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Reuse of plant-based side streams in food production: Overview of chemical food safety hazards

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ABSTRACT

The European Green Deal and consumer demands drive the increased use of side streams in food production. Although this circular use of materials positively impacts sustainability, it may result in the accumulation or introduction of chemical hazards in the final product. This study explored the potential chemical hazards that can be present in side streams from nine raw materials, i.e., apple, beetroot, carrot, citrus, corn, potato, sugar beet, tomato, and wheat, and brewer's spent grain (BSG), a side stream from beer production. A structured approach was developed starting from a list of chemical hazards in the raw materials, supplemented with literature information Rapid Alert System for Feed and Food (RASFF) notifications, and expert judgement. All information was combined to provide a list of relevant hazards that could be present in the selected side streams. This study showed that heavy metals, mycotoxins, and plant protection products are most frequently included as relevant hazards. Citrus peel contained the most identified potential chemical hazards ($n = 59$), whereas root vegetables such as beetroot, sugar beet, and carrot had the lowest number of chemical hazards on the list (respectively 7, 8, and 9). The methodology applied can also be used for side streams from other plant-based raw materials when appropriate data sources are used. The results presented in this study show that this method helps identify potential chemical hazards to be included in monitoring when reusing side streams and can serve as an input for determining chemical food safety in new food product formulations.

1. Introduction

Currently, there is a global push towards a more sustainable and circular food system. This search for circularity requires a new approach to using novel products and technologies to upcycle materials, which were previously largely discarded or otherwise moved to a suboptimal destination such as energy production (Gómez-García et al., 2021). This movement is also occurring in the European Union (EU); although certain legal restrictions can still apply depending on the material – particularly for those of animal origin – new policies such as the 'Green Deal' are increasingly promoting more sustainable options (Boix-Fayos and de Vente, 2023; Meijer et al., 2023). The EU Green Deal establishes policies aiming to become climate neutral in 2050 (European Commission, 2025). One of the options to achieve this is the (re)use of side streams or by-products in food production. EU Member States are responsible for ensuring that targets related to the Waste Framework Directive (Directive 2008/98/EC) are achieved, which requires taking appropriate measures to facilitate waste reduction, re-use, recycling, and other material recovery. In this Directive, a by-product is defined as: "a substance or object resulting from a production process the primary aim of which is not the production of that substance or object is considered not to be waste" . Mottet et al. (2017) estimated that 86 % of global livestock feed was not edible for humans, such as grass, leaves, fodder crops, oilseed cakes, etc. – while the remaining 14 % consisted of grains and other human-edible portions. Apart from reducing waste, a sustainable option is to upcycle streams such as this 14 % edible portion, that are currently unused in food (Rakesh and Mahendran, 2024).

In our research, we have used the term side streams to indicate by-products obtained during food production. An example is brewer's spent grain, which is a side stream obtained during beer production. An evaluation from the EU research project REFRESH showed that side streams from apples, potatoes, sugar beet, and tomatoes present opportunities for valorization, given their high production volumes in the EU (Moates et al., 2016). These crops are generally used for only one or a few primary food products for human consumption, with much of the agricultural biomass classified as side streams. Many of the side streams from these production chains have historically found their way towards animal feed. Examples include materials such as spent grain from brewery waste (Rachwał et al., 2020), straw as a source of fiber for ruminants (Yang et al., 2021), and meals, i.e. the side stream remaining after oil extraction, from different stages of oil-processing (Rakita et al., 2023). Certain other products, however, were considered less suitable

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for that purpose because they can contain toxic or anti-nutritional compounds, such as glycoalkaloids in solanaceous plants (e.g., potato, tomato) (Abu Hafsa et al., 2022) and protease inhibitors in beans (Yang et al., 2021). New processing technologies, such as encapsulation of bioactive compounds from fruit and vegetable side streams (Marcillo-Parra et al., 2021) or pressurised liquid or CO2 extraction (Wijngaard et al., 2012), could provide opportunities to find more sustainable applications for these residual side streams (Marcillo-Parra et al., 2021; Martins et al., 2017; Wijngaard et al., 2012). In some cases, depending on a product's origin and the nature of processing, application of new processing technologies may make a product subject to pre-market authorization as a 'novel food', in the context of Regulation (EU) No 2015/2283. Such authorization would involve the submission of a detailed dossier for evaluation by the European Food Safety Authority (EFSA). Of course, in addition to safety and commercial aspects (Focker et al., 2022), a key factor in ensuring the ecological sustainability of these technologies is that they do not have high energy requirements and/or employ large amounts of hazardous substances ('soft chemistry') (Gómez-García et al., 2021).

Overall, there is potential to reuse side streams in food processing, contributing to closing the loop and thereby reducing environmental impacts. However, currently, there is a lack of information on the safety of these side streams when reusing them in the food chain, which is a major prerequisite for permitting (re-)using side streams in the food and/or feed chain (Van Raamsdonk et al., 2023). A wide range of food safety hazards could be present, e.g., environmental contaminants such as heavy metals that are taken up via the environment into the crop or pesticides that are used during crop cultivation. When considering new destinations for such materials, it is prudent to take food safety into account from the onset of development so that any risks can be identified as soon as possible, preferably at the stage of product development. This is what we call a 'safe-by-design' approach: the identification of food safety issues when (re)designing food products

The safe-by-design approach is becoming increasingly common in the biotechnology industry and also has a clear environmental dimension there (van Gelder et al., 2021). However, the use of this approach in the food chain has, thus far, not frequently been described in scientific literature, with most applications being on the intersection between biotech and food production, for instance, innovations in crop breeding (van Der Berg et al., 2020) or packaging materials (Pavlicek et al., 2021; Robaey et al., 2018).

Especially for the case of side streams, including the use of ingredients thereof, a variety of food or feed safety hazards could be introduced that were not hitherto considered, and research tends to be scarce (Socas-Rodríguez et al., 2021; Van Asselt et al., 2023). A product-specific inventory of food safety risks, employing expert elicitation, is thus needed for safety assessments (James et al., 2022). Although both microbial and chemical hazards are relevant to include in a food safety evaluation, this study focused on chemical hazards only, as these are typically more difficult to remove during further processing, stressing the need for an upfront identification of relevant food safety hazards.

The aim of this study was to provide an overview of chemical food safety hazards related to the use of side streams in food production systems using a structured approach. The outcome of this study can be used as input for food safety management systems, such as HACCP and can be used as a starting point for developing risk-based monitoring programs focusing on the most relevant food safety hazards. Due to major legal limitations on applications using animal by-products, the focus of this study was on side streams from plant-based origin. The selection of side streams represented different food groups that are currently being used in animal feed and could be upscaled to food production or have the potential to be used as novel ingredients in food production. These side streams were peels, pomace, or pulp from apples, beetroot, tomatoes, carrots, potatoes, citrus, and sugar beet. Furthermore, the grain side streams, brewer's spent grain (BSG), wheat bran, corn germ fiber, and corn gluten meal were selected as relevant side streams. This overview will serve as an input for determining chemical food safety in product development.

2. Materials and methods

2.1. Approach

The focus of this study concerned the presence of chemical food safety hazards in side streams from nine raw materials, i.e., apple, beetroot, carrot, citrus, corn, potato, sugar beet, tomato, and wheat, as well as BSG, a side stream from beer production, that could be considered for human consumption. Due to the limited data availability for these side streams, we decided to choose a qualitative approach, meaning we merely identified the potential presence or absence of chemical hazards rather than estimating expected concentration levels. A structured approach was used to identify chemical hazards in these side streams using the following information:

A. Relevant chemical hazards identified in the raw agricultural commodity (i.e., material). This information was obtained from research previously performed (Banach et al., 2019; Hobe et al., 2020; Hoffmans et al., 2020; Klüche et al., 2020; Nijkamp et al., 2019, 2017).
B. Scientific literature screening chemical hazards related to the side streams from the nine raw materials and BSG. This information was obtained from a literature review as described below (see Section 2.2).
C. The Rapid Alert System for Food and Feed (RASFF). RASFF notifications were obtained from the RASFF portal. For this purpose, an internal database was used containing all RASFF notifications scraped from the RASFF portal since 1979 (RASFF: Entire database - WFSR (wur.nl)). For this research, we used a 10-year time period (mid-July 2012 up to mid-July 2022). No geographic boundaries were set as side streams are imported into the EU globally. The contribution of a hazard was calculated by dividing the number of notifications for the hazard by the total number of notifications for the side stream.
D. Expert elicitation. Experts were consulted to provide their opinions on the obtained hazards focusing on potential food use, as indicated below (Section 2.3).
E. Additional evaluation of the plant protection products (PPPs). Solubility, potential plant uptake, and available processing factors were used to assess whether pesticides are likely present in the side streams, as indicated below (Section 2.4).
F. Hazards identified as relevant for animal feed. Since the side streams evaluated are currently sometimes applied in animal feed, information on a risk classification performed by SecureFeed, a Dutch branch organization on animal feed, was used as one of the input variables (Risk classification of feed | SecureFeed). For this purpose, the risk classification of 2022 was used, and hazards were included that were classified as having a basic, low, medium, or high probability of presence.

All available data were gathered in an Excel file, resulting in a long list of potential hazards per side stream. This list was then prioritized as follows: Hazards were included on the short list when they were both found in the raw material (A) and either in the literature review on side streams (B) or when the hazard contributed $\geq$2 % of the RASFF notification of the side stream (C); a threshold used previously to rank hazards in seaweed (Banach et al., 2020). Hazards were also included when scientific experts indicated them to remain or increase in the side stream as compared to the raw material (D) or when more than one industrial expert (factor D and industrial expertise for animal feed as indicated in factor F) identified the hazard as relevant for the side stream. The following formulas were used to decide whether a hazard was included on the final list for the side stream or not:

For all chemical hazards except pesticides, we assumed that if hazards were identified as relevant in the raw materials and confirmed by the literature review and/or the RASFF database (SUM of factor A-$C >$ 1), then the hazard was relevant for the side stream. Also when the scientific expert(s) indicated a hazard was relevant ($D_{scientific} \geq 1$), it was included in the final list and when experts from industry and or the animal feed database indicated a hazard was relevant (Sum of factor $D_{industrial}$ and $F > 1$), the hazard was also included on the list. The formula used to prioritize the hazards was:

$$\mathrm{IF}\big(\mathrm{OR}\big(\mathrm{SUM}(\mathrm{FactorA} : \mathrm{FactorC}) > 1, \mathrm{FactorD_{scientific}} >= 1, \mathrm{SUM}(\mathrm{FactorD_{industrial}}, \mathrm{FactorF}) > 1\big), 1, 0\big) \tag{1}$$

For pesticides we followed the same approach but added pesticides in case their presence was identified as likely according to factor E:

$$\mathrm{IF}(\mathrm{OR}(\mathrm{SUM}(\mathrm{FactorA} : \mathrm{FactorC}) > 1, \mathrm{FactorE} > = 1, \mathrm{SUM}(\mathrm{FactorD_{industrial}}, \mathrm{FactorF}) > 1), 1, 0) \tag{2}$$

When the outcome of Eqs. (1) and (2) was 1, the chemical hazard was included in the final list of relevant hazards. In case the outcome resulted in 0, the hazard was not included. This procedure allowed us to rank the initial long list of hazards that can potentially be present in the raw material to a list of relevant hazards that can be found in the side streams.

2.2. Literature review

A literature review was performed to retrieve papers on chemical food safety hazards related to the side streams from the nine raw materials and BSG. For each raw material, two sets of searches were performed to search for chemical hazards related to the side streams of this raw material. First, keywords were defined for side streams related to the raw materials (indicated as #1 in Annex 1) and combined with keywords describing chemical hazards (indicated as #2 in Annex 1) and keywords indicating the relation with human health (indicated as #3 in Annex 1). For some of the side streams, the number of hits obtained was limited. To make this search more robust, we did an additional search in which the raw materials were combined separately with search terms for side streams, as indicated in Annex 1. No time limit was set since the number of papers on chemical hazards found was limited, and we aimed to obtain as much information on potential hazards as possible. For the same reason, no geographic boundaries were set, so both papers from EU and non-EU countries were included.

The search terms were used in two bibliographic databases: Scopus and Web of Science. The obtained results for both databases were combined into ten separate Endnote files, and duplicates were removed. The results obtained in the Endnote file were evaluated first based on title, keywords, and abstracts. Papers were classified as relevant or not relevant related to the topic. Examples of non-relevant results were papers describing the use of side streams for bioremediation, papers describing quality aspects of side streams, or papers describing food safety hazards related to the raw materials (so not the side stream). Relevant papers were read in full, and information was extracted into an Excel file. Information on the type of hazard studied and the main conclusion obtained from the paper were included.

2.3. Expert elicitation

Given data uncertainties from the literature on chemical food safety hazards of concern in the side streams, experts were elicited for their opinions on the effects of processing on chemical food safety hazards of side stream ingredients.

In total, eight scientific experts were interviewed. Interviews were performed with scientific researchers (academic) with hazard-specific knowledge of chemical food safety hazards (heavy metals, mycotoxins, PPPs, per- and poly-fluoroalkyl substances (PFASs), dioxins, plant toxins, processing contaminants, and polycyclic aromatic hydrocarbons (PAHs)). During each interview, the experts were shown the intended processing steps for each of the aforementioned side streams obtained from the nine raw materials and BSG. The processing schemes used for the interview are included as supplementary material; see Annex 2. These processing schemes were based on information from scientific papers complemented with expert input from Wageningen Food and Biobased Research. The side streams indicated are by-products obtained during food production. Some of these side streams may currently be the main ingredients for feed production. The focus of this research was to identify potential chemical food safety hazards in side streams when used as food ingredients. Scientific experts were asked to identify any critical steps that may increase, decrease, or have a negligible or minimal effect on hazards for which they have expertise. In particular, experts were instructed to focus on the side stream ingredients of interest: apple peel and apple pomace; beetroot peel and beetroot pomace; BSG; carrot peel and carrot pomace; corn germ fiber and corn gluten meal; potato peel, potato pulp, and potato fruit water/processing water; sugar beet pulp; tomato peel and tomato pomace; and wheat bran. A semi-quantitative approach was followed during the interviews, where a score of -1 meant that the hazard would reduce in the side stream compared to the raw material, 1 meant the hazard would stay equal (i.e., a minimal or negligible effect was expected) in the side stream compared to the raw material, and 2 meant the hazard would increase in the side stream compared to the raw material. As the list of pesticides was extensive ($n = 125$), the expert could not evaluate these separately for each side stream. Instead, it was suggested that the pesticide characteristics be used as input for the evaluation as described below (Section 2.4).

Apart from the input from scientific experts, three experts from the industry provided input on the presence of the identified hazards in the side streams. These experts were part of the pre-competitive consortium working on this topic (Food Safety by Design – automated hazard identification tool - WUR). For this purpose, the hazard identification procedure and the side streams to be evaluated were orally explained. Then, the Excel file with the list of hazards per side stream was sent to the experts to evaluate whether the hazards were likely to be found in the side stream (indicated with a score of 1). The information from the scientific and industrial experts was gathered in separate columns in the Excel file.

2.4. Additional evaluation of the plant protection products

The potential presence of PPPs in the above-mentioned side streams was evaluated based on the following parameters: solubility, the mode of action (systemic or non-systemic), and processing factors. Data on the log P_{ow}, water solubility, and mode of action (systemic or non-systemic) were obtained from the UK Pesticide Properties Database (Pesticide Properties Database (herts.ac.uk)). Processing factors (PFs) were extracted for the side stream ingredients of interest (i.e., those shown during the expert elicitation) and PPPs identified during the literature search and expert elicitation. The most recent available version of the European database on processing factors for pesticide residues in food (https://zenodo.org/records/6827098) was consulted to extract available PFs (Version 2 from 13/09/2022). The information on solubility, mode of action, and PFs was obtained and used as indicated below. In addition to the characteristics of the PPPs in combination with the production process of the side streams included, Dutch monitoring data on side streams currently used in animal feed were consulted that were available for the years 2018–2022 (obtained from KAP: Quality Programme for Agricultural Products | RIVM). In case a PPP was found in more than 10 % of the samples, it was included on the list provided that the PPP was analyzed in at least 5 samples.

For the root vegetables included in this study (i.e., carrot, beetroot, sugar beet, and potatoes), the PPP studied was assumed to be absent in the raw material and thus in the side stream when the PPP was identified as non-systemic. An exception was made when PFs above 1 were found in the European database on processing factors. Then, the PPP remained on the list as a worst-case assumption.

Hakme et al. (2024) performed a study on pesticide residues in beer and its side streams, such as BSG, and concluded that highly non-polar pesticides accumulate in spent grain and highly polar pesticides accumulate in the wort, so they are less likely to be found in the spent grain. Therefore, we assumed that PPPs with a log P_{ow} (the octanol-water partition coefficient at pH 7, 20 °C) below 1 (polar, i.e., water-soluble) were expected to be absent in BSG.

Table 1
Results of the literature review on chemical hazards in side streams from nine raw materials and brewer's spent grain.

Side stream from	Total nr hits search 1	Total nr hits search 2	Relevant hits based on Ti-Key-Abs (search 1 and 2 combined)	Relevant hits based on full-text	Hazard groups included
Apple	72	132	29	10	Plant Protection Products (PPPs), mycotoxins, heavy metals and elements
Beetroot	46	54	6	1	Mycotoxins
Brewer's spent grain	195	N.A.	21	3	Mycotoxins, PPPs
Carrot	83	58	17	0	
Citrus peel	135	185	12	0	
Corn	73	62	22	4	Mycotoxins
Potatoes	93	104	26	7	Dioxins and polychlorinated biphenyls (PCBs), Heavy metals and elements, Perfluorinated compounds, PPPs, plant toxins
Sugar beet	43	242	9	1	Mycotoxins
Tomatoes	99	177	43	2	PPPs
Wheat	359	N.A.	76	11	Mycotoxins, heavy metals and elements, PPPs
Total	1198	1014	261	39	

3. Results

3.1. Literature review

In total, 1198 papers were obtained using the search terms for papers on chemical hazards in the specified side streams in the initial search and 1014 for the additional search. Evaluating these papers based on title, keywords, and abstract resulted in 261 papers that were potentially relevant. These papers were read in full, and 39 of them contained relevant information on chemical hazards for side streams. The results obtained for the side streams are indicated in Table 1. Even though more than 2000 papers were found on chemical hazards in the side streams, the number of papers that were relevant to include in our overview was limited. Relevant papers described the presence of a chemical hazard in a side stream obtained from the raw materials studied. Non-relevant papers were studies that focused on nutritional compounds rather than compounds with adverse effects or, e.g., were studies related to a method development or validation, removal of contaminants, reported health benefits, had a quality focus such as color or texture, or had a microbiological or medical focus. The majority of the papers described the presence of mycotoxins, PPPs, and the group of heavy metals and elements.

The hazards mentioned in the relevant papers were taken up in the overarching overview as input for the prioritization. Table 2 shows the hazard groups identified as relevant per side stream. Details on the hazards found within each hazard group can be found in Annex 3. The sections below summarize the results obtained from the literature review, expert elicitation, RASFF notifications, and animal feed classification per side stream.

3.2. Apple side stream

Apples can be processed into products such as apple juice, apple cider, or dried apple pieces. During processing, apple pomace (containing the pulp, peel, seeds, and stem) and apple peel are obtained as side streams. The literature review revealed ten relevant papers that described the potential presence of PPPs, mycotoxins, and the group of heavy metals and elements. No RASFF notifications were found for apple peel or apple pomace. Heavy metals and elements such as cadmium, chromium, lead, nickel, and zinc were seen as potential hazards in the apple side stream based on literature review and expert judgment. Furthermore, the literature review and expert interviews revealed that *Alternaria* toxins and patulin were mycotoxins identified as potentially present in the apple side stream. Apple seeds may contain cyanogenic glycosides, which may be part of apple pomace and, as such, can be present in apple side streams. Finally, a total of 35 PPPs were identified that could be present in apples. As a worst-case approach, it was assumed that these could also end up in the apple side streams.

3.3. Beetroot side stream

Beetroot is used to produce beetroot juice. Like apple, this production process results in the side streams peel and pomace. The literature review revealed only one relevant paper on mycotoxins. Fumonisins and zearalenone were included as relevant for beetroot side streams. Dioxins and polychlorinated biphenyls (PCBs) were identified as potential hazards for beetroot pulp and peel intended for animal feed. As such, it was also included as a relevant hazard when using beetroot side streams in human food production. Arsenic, cadmium, lead, and mercury were seen as relevant hazards for beetroot as raw material, and experts confirmed that they were potentially present in the side streams produced from beetroot. No specific PPPs were identified for these side streams.

Table 2
Results of the prioritization, shown per side stream.

Side stream	Allergens	Dioxins and polychlorinated biphenyls (PCBs)	Heavy metals and elements	Mycotoxins	Perfluorinated substances	Plant Protection Products (PPPs)	Plant toxins	Polycyclic aromatic hydrocarbons (PAHs)
Apple (peel and pomace)			√	√		√	√	
Beetroot (peel and pomace)		√	√	√				
BSG	√		√	√		√	√	√
Carrot (peel and pomace)			√	√		√		
Citrus (peel)		√	√	√		√	√	
Corn (gluten meal and germ fiber)		√	√	√	√	√	√	
Potato (peel, pulp, and fruit water)		√	√		√	√	√	
Sugar beet (pulp and molasses)		√	√	√				
Tomato (peel and pomace)			√	√		√		
Wheat (bran)	√		√	√		√	√	√

3.4. *Brewer's spent grain*

During beer production, spent grain is obtained as a side stream via the mash filter and/or lauter tun. This BSG is currently used as animal feed, but research is ongoing into the valorization of this side stream for food applications (Hakme et al., 2024). The literature review revealed three relevant papers on BSG. The paper from Hakme et al. (2024) was added as it was published after the literature review was performed. Furthermore, a thesis from 2017 on mycotoxins in beer was added as it described a screening of 1000 beer samples, which showed that aflatoxins, deoxynivalenol, fumonisins, ochratoxin A, T2/HT2-toxins and zearalenone were found in beer where deoxynivalenol was most frequently present (Peters et al., 2017). As a result, these mycotoxins may also be present in BSG. Grains are susceptible to mycotoxins, and thus, several mycotoxins can be found in beer produced from these grains. Apart from the mycotoxins indicated above, ergot alkaloids, patulin, and other mycotoxins produced by *Aspergillus clavatus* may also be found in grains and could potentially be found in BSG. According to mycotoxin experts who was consulted, ochratoxin A is less water-soluble and, therefore, more likely to be found in BSG than the other mycotoxins. However, since their presence cannot be excluded, it was decided to include all identified mycotoxins as potential hazards for BSG as a worst-case approach. Apart from mycotoxins, the heavy metals cadmium and lead were identified by a heavy metal expert to be potentially present in grains and, as such, might be found in BSG. Furthermore, in total, 53 PPPs could potentially be present in the raw materials used for beer production. Based on the log P_{ow}, 35 PPPs were identified as relevant for presence in BSG. Tropane alkaloids could be present in grains when harvested together with datura. These may subsequently end up in BSG, although the likelihood is estimated to be small. Likewise, polycyclic aromatic hydrocarbons (PAHs) can be present in cereals, and their subsequent presence in BSG cannot be excluded. Nevertheless, the likelihood of finding PAHs is expected to be low. Finally, since BSG is derived from cereals, gluten are identified as relevant allergen to include in the list.

3.5. *Carrot side stream*

During carrot side stream production, carrot juice, carrot peels, and carrot pomace or pulp can be obtained. The literature review did not reveal any relevant papers on chemical hazards in these side streams. Nevertheless, carrot side streams could contain the heavy metals arsenic, cadmium, lead, and mercury since carrots are grown in the soil and can be contaminated via this route. Carrot peels are likely to contain higher levels of heavy metals than carrot pulp or pomace. Scientific and industrial experts as well as the results from the SecureFeed database indicated that these heavy metals are potential hazards for carrot side streams. Apart from heavy metals, fumonisins may be found in carrots, and since these are primarily found on the outer layers of the crop, they might be found in the carrot peel side stream. Finally, 4 PPPs — azoxystrobin, boscalid, difenoconazole, and linuron — were identified as relevant for the carrot side streams. Although more PPPs were identified to be applied for cultivating root vegetables, some of these were not systemic; therefore, these were concluded not likely to be found in carrots or carrot side streams.

3.6. *Citrus peel*

Citrus fruits are used to make juice or pomace. During this production, citrus peel is obtained after pressing the fruits. Citrus pulp resulted in a major dioxin incidence in the late 1990s, the source of which was traced back to the use of contaminated lime in the production process (Hoogenboom et al., 2020). Since then, citrus peels have been regularly monitored for the presence of dioxins. The RASFF database showed one notification for dioxins in dried citrus peels from South Africa in 2016. As a result, this compound was included on the list of potential hazards for citrus peel. Arsenic, cadmium, lead, and nickel are frequently found in fruits and, in some cases, above maximum limits. Scientific and industrial experts as well as the results from the SecureFeed database indicated that these heavy metals might be present in citrus peels. As such, they were included on the list of potential hazards for this side stream. The mycotoxins mycophenolic acid and tenuazonic acid were identified as relevant hazards in fruits, which may end up in citrus peel. Furthermore, citrus plants can produce the plant toxins coumarins and furanocoumarins, which are found at higher concentrations in the peel than in the pulp (Dugrand-Judek et al., 2015). Finally, 50 PPPs were identified as potential hazards for citrus peels; chlorpyrifos is included on the list as it was notified in the RASFF database in 2019 in orange peels.

3.7. *Corn side stream*

During the production of starch from corn, two side streams are produced, i.e., corn germ fiber and corn gluten meal. From the nine references related to corn side streams, four were found relevant based on the full text. These studies all focused on the detection and quantification of mycotoxins. Aflatoxins, deoxynivalenol, fumonisins B1 and B2, and zearalenone were included since they can be present in the raw material and were reported more than 2 % in RASFF, as well as confirmed by scientific and industrial experts. Water-soluble mycotoxins will be removed during pressing, so they are expected to be absent in corn germ fiber. Apart from these mycotoxins, T2/HT2-toxins and ochratoxin A were identified as relevant by the industrial experts. RASFF showed one notification for dioxins in corn gluten meal and corn gluten feed. Its potential presence was also confirmed by the industrial experts and, as such, taken up as a relevant hazard for corn side streams. Arsenic (both total arsenic and inorganic arsenic) is found to be present in corn (Rosas-Castor et al., 2014), and since processing is not expected to remove arsenic present, it was included on the list of potential hazards for corn side streams. Furthermore, cadmium, lead, methylmercury, and nickel could also be present. Perfluorinated substances, such as perfluorooctanoic acid (PFOA), can be found in corn when grown near polluted areas, as shown by Liu et al. (2019). PFOA is not expected to be removed during processing due to its characteristics, so it can end up in corn side streams, as confirmed by the scientific expert. In total, 17 PPPs were identified as relevant. Some of these are water soluble and will be removed during pressing. As such, these will less likely be found in corn germ fiber. However, corn gluten meal, which is the other side stream, can be produced without pressing. Therefore, for this side stream, it is assumed the PPPs can be present. Pirimiphos-methyl was not identified as relevant for corn raw material, but since this PPP was frequently found in corn used for feed (14 % of the samples), it was added to the list. Finally, the plant toxin scopolamine was added as a relevant plant toxin as it can be present in the raw material, and a RASFF notification was found for corn grits.

3.8. Potato side stream

Potatoes may be processed into potato crisps or fries or can be used to produce starch. Although the production processes of crisps and fries differ slightly, the main steps that may affect food safety hazards are comparable, so it was decided that the processing scheme for potato crisps should only be presented to the experts (see Annex 2). Potato peel, potato pulp, and potato fruit water are obtained as side streams during potato processing. The literature review revealed seven relevant papers related to the side streams of a variety of chemical hazards. Potato peels have been implicated in a dioxin incident in 2004, where elevated dioxin levels in milk could be traced back to the use of kaolinic clay in the potato sorting process (Hoogenboom et al., 2010). As such, it is included as a potential hazard for potato peels. The heavy metals cadmium and lead are frequently found in potatoes and, as such, can be expected in the potato side streams as well. Furthermore, nickel is expected to be present, according to scientific experts, although limited knowledge is available at the moment. As a worst-case approach, nickel was included on the list of potential hazards for potato side streams. Perfluorinated compounds, such as PFOA and perfluorooctane sulfonate (PFOS), may be present in the soil and can be taken up by potatoes (Lechner and Knapp, 2011). Further processing into crisps or starch is not expected to reduce the levels present. Therefore, these compounds were also included on the list of potential hazards. In total, 14 PPPs were included on the list. Most of these are used during cultivation, but chlorpropham was previously used during storage to prevent sprouting. It is persistently present in the environment and can thus end up in the potatoes or potato side stream (European Food Safety et al., 2020). The EU authorization of this compound has been withdrawn in 2020 for toxicity reasons. Due to its persistent nature and its potential use outside the EU, this PPP is included on the list. Finally, the glycoalkaloids solanine and alpha-chaconine are added to the list as these naturally occur in potatoes. As such, they may end up in potato side streams.

3.9. Sugar beet side stream

Sugar beets are washed and sliced prior to treatment with hot water to obtain sugar juice. During this process, sugar beet pulp is obtained as a side stream. The literature review obtained one relevant paper on mycotoxins. Fumonisins and patulin or other toxins from *Aspergillus clavatus* were included. The latter has been implicated in a mycotoxicosis in livestock species that consumed barley and sugar beet side streams (Riet-Correa et al., 2013). A RASFF notification from 2018 showed that non-dioxin-like PCBs were found in molassed sugar beet pulp. Furthermore, mercury was notified in pellets produced from sugar beet. Both chemical hazards were thus included on the list of potential hazards for sugar beet. Other heavy metals that potentially could be present are arsenic, cadmium, lead, and nickel. No relevant PPPs were identified to be included on the list of hazards.

3.10. Tomato side stream

Tomatoes may be processed into tomato paste or tomato juice, during which two side streams - tomato pomace and tomato peel - are obtained. The literature review retrieved two relevant papers that described the presence of PPPs in tomato side streams. Overall, 40 PPPs were included on the list of potential hazards for tomato pomace and tomato peel based on their potential presence in the raw materials and the fact that further processing could not exclude their presence in the side streams. The heavy metals cadmium and lead were identified as potential hazards, although high levels are not to be expected. Furthermore, *Alternaria* toxins, such as tentoxin and tenuazonic acid, may be found in tomatoes, which could end up in the side streams. In general, the levels of tomatine in tomatoes are low, although they are high in green tomatoes. One might find higher concentrations in the seeds. Tomatine would probably survive most steps, e.g., in the case of tomato paste there could be a concentration effect.

3.11. Wheat side stream

During the production of wheat flour, wheat bran is obtained after the milling step. The literature review obtained 11 relevant papers describing the potential presence of mycotoxins, PPPs, and heavy metals. A range of heavy metals, i.e., arsenic, cadmium, chromium, lead, methylmercury, and nickel, might be present in wheat. As such, their presence in wheat bran cannot be excluded, and these hazards were included on the list of potential hazards for this side stream. Cereals are susceptible to mycotoxin contamination. When present in wheat, they are more likely to end up in the wheat bran as mycotoxin concentrations in the outer layers are usually higher than in the kernels. Therefore, aflatoxins, deoxynivalenol, ochratoxin A, T2/HT2-toxins, and zearalenone are included as potential hazards for wheat bran. As indicated for BSG, tropane alkaloids can be present in cereals. Subsequent presence in wheat bran can thus not be excluded. Finally, 23 PPPs were included on the list of potential hazards for wheat bran. Furthermore, gluten was added as relevant allergen since wheat bran is derived from wheat known to induce gluten allergy.

4. Discussion

This study resulted in an overview of chemical hazards that may end up in relevant side streams. Although some of the side streams are currently being used in feed, their use in food is in its early stages. The literature review showed that limited information is currently available on this topic. Combining databases and expert elicitation helped filling the limited data found in the reported literature. Expert elicitation can provide valuable insights, although there is a risk of subjectivity as the outcome is influenced by the method applied and the experts selected. We used a structured approach in which processing schemes were provided to the experts and a list of chemical hazards that had been identified as relevant in raw materials. Based on the processing schemes, the experts could indicate whether they expected certain hazards to be present or not in the obtained side streams. In case experts did not know, a worst-case assumption was used, assuming the hazard remained present in the side stream. As such, we managed to capture relevant information from both experts knowledgeable on the behavior of chemical hazards during processing and experts from the industry who are more knowledgeable about the production process itself. Combining both insights helped to prioritize the initial list of potential hazards.

Several methods are available to prioritize hazards. These methods range from qualitative, e.g., solely based on expert judgment, to quantitative methods, in which human health risks are calculated based on expected concentrations in the end product, consumption patterns, and estimated health-based guidance values. The more quantitative a method is, the more time and financial resources it takes, but above all, data is needed to finalize the task. As indicated previously, the use and reuse of side streams is an upcoming field for which limited data and information are available. Therefore, a more qualitative approach was used to come to a final, prioritized list of potential hazards that are relevant for the side streams included in this study. Nevertheless, a structured approach was applied, incorporating all available information and implementing various sources of information. Several factors were scored binarily. We used a list of hazards identified in raw materials as a starting point and included these when their presence was confirmed either in the literature review on side streams, by scientific experts or industrial experts, or when RASFF notifications above 2 % were found for the side stream. For PPPs, we used additional information on the characteristics to determine their presence in the side streams. The resulting list of chemical hazards is provided in Table 2, with more details in Annex 3. Once more data becomes available, a more quantitative evaluation becomes possible.

The prioritized list shows that citrus peel had the longest list of potential chemical hazards (n = 59), whereas root vegetables such as beetroot, sugar beet, and carrot had the lowest number of potential chemical hazards (n = 7, 8, or 9, respectively). The results have been summarized in a web-based tool: www.fsbd.wur.nl (Riley et al., 2024). The most frequently encountered hazards in the various side streams are mycotoxins, heavy metals, and PPPs. Mycotoxins are produced by fungi pre- or post-harvest, depending on the conditions. The type of mycotoxins to be expected is crop-dependent (Sweeney and Dobson, 1998). For instance, cereals are vulnerable to infection by *Fusarium* spp. and *Aspergillus* spp., and they are, therefore, associated with a wide variety of mycotoxins (Hassan et al., 2019; Khodaei et al., 2021; Mousavi Khaneghah et al., 2018). Tomatoes, on the other hand, have been identified as a major contributor to dietary exposure to *Alternaria* toxins (European Food Safety Authority et al., 2016). These mycotoxins are usually present at higher concentrations on the outer layers of the crop, e.g., wheat bran, when compared to the inner parts. Most mycotoxins are heat stable, and, thus, during processing, they will remain in the product and can end up in the side streams, especially when the outer layers, such as the peel, are used as side streams (Hoffmans et al., 2022). In general, peels will contain higher levels of other chemical hazards than the inner parts of the crop. This has, for example, also been demonstrated for heavy metals (Davies and Crews, 1983) and plant toxins (Friedman, 2006; Nie et al., 2018; Ostry et al., 2010). Heavy metals may be present in the soil and are known to be taken up by plants. Therefore, their potential presence is expected in the plant-based side streams included in this study. Nevertheless, levels are expected to differ depending on the side stream and quality of the soil the crop was grown in. In general, it can be assumed that root and leafy vegetables absorb higher levels of heavy metals than stems and fruits because they are in closer contact with the soil (Manzoor et al., 2018). PPPs are identified as relevant for most of the side streams, as PPPs are regularly applied during crop cultivation to combat fungi, insects, etc. For the root vegetables beetroot and sugar beet, no PPPs were identified as relevant. Foliar application of several herbicides does not appear to result in residues that are harmful to consumers (Cheng et al., 2024). In the past, neonicotinoid pesticides were allowed to be used as a seed treatment for these types of crops, but field applications in the EU were banned after a risk assessment showed potential harm for pollinating bees (see, e.g., Regulation (EC) 2018/783 and European Food Safety Authority (2018)). For some time, national emergency exemptions had been allowed for continued field use, but a 2023 ruling by the Court of Justice of the EU (CJEU) put an end to this (judgment in C-162/21). Several alternative strategies have been suggested for pest management of these types of crops (Verheggen et al., 2022; Vojvodić and Bažok, 2021).

Many of the specific side streams considered in this assessment have a history of use as feed rather than food. Risk-based monitoring of chemical hazards in feed materials is already in place in many countries (Van der Fels-Klerx et al., 2017), and the product-specific basis for this monitoring could be used to inform the safety of redirecting such materials to food rather than feed. This approach can also be used to gather more insights into the concentrations of specific hazards to be anticipated in such side streams, although it must be noted that the different types of processing to make these materials human-edible can alter their safety profiles. The overview provided in this paper can be seen as a list of hazards that can potentially be present in side streams. To our knowledge, this is the first study presenting a method for ranking chemical hazards in side streams. The ranking was primarily based on qualitative information and, in some cases, is based on worst-case assumptions due to the limited availability of data. Therefore, it does not provide insight into the levels to be expected. Instead, it can be used as a basis for food producers when drafting a HACCP plan and designing monitoring plans and can provide insights in the short to long term FBOs' food safety preparedness. The effect of further processing from using side streams as ingredients and producing a food product was not assessed in this study and should be taken up in a HACCP plan. As the use and reuse of side streams are anticipated due to the transition towards circular food systems, it is expected that the amount of information on food safety hazards will increase in the coming years. Once more information becomes available, the identified list of hazards can be updated.

Ethical statement

The authors declare that no human or animal studies were performed within the research described in this paper.

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CRediT authorship contribution statement

E.D. van Asselt: Writing – original draft, Supervision, Validation, Methodology, Funding acquisition, Project administration, Formal analysis, Conceptualization. **N. Dam:** Writing – review & editing, Investigation, Visualization. **W. Tao:** Investigation, Writing – review & editing. **N. Meijer:** Writing – original draft. **R.M. de Jongh:** Visualization, Writing – review & editing. **J.L. Banach:** Investigation, Writing – original draft, Conceptualization, Formal analysis.

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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Supplementary materials

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Data availability

Data will be made available on request.

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