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Sustainable food chains designed for optimised resource use: Optimising downscaled food chains for sustainable resource use: A comprehensive case study on tomato juice

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ABSTRACT

As consumers increasingly prefer locally sourced food, there is a growing movement towards optimising resource use and reducing emissions in supply chains. While Short Food Supply Chains (SFSCs) traditionally emphasise social and institutional proximity, this study strategically addresses the environmental impact by implementing innovative technologies on a smaller scale. This article explores the possibility of implementing a mobile processing unit (FOX unit) that utilises two innovative technologies, one for gentle juice extraction (spiral filter) and the other for preservation of freshly pressed products (pulsed electric fields - PEF). The study investigates a solution that could streamline the supply chain between producers and consumers by offering a decentralised and modular approach to processing. Using Life Cycle Assessment (LCA), tomato juice production is compared under traditional thermal pasteurisation (Scenario 1) and the FOX unit (Scenario 2). This study also assesses the impacts of centralising production and shipping raw materials between countries (Scenario 3), considering the FOX unit as part of the evaluation. Further analysis includes relocating this unit to the countries of raw material origin (Scenario 4). Data retrieved from literature, databases, and practical trials, revealed that tomato juice production with the FOX unit led to a 15% reduction in environmental impact across all categories compared to traditional thermal pasteurisation. When relocating the unit, the overall environmental impact decreased as the volume of processed raw materials increased, reaching levels comparable to the results obtained from shipping 1 ton of raw material to a centralised location in various studied countries (with variations in midpoint categories depending on the location, such as 200 tons in France, 15 tons in Italy, and 45 tons in Spain), albeit with variation in the categories. This study highlights the potential environmental benefits of integrating the FOX unit in SFSCs, offering valuable insights for sustainable food supply chain practices.

1. Introduction

Food waste and loss continue to rise, despite ongoing efforts to reduce them in the food industry. Fresh products, particularly fruits and vegetables, are particularly vulnerable to wastage due to their perishable nature and sensitivity to various factors (FAO, 2019). Inefficiencies and logistical challenges throughout the production chain contribute to these losses (Aschemann-Witzel et al., 2019; Ojha et al., 2020; Read et al., 2020). While establishing direct connections between producers and consumers may contribute to reducing food waste (Jarzębowski et al., 2020), it is recognised that the impact on environmental emissions is subject to several variables, including transportation methods, production practices, and supply chain configurations. Additionally, as defined by the European Union (EU), Short Food Supply Chains (SFSCs) involve “a limited number of economic operators committed to cooperation, local economic development, and maintaining close geographical and social relations between food producers, processors, and consumers” (EUFIC, 2021). SFSCs offer producers opportunities for increased profits and allow consumers to easily trace the source of their purchases (Jarzębowski et al., 2020; Kriewald et al., 2019).

However, it is important to note that the environmental

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List of abbreviations

SFSCs	Short Food Supply Chains
PEF	Pulsed Electric Fields
LCA	Life Cycle Assessment
EU	European Union
HPP	High Pressure Processing
SDGs	Sustainable Development Goals

sustainability of SFSCs is a complex and debated topic. While often associated with greater social benefits (EUFIC, 2021) and potentially higher profit margins (Malak-Rawlikowska et al., 2019), their environmental impact can vary. For instance, Majewski et al. (2020) point out the potential higher emissions per kilogram of product in short chains than in long chains. On the other hand, research from Malak-Rawlikowska et al. (2019) suggests that environmental sustainability is a nuanced aspect of SFSCs. Moreover, recent conceptual frameworks proposed by Thomé et al. (2021) shed light on the coexistence of both types of chains, challenging the conventional narrative of their opposing models. This framework emphasises factors such as convergence of interests and the need to add value, revealing the intricate ways these chain models interact—independently, competitively, cooperatively, or coordinatively. Additionally, Smith et al. (2016) demonstrate the resilience of both short and long-food chains during severe weather events, underscoring the importance of considering key resilience elements such as scale, diversity, flexibility, and cohesion.

Consumers tend to trust products purchased closer to their source (EIT Food, 2021), supporting the development of short chains; challenges arise when scaling down processing technologies. Food chains are global and optimised for high volumes. Technologies like thermal processing (Lee et al., 2020), which are cost-effective, may not easily scale down due to factors like initial investment, space requirements, and electrical power availability (Sampedro et al., 2014). Emerging technologies, such as high-pressure processing (HPP), pulsed electric field (PEF), and ultrasound, offer cost-effective alternatives for processing even small volumes. These technologies have advantages, including lower capital costs, lower operational costs, shorter processing times, and scalability potential (Aganovic et al., 2021). Consumers' preference for minimally processed products drives the adoption of these technologies (Siemer et al., 2014).

In 2017 (Aganovic et al., 2017) reported that the food industry had over 250 HPP and over 40 PEF units worldwide, but those numbers have more than doubled in 2023 (Personal Communication, 2024). It is noteworthy that classical technologies that can have higher operational costs and processing times can sometimes surpass emerging technologies in terms of cost and time efficiency. Studies (Atuonwu et al., 2018; Khan et al., 2017; Picart-Palmade et al., 2019) indicate that emerging technologies may consume more energy and water, adding a layer of complexity to this comparison with classical methods. A processing decentralisation strategy offers several potential benefits related to local sourcing and strengthening local economies. This also provides resilience and adaptability to the chains, as they become less vulnerable to supply chain disruptions (e.g., natural disasters, transportation issues, conflicts, or others).

While SFSCs and the implementation of innovative technologies are recognised for their potential to reduce environmental impact, there exists a gap in the literature concerning the specific environmental implications of scaling down processing technologies within SFSCs. This study contributes to filling this gap by providing insights into the environmental performance of the FOX unit, a mobile processing unit, compared to traditional thermal pasteurisation. Furthermore, our research addresses the practicality of transporting mobile processing units versus centralising production, which has received limited attention in the current literature. Understanding the environmental impact of scaled-down processing technologies is crucial for shaping sustainable food chains.

Projects like FOX ("Innovative down-scaled food processing in a box", GA 817683) and RADIANT ("Realising Dynamic Value Chains for Underutilised Crops", GA 101000622) funded under the H2020 Research and Innovation initiative, collaboratively seek to revolutionise food chains by developing innovative and sustainable solutions. The FOX project focuses on designing, building and evaluating decentralised and small-scale mobile processing units, reducing the need for long-distance transportation. One of three mobile processing prototypes developed processes for turning fruits and vegetables into juices or purees. This prototype is named the "FOX unit" in this article. RADIANT promotes crop diversification and environmental preservation while integrating underutilised crops into existing chains. Collaboration between these projects explores innovative solutions and exemplifies the convergence of sustainable practices and innovative processing methods.

Building upon the established success in apple production, as demonstrated by Zdravkovic et al.'s (2021) study, this research aims to extend the understanding of the FOX unit's capabilities by evaluating its performance in tomato juice production. Considering the distinctive nature of tomato processing and its significant role in the EU agricultural landscape (with more than 200 tomato processing entities, which transform more than 9.5 millions tons of fresh tomatoes into tomato derivatives annually (TomatoEurope, n.d.), it becomes imperative to explore the FOX unit's adaptability to different crops. This study seeks to uncover potential variations in outcomes, contributing valuable insights into the broader applicability of the FOX unit across diverse agricultural contexts. By bridging the gap between previous applications in apple production and our current focus on tomatoes, we aim to enhance our understanding of the FOX unit's role in fostering sustainable practices within the food industry.

This research aims to answer several key questions: Can the environmental impact of a food chain, such as tomato juice production, be reduced by scaling down processing and shortening the supply chain? What are the advantages of switching from thermal to PEF processing technologies? When is it more practical to transport a mobile processing unit like the FOX unit to a region with raw materials rather than shipping them to a central location? Ultimately, this study sheds light on how collaborations between projects like these shape the landscape of sustainable food chains, with a specific focus on evaluating the environmental impact of producing tomato juice with traditional (thermal pasteurisation) or novel technology (PEF) using the FOX unit. For the processing capacity for the thermal pasteurisation line, the values as (Zdravkovic et al., 2021) and 154 L/h for the FOX unit were utilised. Additionally, it assessed the environmental impact of transporting the FOX unit to raw producers' locations versus centralising production. The functional unit for this study was 1 kg of packed tomato juice at the factory gate.

2. Methodology

The Life Cycle Assessment (LCA) was conducted according to ISO standards 14040-14044 (ISO, 2006a, 2006b). Employing the prospective attributional LCA approach (Hospido et al., 2010), the study compared the environmental impacts of traditional thermal pasteurisation and novel pulsed electric fields (PEF) technology using the FOX unit. The FOX unit, developed under the FOX project (GA 817683), underwent initial validation with apples as raw material (Zdravkovic et al., 2021). The same paper describes the system's construction, parts, and experimental parameters. Parameters for tomato processing were optimised for tailoring the tomato juice processing: (1) feed pump of 30 % and (2) mill of 100 %. The 4- and 6- 6-channel compression spirals were used for the juice extraction with 220 μm sieve pore size. Sieves with smaller pore sizes were tested, but the obtained juice was effectively just transparent liquid. The difference in the sieve between both studies accounts for higher water content between the different fruits processed (tomatoes have ~ 90–95 % water content (Hou et al., 2020), and apples have ~ 80–85 % (Rasooli Sharabiani et al., 2021)) The tomato juice was constantly mixed during production in the buffer tank with the in-built mixer due to the tendency of the juice for phase separation.

2.1. Description of the FOX juice production system

The FOX unit, located at DIL e.V. (Quakenbrueck, Lower Saxony, Germany), processes tomatoes using a Multicut unit, vacuum spiral filter (Vaculiq, Vacuum Spiral Filter, GEA, Germany), Liquid Handling System (LHS) (with pre-heating at 35 °C), PEF treatment (voltage of 16 kV and a specific energy of 110 kJ/L, reaching a temperature of 70 °C), cooling system (cooling the product below 10 °C to reduce the thermal load and prevent the loss of thermally sensitive compounds), and filling unit. More detailed information can be found in (Zdravkovic et al., 2021).

2.2. Modification and adaptation of a thermal pasteurisation juice model

The classic juice pasteurisation unit was modelled with data from the Agribalyse database (version 3.1) (ADEME and INRAE, France). The model consisted of processing Spanish, Italian and French tomatoes in France. In the adapted model tomatoes were collected from France, Spain and Italy and shipped to be processed in Quakenbrück, Germany. The tomatoes would be sent by train from the countries' capital's central station to Hannover main station (Lower Saxony) and then transported to the processing facility via lorry (approximately 125 km). They would be processed and pasteurised as in the original process (Fig. 1).

2.3. Life cycle assessment of tomato juice production systems (Scenarios 1 and 2)

The LCA compared environmental impacts of processing tomato juice with traditional thermal pasteurisation (Scenario 1) and the FOX unit (Scenario 2). System boundaries were cradle-to-processing gate (Fig. 2), with both scenarios using the same tomato production model (tomatoes from France, Italy and Spain) and the only difference is the processing technology: thermal pasteurisation (Scenario 1) or PEF (Scenario 2). This data was then run by SimaPro (version 9.4.0.2, PRé Sustainability B.V., Amersfoort, the Netherlands) software, using the IMPACT 2002 + V2.12 methodology. Table 1 summarises all the inputs and outputs for both scenarios (1 and 2) (see Fig. 3).

2.4. Environmental impact of moving the unit (Scenarios 3 and 4)

FOX, being a mobile processing unit, offers several advantages. One of these benefits is the ability to position it closer to the source of raw materials, which was implemented in the project. As a result, two new scenarios were developed to assess the environmental impact of (1) centralising production (FOX unit, located in DIL e. V. in Quakenbrück, Lower Saxony) and shipping raw materials between countries (Scenario 3), and (2) relocating the unit to the countries of raw material origin (France, Spain or Italy) (Scenario 4).

To calculate the environmental impact in Scenario 3, a reference point of shipping 1 ton of tomatoes from France, Spain, or Italy to Germany was used and processed in the mobile unit. In Scenario 4, the transport of the unit was modelled from Quakenbruck, Germany, to the capital cities of the respective countries (Paris for France, Madrid for Spain, or Rome for Italy) and the processing of varying amounts of produce until the environmental impact in both scenarios becomes equal.

3. Results and discussion

The yield of the extraction process in the FOX unit with tomatoes was 78.52% (w/v), while it was 54.04% (w/v) for thermally pasteurised tomato juice. It is worth noting that during this process, 8.10 % of tomato pomace was generated, which holds economic value. Furthermore, the tomato juice exhibited a high electrical conductivity of 5.3 mS/cm, which allowed the FOX unit to operate optimally at a processing capacity of approximately 200 L/h. Importantly, no phase separation was observed in the obtained juice and puree, this is due to enzymes. Regarding energy consumption, measurements in the FOX unit revealed that 75.84 kW of energy was used when processing 1000 kg of tomatoes.

Regardless, an industrial line with thermal pasteurisation is known to have a higher processing capacity than the mobile unit's. Besides this,

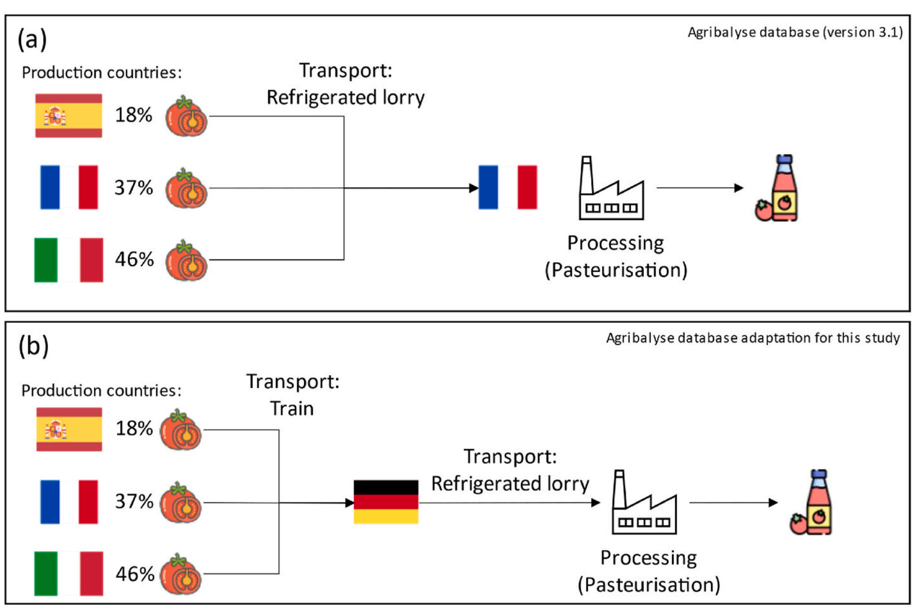

Fig. 1. Adaptation of the data available in the Agribalyse database for modelling the scenario of tomato juice processing and production in Germany. On top is the diagram of the original data, whereas the bottom of the figure shows the remodelled and adapted data for juice production in Germany. The percentages in the figure show the ratio of tomatoes from the different countries used to create the final tomato juice.

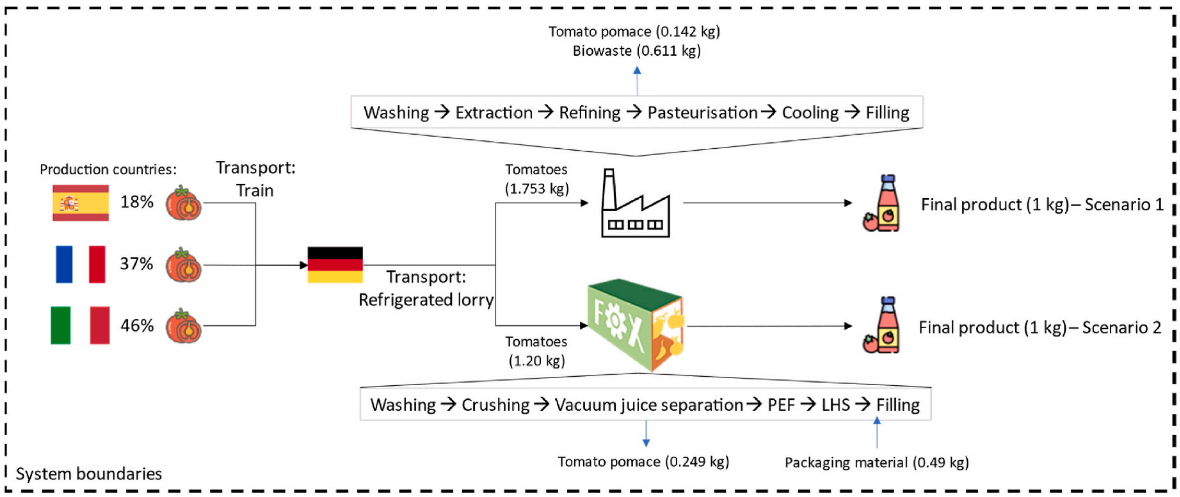

Fig. 2. System Boundaries for Scenarios 1 and 2. Scenario 1 relates to producing 1 kg of thermally pasteurised tomato juice, and Scenario 2 relates to producing 1 kg of PEF-treated tomato juice. The arrows in scenario 1 refer to the outputs from the complete processing chain, whereas in scenario 2, there are both (material) inputs and outputs in specific parts of the chain.

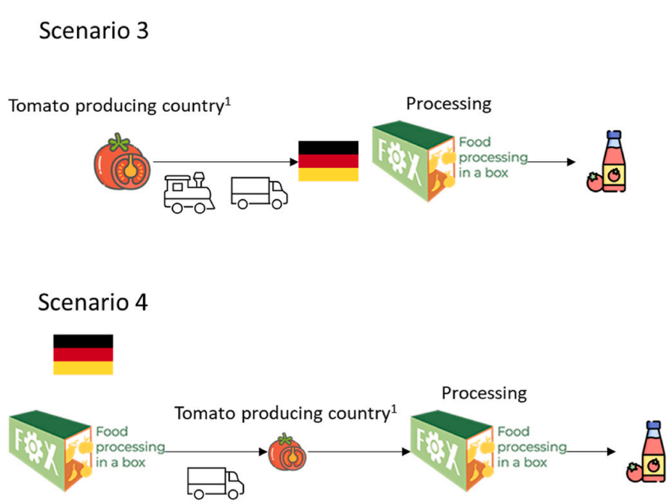

Fig. 3. Possible scenarios of working with the mobile unit. (1) The country in the case can be one of three: France, Italy or Spain. In scenario 3, the unit is centralised (in this case, in Germany, Lower Saxony), and juice production occurs with raw materials from other countries (100 % raw materials from either France, Italy or Spain, transported via train and lorry). In scenario 4, the unit is shipped via lorry to the tomato-producing countries (France, Italy or Spain), and processing occurs with local produce.

Table 1
Inputs and outputs for scenarios 1 (thermal pasteurisation) and 2 (Fox unit system) for 1 kg of packed tomato juice.

	Unit	Scenario 1 Thermal pasteurisation	Scenario 2 FOX unit (PEF)
Inputs			
Tomato	kg	1.75308642	1.199372
Electricity	kWh	0.043412	0.089269
Nitrogen (gas)	kg		0.002399
Water	kg	1.281215	3.245739
Chlorine	kg	0.000969	
Heat	MJ	0.127485	
Transport			
Lorry (with refrigeration)	tkm	0.582726	0.199336
Lorry (no refrigeration)	tkm	0.00437	
Train (with refrigeration)	tkm	4.951687	1.693845
Train (no refrigeration)	tkm	0.00532	
Ship	tkm	0.00684	
Packaging			
Cardboard box	kg		0.039723
Bag (for bag-in-box filling)	kg		0.010075
Plastic bottles	kg	0.038	
Outputs			
Packed juice	kg	1	1
Waste (pomace)	kg	0.142	0.249169
Waste (biowaste)	kg	0.61108642	
Heat	MJ	0.050994	
Wastewater	m3	0.000399	

the obtained final product is different organoleptically: consumers report that PEF-treated juice has a more similar organoleptic profile to the freshly squeezed juice, whereas the pasteurised juices are very different (Lee et al., 2020). Besides this, while thermally pasteurising juice, many thermally volatile nutrients are lost while being retained with PEF treatment (Lee et al., 2020).

3.1. Life cycle assessment of tomato juice production systems (Scenarios 1 and 2)

In Scenarios 1 and 2, this study explores the feasibility of integrating the FOX system, particularly emphasising shortening the distance between producers and consumers in the supply chain. This focus on proximity and its implications on supply chain dynamics presents a novel angle, offering insights not extensively explored in the previous research by Zdravkovic et al. (2021). The environmental footprint associated with 1 kg of tomato-packed juice is reduced when pasteurised using innovative technology like PEF, as illustrated in Fig. 4. The environmental impact is notably lower compared to the traditional thermal pasteurisation method. In Scenario 1, which involves a tomato mix and pasteurised juice, the environmental impact is generally higher across all categories except for aquatic eutrophication (not displayed) and mineral extraction. These distinctions have been observed and substantiated through Monte Carlo Analysis, particularly in the Single Score category.

Furthermore, the input amount of raw materials (which is different for both scenarios) indeed affects the final results. However, it is important to refer to the functional unit in these cases (1 kg of juice). As two processing lines are compared, it is normal for them to present different yields (hence the different volumes of input), which means that the final product will have a different environmental impact.

The FOX unit should undergo cleaning each time a new batch of juice is produced to prevent any potential contamination from the previous batch. Additionally, there is the option to clean it either at the end of the

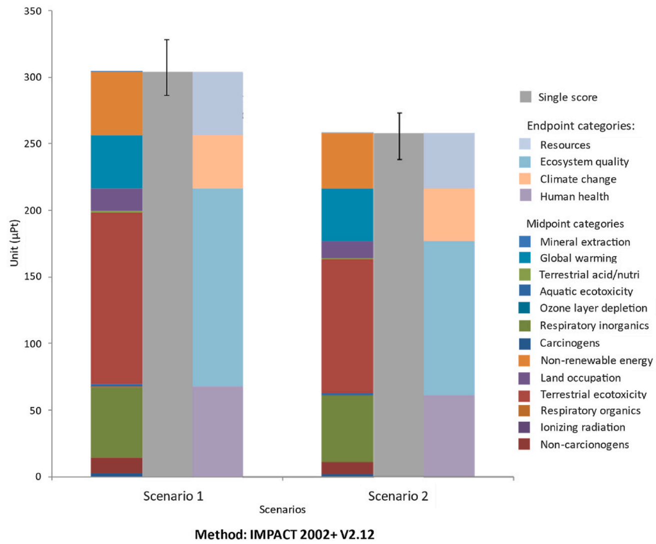

Fig. 4. Environmental impact of Scenarios 1 (Pasteurised tomato juice) and 2 (PEFed tomato juice). The first bar from each group shows the damage categories (endpoints); the second bar shows the single score and the uncertainty (with 10000 Monte Carlo Runs) associated with it; the third bar shows the midpoints of these processes. The production of 1 kg of packaged pasteurised juice is 17.6 % higher than that of PEFed juice.

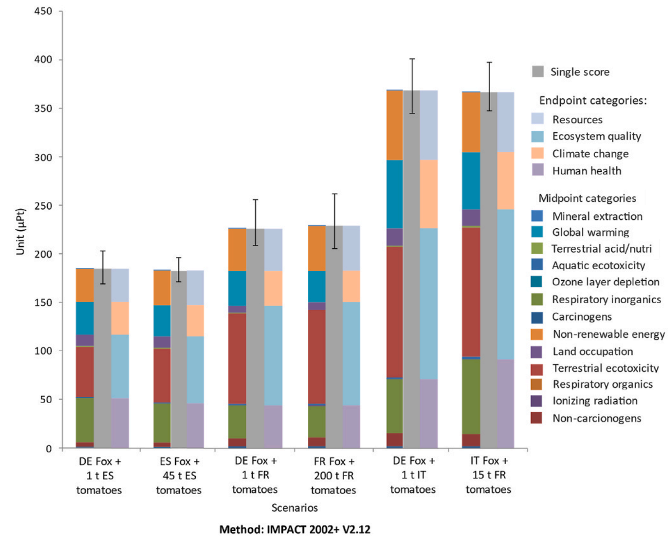

Fig. 5. Environmental impact of scenarios 3 (FOX in Germany (DE) + 1 t of tomatoes from different countries) and 4 (transport of FOX to different countries (ES – Spain; FR – France; IT – Italy) + different amounts of local tomatoes) per kilogram of processed and packed tomato juice. The first bar from each group shows the damage categories (endpoints); the second bar shows the single score and the uncertainty (with 10000 Monte Carlo Runs) associated with it; the third bar shows the midpoints of these processes. The volume of local tomatoes varies from country to country to find the break-even point of both scenarios.

production day or once a week, particularly when continuous production of the same juice occurs over an extended period. It is worth noting that neither scenario considered the impact of cleaning the facilities and equipment, as this varies from one company to another. Including a cleaning step, which typically involves the use of water, soap, and a NaOH solution, results in a 2.1 % increase in the environmental impact of Scenario 2, approximately equivalent to 5.43 µPt (data not shown).

3.2. *Environmental impact of moving the unit*

The mobility of the FOX processing unit offers a unique opportunity to streamline the production chain and provide consumers with direct access to fresh juice. However, this advantage comes with some trade-offs. Scenarios 3 and 4 assess the environmental consequences of centralisation versus local processing. These scenarios contribute to a more comprehensive understanding of the potential environmental consequences and benefits of different supply chain configurations. This expansion expands the scope of (Zdravkovic et al., 2021), providing a more nuanced exploration of the scenarios that could influence the environmental impact of the FOX system implementation.

SimaPro was used to calculate the break-even point, where the emissions associated with shipping the raw materials to Germany (Scenario 3) and processing them in the unit become equivalent to sending the unit to the countries where the raw materials are produced (Scenario 4). At this break-even point, the environmental impact of shipping 1 ton of raw material from different countries (Spain, France, or Italy) and processing it in Germany matches that of sending the unit and processing varying amounts of local raw materials (approximately 200 tons for France, 15 tons for Italy, and 45 tons for Spain), as depicted in Fig. 5. Increasing the volume of raw material processed in any of these countries further reduces the environmental impact of the final product (Fig. 6).

The juice with the lowest environmental impact is from Spanish tomatoes. This is because tomato production in Spain requires fewer inputs, unlike the other two countries (see Table 2). Two key factors influence the environmental impact values: the distance of transport and the production of raw materials. The FOX unit weighs approximately 15 tons and can only be transported by lorry, which increases its environmental footprint, potentially surpassing the impact of shipping raw materials and processing them in a centralised country like Germany. However, transporting raw materials from different countries can also involve train transportation (at least partially), which can mitigate the environmental impact. Nevertheless, it is crucial to recognise that raw material production remains the most significant contributor to the overall environmental impact.

3.3. *Contribution analysis*

Scenario 2 stands out with reduced environmental impact. The figure below illustrates the contribution of each stage in the current PEF tomato juice production process. On average, the stage that consistently exerts the most significant impact across various environmental categories is the production of raw materials, ranging from 14 % to 94 % (Fig. 7). Therefore, if the goal is to diminish the environmental impact of this process, targeting improvements in the raw material production stage should be a priority.

Various strategies are available for reducing the environmental impact of sourcing raw materials, as highlighted by Silva et al. (2023). However, it is crucial to recognise that these strategies cannot be applied indiscriminately, as their implementation can create a ripple effect throughout the entire supply chain. First, the environmental impact of a crop is closely tied to the chosen farming method, and different methods can yield varying environmental outcomes (Commission on Sustainable Agriculture and Climate Change, 2012; Nemecek et al., 2010). Therefore, any adjustments or shifts in cultivation methods will inevitably lead to changes in emissions during this stage (Barreiro-Hurle et al., 2021; Weituschat et al., 2022). Moreover, Scenario 3 illustrates that the selection of different sources of raw materials can result in varying emission levels. In this case, using tomatoes from Spain yields a lower environmental impact than tomatoes from France or Italy or a combination of the three sources. This shift translates into a notable reduction of 6 %–52 % across various environmental impact categories (specific data not shown).

Lastly, several studies (Commission on Sustainable Agriculture and Climate Change, 2012; RADIANT Project, 2021; Silva et al., 2023)

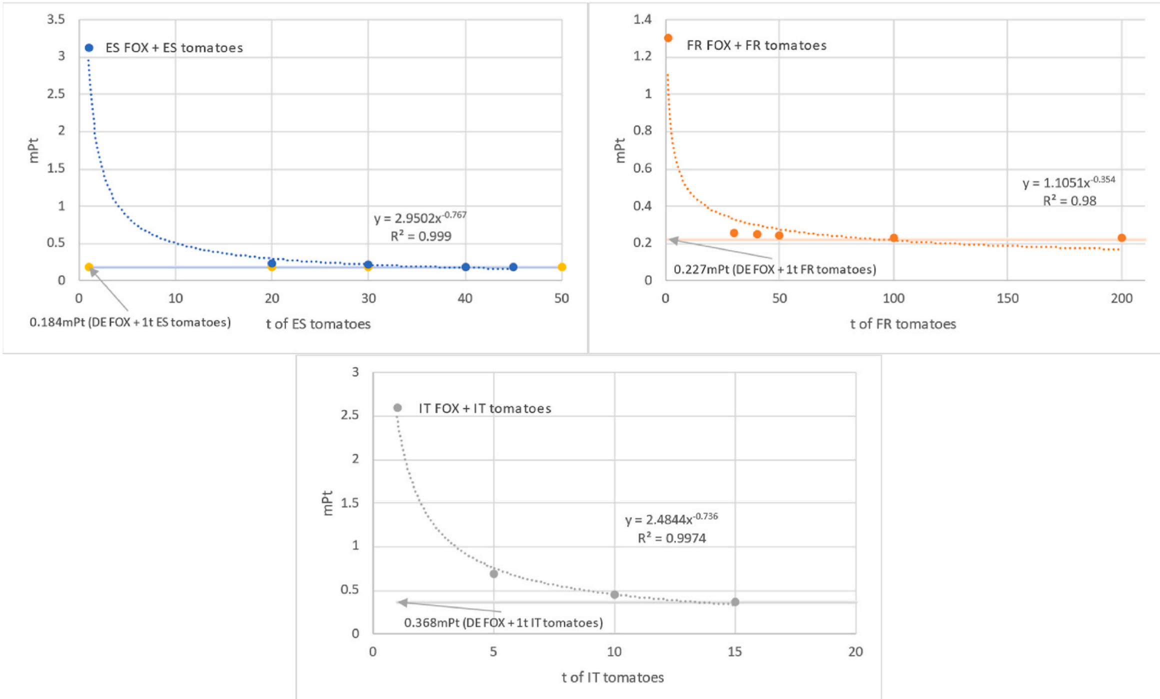

Fig. 6. Break-even point for Scenario 3 (FOX in Germany (DE) + 1 t of tomatoes from different countries [line]) and 4 (transport of FOX to different countries (ES – Spain; FR – France; IT – Italy) + different amounts of local tomatoes) per kilogram of processed and packed tomato juice). The environmental impact of 1 kg of packed juice produced by the mobile unit in different countries (Spain, France and Italy) with local raw materials decreases with the amount of processed material. The intersection of the lines in the graphs corresponds to the point where the environmental impacts of both scenarios equalise; from then forward (following the equations generated from the charts), the higher the volume of local raw material processed, the lower the impact.

Table 2
Main inputs and outputs in tomato production in the three countries. This table presents key inputs and outputs associated with tomato production in three countries (Spain, Italy, and France). Data sources include ecoinvent (ES and IT) and agibalyse (FR), with process names matching those in the respective databases. The table also incorporates World Food LCA Database (WFLDB) information. Note: Descriptions at the top of the table correspond to database process names.

	Tomato, processing grade, open field, at farm {ES} - Adapted from WFLDB U	Tomato, processing grade, open field, at farm {IT} - Adapted from WFLDB U	Tomato, average basket, conventional, soil based, non-heated greenhouse, at greenhouse {FR} U
Outputs			
Yield	103,000 kg	71,000 kg	159,100 kg
Inputs			
Occupation	10,027 m^2a	10,027 m^2a	n.d.
CO_2	10,354 kg	7137.3 kg	12,256.01 kg
Water (river)	4404.9 m^3	1211.4 m^3	4912.5 m^3
Water (well)	2599.1 m^3	588.57 m^3	n.d.
Tomato seedling	23,000 p	34,000 p	10,500 p
Energy	93,076 MJ	64,159 MJ	121,016.1 MJ

advocate for incorporating underutilised crop species to enhance resilience and combat the effects of climate change. These lesser-known crops possess unique characteristics that enable them to thrive in diverse climates and landscapes. Additionally, they often offer high nutritional value, providing a wide range of essential nutrients that can enhance food security and human health (Weituschat et al., 2022). These alternative crops can complement or even replace some commercially dominant counterparts, reducing the overall environmental impact (Mabhaudhi et al., 2018). Decreasing the environmental impact of the production of raw materials might lead to a decrease in the impact across the chain (Ritchie et al., 2020; Silva et al., 2023).

3.4. Geographical dimension and added value of the FOX unit

The geographical dimension plays a crucial role in evaluating the FOX unit's overall impact and added value, particularly in the context of tomato processing. Our study has focused on the benefits derived from the FOX system, emphasising its potential to optimise SFSCs and reduce environmental impacts. However, the FOX unit's effectiveness is tied to the geographic proximity of the processing unit to the raw material sources. One of the significant advantages of the FOX unit becomes evident when it is employed by small-scale producers processing local raw materials for local retailers. The technological capabilities of the FOX system, coupled with the reduced transport of raw materials, create a scenario where small processors can add substantial value to their products. This not only enhances the quality of the final product but also allows for the possibility of commanding higher prices in local markets. However, long-distance transportation of the final product may offset environmental gains during processing. For instance, if processed tomato juice from South Europe is transported to Germany for consumption, the environmental benefits accrued during processing may be offset by the emissions associated with transportation.

4. Limitations of the study

While our study sheds light on the potential benefits of creating more resilient SFSCs using a mobile unit, it is essential to acknowledge certain limitations: a) Focus on Environmental Impact: Our study primarily concentrated on assessing the environmental impact of tomato juice production using the FOX unit in comparison to thermal pasteurisation.

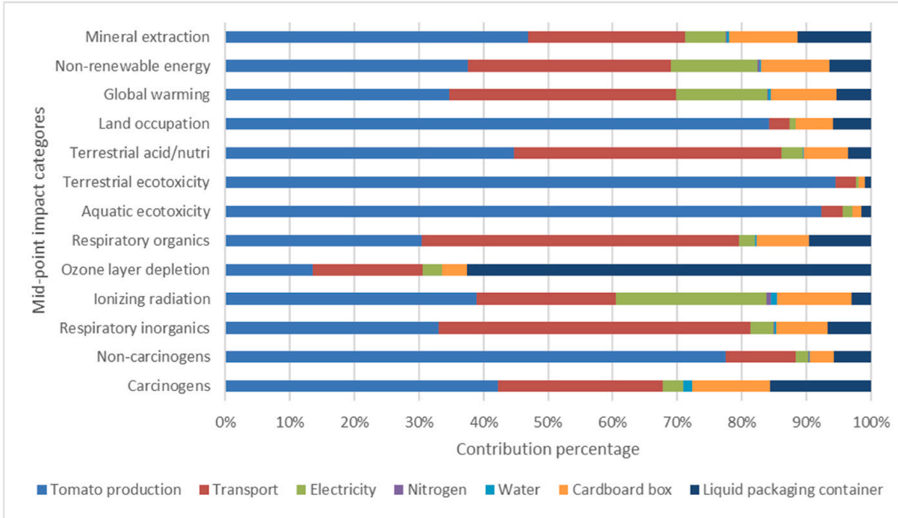

Fig. 7. Contributional analysis for Scenario 2. Here, it is possible to see the contribution of each stage of the process. The category"Tomato production" includes the impact of the production of tomatoes in three countries (Italy, France and Spain). The category "Transport" consists of transporting tomatoes from those countries to Germany via lorry and train.

The results were generated using available databases and real data. However, the inherent limitations of the LCA methodology, such as data availability, quality, system boundaries, and allocation methods, should be considered when interpreting the environmental impact findings; b) Exclusive Environmental Perspective: The study primarily explored the environmental impact of implementing the FOX unit in SFSCs and did not address other potential economic and social benefits associated with SFSCs; c) Geographical Specificity: Our analysis was conducted within the context of three European countries, and implementing the mobile unit in different regions could yield significantly different results, potentially altering the environmental impact of SFSCs; d) Data Quality and Variability: The data used in this study, derived from available databases, carries a certain level of accuracy and reliability. However, variations in data quality, methodologies, and specific parameters across different sources can introduce uncertainties and potential biases in the findings. Therefore, caution should be exercised when interpreting and extrapolating these results to real-world scenarios; e) Place of Consumption Consideration: It is important to consider the potential impact on the study's outcomes when accounting for the place of consumption. In Scenario 3, where the finished product is in Germany, and Scenario 4, where it is produced in either France, Spain or Italy, the transportation of the final product to the place of consumption is a factor not accounted for in the analysis due to the applied system boundaries (cradle-to-factory gate). Ideally, the product should be consumed locally, as any benefits generated from this "local processing" will be cancelled out if the product is transported long distances to the place of consumption. This introduces another level of complexity that should be acknowledged and is an important consideration within the study's limitations. Future research should aim to validate and expand upon these findings with real-world data on tomato production and processing using pasteurisation and mobile units.

5. Conclusions

In conclusion, implementing a mobile unit, exemplified by the FOX unit, offers numerous advantages, including the potential for the optimisation of SFSCs. The findings of this study align with the growing prominence of situating processing units near raw material production sites, responding to the economic viability of transporting compact processing units over extensive distances rather than large quantities of raw materials. This proximity between production and processing sites has consistently proven effective in reducing losses along the supply chain, contributing to the overall resilience of the chains. Furthermore, localised processing units and SFSCs align with Sustainable Development Goals (SDGs) by curbing losses and bolstering resilience against supply chain disruptions. Adopting a mobile processing unit presents a promising avenue for mitigating the environmental impact of food production, especially in tomato juice production.

This study highlights the advantages of the implementation of novel technologies like PEF in the processing of agricultural products, particularly in the context of tomato juice production. The environmental benefits of choosing raw materials carefully, emphasises the impact of raw material selection in minimising the overall impact of the chain, as shown across the literature. In this study, using tomatoes sourced from Spain yields the lowest environmental impact, underscoring the strategic significance of raw material selection in minimising environmental repercussions.

Additionally, as the farming phase of product production accounts for the most substantial portion of the environmental impact, adopting diverse agricultural practices can either heighten or diminish the environmental footprint of the final product. To address this, incorporating underutilised crops and optimising their cultivation conditions can enhance the resilience of food supply chains and reduce their environmental impact. These crops possess adaptability to various climates, offer nutritional diversity, and enhance food security. While our study primarily focuses on environmental impacts, it is imperative to acknowledge that implementing mobile units and SFSCs can yield broader economic and social benefits, such as bolstering local economies and fortifying community bonds. Investigating these benefits is essential for further strengthening supply chains and policies. Nonetheless, our study has several limitations, including data uncertainties, the study's geographic scope, and its omission of a comprehensive exploration of the economic and social advantages of short food supply chains.

6. Future work

Future research should prioritise collecting and organising new data to construct scenarios that closely resemble real-world conditions. During this study, data from databases for thermal tomato juice processing and tomato cultivation was collected. While these data are rooted in actual information, they may not always precisely mirror real-world scenarios. Practical experiences with mobile units and short supply chains can also offer valuable insights. Furthermore, decision-makers in the food industry and policymakers should consider advocating for the use of mobile processing units like the FOX project. This can effectively reduce transportation emissions, enhance supply chain sustainability, and promote strategic raw material sourcing, accounting for environmental impact. The formulation of diverse policies supporting the establishment of SFSCs will, in turn, back initiatives prioritising local and sustainable production practices, thereby reducing the overall environmental impact of the supply chain. Simultaneously, encouraging and financing the cultivation of underutilised crops can enhance resilience and diminish environmental impact. These crops can complement existing commercial varieties and offer added benefits in terms of nutrition and climate resilience.

CRediT authorship contribution statement

Beatriz Q. Silva: Writing – review & editing, Writing – original draft, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Eva Kancirova:** Data curation. **Milena Zdravkovic:** Supervision, Data curation. **Uday Batta:** Data curation. **János-István Petrusán:** Writing – review & editing, Project administration, Funding acquisition. **Kerstin Pasch:** Writing – review & editing, Project administration, Funding acquisition. **Aganovic Kemal:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Marta W. Vasconcelos:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Sergiy Smetana:** Writing – review & editing, Supervision, Project administration, 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.

Data availability

Data will be made available on request.

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