. Retrieved from https://www.fao.org/fao-who-codexalimentarius/sh-proxy/en/?lnk=1&url=https%253A%252F%252Fworkspace.fao.org%252Fsites%252Fcodex%252FStandards%252FCXG%2B69-2008%252FCXG_069e.pdf. Accessed March 1, 2024.

Codex Alimentarius (2020). *Code of practice on food allergen management for food business operators CXC 80-2020*. Retrieved from https://www.fao.org/fao-who-codexalimentarius/sh-proxy/en/?lnk=1&url=https%253A%252F%252Fworkspace.fao.org%252Fsites%252Fcodex%252FStandards%252FCXC%2B80-2020%252FCXC_080e.pdf. Accessed March 1, 2024.

Codex Alimentarius (2022). *General principles of food hygiene, CXC 1, adopted 1969. revised 1997, 2003, 2020, 2022*. https://www.fao.org/fao-who-codexalimentarius/sh-proxy/en/?lnk=1&url=https%253A%252F%252Fworkspace.fao.org%252Fsites%252Fcodex%252FStandards%252FCXC%2B1-1969%252FCXC_001e.pdf.

CROPDIVA (2023). *Enhancing European agrobiodiversity*. Retrieved from https://cordis.europa.eu/project/id/101000847. Accessed 15 May 2023.

de Oliveira, C. A. F., da Cruz, A. G., Tavolaro, P., & Corassin, C. H. (2016). Chapter 10 – Food safety: Good Manufacturing Practices (GMP), Sanitation Standard Operating Procedures (SSOP), Hazard Analysis and Critical Control Point (HACCP). In J. Barros-Velázquez (Ed.), *Antimicrobial food packaging* (pp. 129–139). Academic Press. https://doi.org/10.1016/B978-0-12-800723-5.00010-3.

Drakopoulos, D., Kägi, A., Gimeno, A., Six, J., Jenny, E., Forrer, H.-R., Musa, T., Meca, G., & Vogelgsang, S. (2020). Prevention of Fusarium head blight infection and mycotoxins in wheat with cut-and-carry biofumigation and botanicals. *Field Crops Research, 246*, 107681. https://doi.org/10.1016/j.fcr.2019.107681.

Dzwolak, W. (2019). Assessment of HACCP plans in standardized food safety management systems – The case of small-sized Polish food businesses. *Food Control, 106*, 106716. https://doi.org/10.1016/j.foodcont.2019.106716.

EFSA Panel on Contaminants in the Food Chain (2012). Scientific opinion on the risks for animal and public health related to the presence of phomopsins in feed and food. *EFSA Journal, 10*(2), 2567. https://doi.org/10.2903/j.efsa.2012.2567.

EFSA Panel on Contaminants in the Food Chain (2019). Scientific opinion on the risks for animal and human health related to the presence of quinolizidine alkaloids in feed and food, in particular in lupins and lupin-derived products. *EFSA Journal, 17*(11), e05860.

European Commission (2002). *Regulation (EC) No 178/2002 of the European Parliament and of the Council of 28 January 2002 laying down the general principles and requirements of food law, establishing the European Food Safety Authority and laying down procedures in matters of food safety*. Retrieved from https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=celex:32002R0178#. Accessed May 15, 2023.

European Commission (2005). *Regulation (EC) No 396/2005 of the European Parliament and of the Council of 23 February 2005 on maximum residue levels of pesticides in or on food and feed of plant and animal origin and amending Council Directive 91/414/EEC*. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32005R0396. Accessed May 15, 2023.

European Commission (2005). *Commission Regulation (EC) No. 2073/2005 of 15 November 2005*. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32005R2073. Accessed May 15, 2023.

European Commission (2011). *Regulation (EU) No. 1169/2011 of the European Parliament and of the Council of 25 October 2011*. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32011R1169&qid=1689523738076. Accessed May 15, 2023.

European Commission (2023). *Commission Regulation (EU) 2023/915 of 25 April 2023 on maximum levels for certain contaminants in food and repealing Regulation (EC) No 1881/2006*. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32023R0915&qid=1688376879435. Accessed May 15, 2023.

FAO (2016). *A scheme and training manual on Good Agricultural Practices (GAP) for fruits and vegetables*. Retrieved from https://www.fao.org/3/i6677e/i6677e.pdf. Accessed May 15, 2023.

FAO (2021). *Climate change, biodiversity and nutrition nexus – Evidence and emerging policy and programming opportunities*. https://doi.org/10.4060/cb6701en.

FAO (2023). *FAO Good Hygiene Practices (GHP) and Hazard Analysis and Critical Control Point (HACCP) toolbox for food safety*. https://doi.org/10.4060/cc6227en.

FAO and WHO. (2022). *Risk Assessment of Food Allergens. Part 1 – Review and validation of Codex Alimentarius priority allergen list through risk assessment* [Meeting Report] Food Safety and Quality Series No. 14. https://doi.org/10.4060/cb9070en.

Ferelli, A. M. C., & Micallef, S. A. (2019). Chapter 7 – Food safety risks and issues associated with farming and handling practices for organic certified fresh produce. In D. Biswas & S. A. Micallef (Eds.), *Safety and practice for organic food* (pp. 151–180). Academic Press. https://doi.org/10.1016/B978-0-12-812060-6.00007-6.

Ferreira, H., Pinto, E., & Vasconcelos, M. W. (2021). Legumes as a cornerstone of the transition toward more sustainable agri-food systems and diets in Europe. *Frontiers in Sustainable Food Systems, 5*. https://doi.org/10.3389/fsufs.2021.694121.

Francis, C. A., & Porter, P. (2017). Multicropping. In B. Thomas, B. G. Murray, & D. J. Murphy (Eds.), *Encyclopedia of applied plant sciences* (2nd ed., pp. 29–33). Academic Press. https://doi.org/10.1016/B978-0-12-394807-6.00024-1.

FSSC 22000 (2019). *Food Safety System Certification 22000: Guidance document ISO 22000 -Interpretation version 5 December 2019*. Retrieved from https://www.fssc.com/wp-content/uploads/19.1210-Guidance_ISO-22000-Interpretation_Version-5.pdf. Accessed May 15, 2023.

Garcia, J. M., & Teixeira, P. (2017). Organic versus conventional food: a comparison regarding food safety. *Food Reviews International, 33*(4), 424–446. https://doi.org/10.1080/87559129.2016.1196490.

Gil, M. I., Selma, M. V., Suslow, T., Jacxsens, L., Uyttendaele, M., & Allende, A. (2015). Pre- and postharvest preventive measures and intervention strategies to control microbial food safety hazards of fresh leafy vegetables. *Critical Reviews in Food Science and Nutrition, 55*(4), 453–468. https://doi.org/10.1080/10408398.2012.657808.

Gresta, F., Wink, M., Prins, U., Abberton, M., Capraro, J., Scarafoni, A., & Hill, G. (2017). Lupins in European cropping systems. In D. Murphy-Bokern, F. L. Stoddard, & C. A. Watson (Eds.), *Legumes in cropping system* (pp. 88–108). CABI International. https://doi.org/10.1079/9781780644981.0088.

Guo, B., Chen, Z.-Y., Lee, R. D., & Scully, B. T. (2008). Drought stress and preharvest aflatoxin contamination in agricultural commodity: genetics, genomics and proteomics. *Journal of Integrative Plant Biology, 50*(10), 1281–1291. https://doi.org/10.1111/j.1744-7909.2008.00739.x.

Herrera, M., Cavero, J., Franco-Luesma, S., Álvaro-Fuentes, J., Ariño, A., & Lorán, S. (2023). Mycotoxins and crop yield in maize as affected by irrigation management and tillage practices. *Agronomy, 13*(3), 798. https://doi.org/10.3390/agronomy13030798.

Janssen, E. M., Mourits, M. C. M., van der Fels-Klerx, H. J., & Lansink, A. G. J. M. O. (2019). Pre-harvest measures against *Fusarium* spp. infection and related mycotoxins implemented by Dutch wheat farmers. *Crop Protection, 122*, 9–18. https://doi.org/10.1016/j.cropro.2019.04.005.

Kebede, B. (2017). Intercropping practice as an alternative pathway for sustainable agriculture. *Academic Research Journal of Agricultural Science and Research, 5*(6). https://doi.org/10.14662/ARJASR2017.057.

Kiær, L. P., Weedon, O. D., Bedoussac, L., Bickler, C., Finckh, M. R., Haug, B., Iannetta, P. P. M., Raaphorst-Travaille, G., Weih, M., & Karley, A. J. (2022). Supply chain perspectives on breeding for legume–cereal intercrops. *Frontiers in Plant Science, 13*. https://doi.org/10.3389/fpls.2022.844635.

Księżak, J., Staniak, M., & Stalenga, J. (2023). Restoring the importance of cereal-grain legume mixtures in low-input farming systems. *Agriculture, 13*(2), 341. https://doi.org/10.3390/agriculture13020341.

Kumawat, A., Bamboriya, S. D., Meena, R. S., Yadav, D., Kumar, A., Kumar, S., Raj, A., & Pradhan, G. (2022). Chapter 16 - Legume-based inter-cropping to achieve the crop, soil, and environmental health security. In R. S. Meena & S. Kumar (Eds.), *Advances in legumes for sustainable intensification* (pp. 307–328). Academic Press. https://doi.org/10.1016/B978-0-323-85797-0.00005-7.

Kunz, B. M., Pförtner, L., Weigel, S., Rohn, S., Lehmacher, A., & Maul, R. (2022). Growth and toxin production of phomopsin A and ochratoxin A forming fungi under different storage conditions in a pea (*Pisum sativum*) model system. *Mycotoxin Research, 38*(1), 37–50. https://doi.org/10.1007/s12550-021-00446-8.

Linders, Y. F. M., Lentz, L. R., Blom, W. M., Michelsen-Huisman, A., Strikwerda, J., van Dijk, L. M., Knulst, A. C., Houben, G. F., van Os-Medendorp, H., & Holleman, B. C. (2023). Precautionary allergen labeling: current communication problems and potential for future improvements. *Food Control, 147*, 109561. https://doi.org/10.1016/j.foodcont.2022.109561.

Liu, C., Manstretta, V., Rossi, V., & Van der Fels-Klerx, H. J. (2018). Comparison of three modelling approaches for predicting doxynivalenol contamination in winter wheat. *Toxins, 10*(7), 267. https://doi.org/10.3390/toxins10070267.

Liu, G. (2018). The impact of supply chain relationship on food quality. *Procedia Computer Science, 131*, 860–865. https://doi.org/10.1016/j.procs.2018.04.286.

Lucas, M. M., Stoddard, F., Annicchiarico, P., Frias, J., Martinez-Villaluenga, C., Sussmann, D., Duranti, M., Seger, A., Zander, P., & Pueyo, J. (2015). The future of lupin as a protein crop in Europe. *Frontiers in Plant Science, 6*. https://doi.org/10.3389/fpls.2015.00705.

Mazzafera, P., Favarin, J. L., & Andrade, S. A. L. D. (2021). Editorial: Intercropping systems in sustainable agriculture. *Frontiers in Sustainable Food Systems, 5*. https://doi.org/10.3389/fsufs.2021.634361.

Muluneh, M. G. (2021). Impact of climate change on biodiversity and food security: a global perspective—a review article. *Agriculture & Food Security, 10*(1), 36. https://doi.org/10.1186/s40066-021-00318-5.

Neme, K., & Mohammed, A. (2017). Mycotoxin occurrence in grains and the role of postharvest management as a mitigation strategies. A review. *Food Control, 78*, 412–425. https://doi.org/10.1016/j.foodcont.2017.03.012.

Pitt, J. I. (2014). Mycotoxins: Mycotoxins – general. In Y. Motarjemi (Ed.), *Encyclopedia of Food Safety* (pp. 283–288). Academic Press. https://doi.org/10.1016/B978-0-12-378612-8.00411-X.

Pueyo, J. J., Quiñones, M. A., Coba de la Peña, T., Fedorova, E. E., & Lucas, M. M. (2021). Nitrogen and phosphorus interplay in lupin root nodules and cluster roots. *Frontiers in Plant Science, 12*, 644218. https://doi.org/10.3389/fpls.2021.644218.

Rodés-Bachs, C., & Van der Fels-Klerx, H. J. (2023). Impact of environmental factors on the presence of quinolizidine alkaloids in lupins: a review. *Food Additives & Contaminants: Part A, 40*(6), 757–769. https://doi.org/10.1080/19440049.2023.2217273.

Sarmast, E., Fallah, A. A., Jafari, T., & Mousavi Khaneghah, A. (2021). Occurrence and fate of mycotoxins in cereals and cereal-based products: a narrative review of systematic reviews and meta-analyses studies. *Current Opinion in Food Science, 39*, 68–75. https://doi.org/10.1016/j.cofs.2020.12.013.

Sharma, M., & Reynnells, R. (2016). Importance of soil amendments: survival of bacterial pathogens in manure and compost used as organic fertilizers. *Microbiology Spectrum, 4*(4). https://doi.org/10.1128/microbiolspec.pfs-0010-2015.

Tarazona, A., Gómez, J. V., Mateo, F., Jiménez, M., & Mateo, E. M. (2021). Potential health risk associated with mycotoxins in oat grains consumed in Spain. *Toxins (Basel), 13*(6). https://doi.org/10.3390/toxins13060421.

Torres, A. M., Palacios, S. A., Yerkovich, N., Palazzini, J. M., Battilani, P., Leslie, J. F., Logrieco, A. F., & Chulze, S. N. (2019). *Fusarium* head blight and mycotoxins in wheat: prevention and control strategies across the food chain. *World Mycotoxin Journal, 12*(4), 333–355. https://doi.org/10.3920/wmj2019.2438.

Verheijen, P., Smits, N., Barbu, I., Voorhuijzen, M., Hoek, E., & Koops, A. (2021). *Allergeen lupine in roggebrood: kruisbesmetting of bronbesmetting?* VMT. Retrieved from https://www.vmt.nl/52120/allergeen-lupine-in-roggebrood-kruisbesmetting-of-bronbesmetting. Accessed August 15, 2023.

Wallace, C. A., Holyoak, L., Powell, S. C., & Dykes, F. C. (2014). HACCP – The difficulty with hazard analysis. *Food Control, 35*(1), 233–240. https://doi.org/10.1016/j.foodcont.2013.07.012.

Zhang, C., Dong, Y., Tang, L., Zheng, Y., Makowski, D., Yu, Y., Zhang, F., & van der Werf, W. (2019). Intercropping cereals with faba bean reduces plant disease incidence regardless of fertilizer input; a meta-analysis. *European Journal of Plant Pathology, 154*(4), 931–942. https://doi.org/10.1007/s10658-019-01711-4.