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Towards sustainable production of sesame products: Comparison of traditional and modern production systems via a life cycle assessment approach

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ABSTRACT

Burgeoning ecological crises of food production sector has made the environmental impact evaluation of various food products a sustainability imperative. Specifically, in pursuit of identifying a sustainable production model of high-demand food items, implementing a comparative life cycle assessment of various production approaches is of paramount importance. The energy consumption and environmental impacts of manufacturing two popular sesame products, Tahini (milled sesame paste) and Halva (sweetened sesame paste) in Iran was realized by using life cycle assessment methodology. In this regard, two production systems of traditional and modern, based on sesame cultivation and processing seeds were modeled. Moreover, production of milling stone, as the main instrument in Tahini and Halva production, was evaluated within the boundary of each product system. The highest energy used pattern and carbon footprint were attributed to the traditionally produced Tahini with 89.3 MJ/kg and 12.4 kg CO_2eq/kg respectively; while, the lowest results were associated with modern-based Halva production with 47.8 MJ/kg and 5.4 kg CO_2eq/kg. Compared to the traditional method, modern production of tahini was found to increase acidification potential and ozone layer depletion potential the most, with 73.1 g SO_2eq and 0.735 mg R11eq respectively. Production of milling stone was the predominant hotspot for all products in traditional and modern systems, with average of 56% and 45% contribution to the total energy used, and 75% and 71% contribution to the carbon footprint of products in the former and latter systems respectively. Moreover, implementation of agrivoltaics system and circular economy-based milling stone as the alternative scenarios were evaluated from LCA perspective, which demonstrated that adoption of alternative milling stone could reduce the impact results significantly. It is believed that the novel evaluation framework of this study could serve as an example for future LCA studies to expand the common routine of evaluation and include production of instrument within the product's system boundary.

1. Introduction

1.1. Background on the topic

The global population is experiencing growth, accompanied by an escalating demand for food products. In response to this augmenting demand, consumption of raw materials and energy resources has been on the rise. Large consumption of water, fertilizers, pesticides and fuels during the agricultural production stage or energy resources, chemicals and packaging materials in the food processing stage are essential to satisfy growing food demand properly. From an ecological perspective, our present resource-intensive practices within the food production sector would exacerbate the severity of climate change effect, especially in terms of agricultural activities which is responsible for 15% of the global warming impact (Gómez-Zavaglia et al., 2020). Significant waste generation associated with the food production sector, due to the rising consumption of resources has also presented serious environmental challenges, as approximately a third of food is estimated to be wasted annually (Slorach et al., 2020). Moreover, rising wastewater as a result of large-scale food processing practices has become a crucial concern in many regions (Shrivastava et al., 2022), as discharging wastewater without proper treatment could trigger water-related diseases significantly (Menegassi et al., 2020). Taking these significant environmental consequences into account, it's safe to say that the predominant food production practices in a region are decisive factors, shaping the

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Nomenclature

Abbreviation

MSFPS	Medium-scale food production system
LSFPS	Large-scale food production system
FU_T	Functional unit of Tahini
FU_H	Functional unit of Halva
GHG	Greenhouse gas
CF	Carbon footprint
AP	Acidification potential
EP	Eutrophication potential
ODP	Ozone depletion potential
POCP	Photochemical smog potential
HTP	Human toxicity potential

regional sustainability profile significantly. Therefore, a comprehensive investigation of regionally based food production models in terms of resource consumption patterns and ecological impacts is an imperative practice towards achieving sustainability in any region.

Various food production models are mainly categorized into two primary production systems: large-scale and medium-scale. In large-scale food production systems (LSFPS), modern technology and machinery are utilized to swiftly process substantial food quantities. Conversely, medium-scale food production systems (MSFPS) place a greater reliance on human labor and incorporate less automation. Distinct approaches to consumption and processing of raw materials are also employed by LSFPS and MSFPS, resulting in diverse environmental consequences. Therefore, production of similar products in LSFPS and MSFPS can lead to utterly different environmental profiles, owing to the employment of divergent production approaches and technologies. To track and compare the environmentally incompatible resource use patterns in LSFPS and MSFPS more effectively, understanding the environmental impacts of similar products manufactured in these systems is a prerequisite. This approach could be specifically valuable for the case of high-demand food items, as resource exhaustion and consequently ecological impacts associated with the manufacturing of such products are more considerable.

Sesame-based products in some parts of the world typify high-demand food items whose productions are mainly attributed to LSFPS and MSFPS. Since ancient times, cultivating sesame seeds as one of the most nutritional oily crops has been practiced across different agricultural areas of the world, especially in the tropical regions (Sharaby and Butovchenko, 2019). Containing of 45–60% oil and approximately 25% protein, sesame seed is regarded as one of the most valuable nutritious ingredients with widespread health benefits (Wei et al., 2022). It is estimated that the global land allocated to sesame cultivation was more than 10 million hectares in 2017, which resulted in an annual production of 5.9 metric tons sesame (Sharaby and Butovchenko, 2019). Sesame seeds has been used mainly for production of valuable edible oil or decorating dishes for a long time (Sharaby and Butovchenko, 2019). The application of this versatile seed extends beyond sesame oil production. In this regard, pulverizing sesame seeds for production of Tahini which is the valuable paste of ground sesame and also Halva or sweetened mashed sesame-based confection has considerably been practiced in different parts of the world. Such sesame-based products are especially preferred in the Middle Eastern and North African regions, where incorporation of these items in the preparation of various cuisines is a common practice. (Sirany and Tadele, 2022). For instance, it was estimated that approximately 8 thousand tons of Tahini are consumed in Egypt annually (Sebaei et al., 2020).

Tahini and halva consumption is also very popular in Iran, where production and consumption of sesame-based products have a long history (Mokhber et al., 2019). In Iran, the total cultivation land area of sesame seed was estimated around 60 thousand hectares in 2021 (The share of Iranian sesame, 2023), which has expanded annually due to the satisfactory tolerance of this oily crop to the drought condition and growing consumers' demands. In particular, the Ardakan county of the ancient Yazd province in the center of Iran, is considered a pivotal sesame hub, where the daily production of sesame-based products during peak season is estimated to be around 90 tons (Daily production of, 2017). From production system point of view, processing of sesame seeds occurs in both MSFPS and LSFPS in this arid region, by undertaking traditional and modern methods of production respectively. Despite significant strides towards modernization, traditional methods continue to dominate the sesame-related markets in the region. It is believed that MSFPS, as one of the major contributors to the regional economy, constitutes more than 85% of processing sites in this city (Where is the biggest, 2018).

1.2. *Research motivation*

Processing and production of sesame products, like other food products entail employment of diverse machinery and consumption of significant raw materials and energy resources. In terms of sesame processing, the milling procedure, where raw or roasted seeds transform into soft oily paste, is regarded as the main stage of tahini and halva production. As far as milling process is concerned, utilizing different types of stones in the grinding instruments is observed. The geological features of Yazd province, which boasts extensive and diverse mineral reserves, have positioned it as a valuable center for mining minerals and extracting natural stones. According to the Industry, Mine, and Trade Office of Yazd, the province's annual extraction rate of nearly one million tons of stone has established it as a prominent natural stone producer in Iran (ISNA Yazd, 2019). This significant geological characteristic of Yazd has resulted in the manufacturers of semi-automated milling devices (for operating in MSFPS) primarily rely on locally extracted natural stones, while advanced industrial milling machines (utilizing in LSFPS) are commonly equipped with grinding blades or artificial stones. Given the potential of severe ecological imbalances in this arid region, a thorough identification of the environmental consequences as a result of extensive manufacturing of sesame-products in MSFPS and LSFPS is the sustainability imperative. In this context, a comprehensive determination of the environmental impacts should be reflective of all practices involved in the sesame-product supply chain, entailing the primary extraction of natural stones for manufacturing milling device. Considering the different production activities of LSFPS and MSFPS, this study aims to identify the environmental consequences associated with sesame-products manufacturing in the Ardakan county, based on all relevant practices in this regard including the manufacturing of milling device.

1.3. *Background on the methodology*

Life Cycle Assessment (LCA) methodology as a viable approach for thorough evaluation of various products manufacturing in terms of the energy use and environmental impacts is employed in this study. LCA is an effective tool for understanding the environmental impacts of product systems (Loiseau et al., 2023), which cover the entire life cycle of a product in terms of resource use, generated waste and potential emissions. From primary extraction of raw materials to the production and use stages and finally end of life, all stages entailed in a product's life cycle undergo evaluation process in LCA. What add to the effectiveness of this sustainability-oriented framework is it's ability to highlight the favorable and also less favorable aspects of product systems from environmental point of view. To disclose broader aspects of resource use patterns and environmental impacts of diverse activities associated with production system, the scope of LCA modeling is considered decisive. The common approach in defining the scope of LCA study of manufacturing food items is mostly limited to the activities of the primary agricultural, processing final products, distribution and consumption by consumers. However, the influence of other important elements of food production domain including the manufacturing of machinery on the food products' environmental profile has been investigated less frequently. Employing diverse technologies in the food supply chain entails exhaustion of a substantial amount of raw materials and energy resources for manufacturing various instruments and machinery associated with those technologies (Stefanini et al., 2022). Therefore, in LCA modeling of a food product, expanding the mainstream of evaluation boundary to include manufacturing of the instruments and machinery utilized in the production systems, can add a remarkable depth to the evaluation process. The outcomes of such a comprehensive LCA can be environmentally informing not only for food producers, but also for manufacturers of processing instruments, involved in the upstream and downstream of food supply chain.

Inclusion of instruments production in the LCA modeling can specifically be valuable for the case of milling devices utilized in the sesame-products manufacturing, as production of them entails resource-intensive operations. To this end, conduction of a comprehensive LCA comparison of Tahini and Halva manufacturing in LSFPS and MSFPS in Ardakan county constitutes the main quantitative approach in the present study for tracking the environmentally compatible and incompatible resource consumption patterns in each production system.

1.4. Contributions and novelty

The following summarized the contributions of the present study.

- identify the energy use and environmental impacts of Tahini and Halva produced in LSFPS and MSFPS in Arkadan city
- highlighting the major contributors to the energy used and environmental impacts of Tahini and Halva production systems
- elaboration of sustainability-oriented alternatives to mitigate the main hotspots

It is believed that the outcomes of novel evaluation framework of present study offer valuable insights into the environmental profile of sesame products, and contribute to the sustainability enhancement of modern and traditional sesame production chains. The study is structured as follows: section 2 covers the literature review where the novelty of present study is justified, section 3 presents the methodology, section 4 discusses the results and offers a discussion, section 5 details the implication and section 6 provides the conclusion.

2. Literature review

LCA-based studies were scrutinized to highlight researches related to the energy usage and environmental impact assessments of following categories.

a) confectioneries and ground/milled products
b) food items produced in the various production systems

In terms of the confectioneries, (Miah et al., 2018) conducted an environmental impact assessment of dark chocolate, sugar, and some milk-based confectioneries using LCA. They found that dark chocolate had the highest environmental impact, while sugar confectionery had the lowest. The main environmental concerns were related to raw material acquisition, factory production, and packaging. Chocolate, in particular, received significant attention in LCA studies. (Vesce et al., 2016) conducted an LCA study on medium-scale chocolate production in Italy and found that the production stage consumed the most energy and had significant environmental impacts. (Boakye-Yiadom et al., 2021) examined the environmental impact of wrapped chocolate bars in Ghana and identified the manufacturing stage as the primary hotspot. Production of white, dark and milk chocolates from environmental impacts perspective was evaluated in (Bianchi et al., 2020), using LCA. Different farming methods were evaluated for 3 counties (Indonesia, Ghana and Ecuador) as the producers of cocoa beans. It was revealed that raw material manufacturing was the major hotspot. Moreover, production of dark chocolate offered more favorable environmental performance. (Konstantas et al., 2019b) assessed industrially-made cakes in the UK and found that cheese-cake production had the highest environmental impact, while whole cake production had more favorable results. Raw materials were a significant factor in environmental impacts. The production of gluten-free biscuits was also studied (Stojceska, 2018), with a focus on the manufacturing of ingredients and transportation. Increasing recycling and using locally sourced ingredients were identified as ways to improve the environmental profile of biscuit supply chains.

Regarding the ground food items, some LCA-based studies were found in the literature. (Espadas-Aldana et al., 2021) evaluated the environmental impact of using olive pomace for polymeric bio-composite products, attributing the environmental hotspot to the compounding procedure. (Astuti et al., 2021) assessed the environmental impact of ground coffee production using LCA. It was revealed that the regular and instant coffee are having the highest emissions. Plastic packaging and coffee waste were highlighted as the significant contributors to environmental impacts. Authors recommended the recycling of coffee waste as an alternative for enhancing the environmental impacts. LCA of sugar cane-derived sucralose production was carried out in (Blenkley et al. 2023). According to the results, reagent production was the main hotspot, contributing to the most of the environmental impact categories. It was disclosed that sugar, as the main material in the sucralose production process was not a considerable contributor to the impact categories. It was also revealed the enhancement of reagent usage could ameliorate the emission profile of sucralose by more than 45%. As process data were derived from literature, uncertainty level was considered high. In the realm of milled products, the main focus of LCA-based studies has been on the environmental impact assessments of flour, rice, or sugar production. It is important to note that the milling processes for these food products differ significantly. While, transforming grains into the a finely powdered product is the main aim of milling process in flour production, crushing the outer layers of crops for segregation of the kernel is regarded the objective of the milling process in rice and sugar production. As a result, distinct milling instruments are employed in each of these production processes. In this regard, (Nabavi-Pelesaraei et al., 2019) evaluated white rice production in Iran and concluded that combustion of natural gas was the major hotspot. Production of sugar from cultivation to the final processing was evaluated in (Gunawan et al., 2019) using LCA, where authors demonstrated that sugar processing followed by fertilizer production are the main hotspots. In terms of sugar cultivation stage, the highest share of CO_2 emission was due to the manufacturing of fertilizer (73.48%), followed by the manufacturing of pesticide (22.5%). The environmental consequences of cane sugar production in Mexico were evaluated in (Meza-Palacios et al., 2019) using LCA. In this regard, cultivation and harvesting of sugarcane, transportation, sugar milling and bagasse-based electricity cogeneration were investigated comprehensively. According to the results, more than 52% of the environmental impacts was due to the cultivation of sugarcane, followed by bagasse-based electricity cogeneration with 25.7% contribution. Various management practices of rice straw were investigated from LCA perspective in (Hùng et al., 2019), to identify the environmental performances, energy efficiency, and greenhouse gas (GHG) emission of rice production. According to the results, incorporation and removal of rice straw from the soil resulted in the highest and lowest GHG emission results respectively. It was indicated that burning rice straw which is a common practice can only lead to high amounts of GHG emission and human toxicity impact. Moreover, it was suggested that removing the rice straw from the farming field for the production of mushroom or bioenergy can enhance the energy efficiency and environmental impacts effectively. A cradle-to-gat LCA of conventional rice farming was conducted in (Rahman et al., 2019), covering the preparation of seed, cultivation and transportation to the milling site. According to the GHG emission results, CH_4 held the highest share of GHG emission (76.85%) mainly due to the cultivation stage of rice life cycle. Authors suggested that adoption of on-field water and biomass management could enhance the environmental burdens effectively. The environmental impact evaluation of 2 popular types of bread in Iran, namely Sangak and Lavash, was conducted in (Jalilian et al., 2020) using questionnaire method which is similar to LCA. Authors mentioned that large consumption of inputs (mainly wheat flour) in Sangak production resulted in higher environmental impacts associated with this bread compared to Lavash production. Moreover, the most affected impact categories were marine water ecotoxicity, depletion of inorganic sources and global warming. LCA of sugar production in Iran from sugar beet was carried out in (Gholamrezaee et al., 2021), where authors revealed that the share of natural gas consumption in total energy used was significant (43%). In terms of the environmental impacts, sugar beet, machinery, nylon and limestone were highlighted as the main hotspots respectively.

In terms of different food production systems, (Stone et al., 2021) conducted LCA of 18 vegetables production in the US, considering 3 different systems of small, medium and large-scale. According to the results of this study, the highest emission was observed for the large-scale production system. The LCA of rose water and rose oil manufacturing was conducted in (Fereidani and Üçtuğ, 2023), considering the modern and conventional manufacturing systems. The best environmental performance was attributed to the modern approach of rose oil and rose water production. Moreover, the natural gas and rose petal consumptions were highlighted as the major environmental hotspots in the traditional and modern production systems respectively. Production of 21 different varieties of breads across Europe was evaluated from the environmental impacts perspective in (Notarnicola et al., 2017), where it was concluded that the cultural environment of countries can influence the results considerably. In this context, the national import of grains, electricity generation and efficiency of material production were highlighted as the decisive factors on the overall environmental profile of bread. Moreover, the significance of evaluating food products based on different functional units was emphasized in this study, as a way to justify foods' nutritional, cultural, social and other relevant factors more appropriately. The environmental impact evaluation of various treatment and utilization of olive pomace in Turkey was conducted in (Duman et al., 2020), considering traditional, 2 phase and 3 phase olive oil production, and also fodder additives and compost production using olive pomace. Authors indicated that lower environmental impacts were associated with the traditional method of olive oil production, in comparison with 2 and 3-phase olive oil production. Moreover, the major hotspots were found to be related to the operational processes and consumption. Commercial-scale cultivated meat (CM) production was compared to the conventional system in producing meat from LCA perspective in (Sinke et al., 2023) to provide clear picture of environmental impacts for each system. Authors demonstrated that production of CM commercially can result in better environmental impacts than the other system. The only downstream to CM production was related to the high energy consumption during processing stage. It was suggested that renewable energy utilization can enhance the sustainability profile of CM effectively. The environmental impacts of Galician bread in Spain were evaluated in (Câmara-Salim et al., 2020), using LCA and considering two different agricultural methods (crop rotation and monoculture) in the production of wheat. It was revealed that the cultivation process contributed the most to the bread's environmental impacts, with crop rotation resulted in better environmental burdens. LCA of rice production in Iran was conducted in (Habibi et al., 2019), where authors investigated the environmental impacts of three cultivation systems of low-inputs, conventional and high-inputs, two planting approaches of semi-mechanized and conventional and three farm size of small, medium and large. The highest emission results were observed for the high-input cultivation system using semi-mechanized planting method, specially in terms of carbon change, global warming and cumulative energy demand categories. Moreover, it was indicated that high-input cultivation system, traditional planting and small size farm demonstrated the highest emission results in impact categories such as marine eutrophication, water depletion, agricultural land occupation, freshwater eutrophication, fossil depletion and terrestrial acidification. Consumption of chemicals like fertilizers contributed to the emission results of high-input and conventional planting systems significantly. Various rice cropping methods of low-input, high-input, conventional, improved and organic in the semi-mechanized and traditional planting systems was also the main focus of (Youseftabar et al., 2021) from LCA point of view. Authors concluded that lowest global warming potential results are associated with low-input and organic systems using traditional planting method. In terms of CED, the highest results were observed for high-input and conventional systems respectively. Moreover, Low-input and high-input cropping systems demonstrated the lowest and highest heavy metal emission in the air, water and soil, respectively. Authors indicated that resource inputs and field management methods could influence the environmental impacts considerably.

To the best of the authors' knowledge, there has been no prior research in the literature that focuses on conducting a life cycle assessment of Tahini and Halva production in two distinct manufacturing systems: modern (MSFPS) and traditional (LSFPS). This study specifically aims to provide a thorough comprehension of the energy usage and environmental impacts associated with Tahini and Halva manufacturing in the Ardakan city of Iran, considering both modern and traditional methods. Taking the LCA studies of food products mentioned earlier into account, the main source of environmental impacts has been identified as either energy use during the processing stage or diverse activities associated with cultivation stage. The scope of the energy consumption and emissions calculation in this study, encompasses all processes involved in Tahini and Halva production, starting from primary sesame cultivation and extending to downstream processing, including the production of the milling stones used in the sesame grinding process. In essence, the novelty of this LCA study lies in its evaluation of two interconnected production chains: firstly, the production of milling stones (the main tool used); secondly, the production of Tahini and Halva (the main final products). This approach is expected to not only enhance our understanding of the true environmental impacts of these products but also promote the adoption of environmentally friendly tools and instruments. The findings of this study are anticipated to provide valuable insights for decision-makers and stakeholders involved in the sesame-based product and milling instrument production chains. Furthermore, the evaluation methodology employed in this study could serve as a model for future LCA studies, encouraging a broader consideration of product systems that includes the evaluation of the technologies and instruments used.

3. Methodology

3.1. Life cycle assessment

In this research, a LCA comparison was conducted to shed light on the energy flow pattern and environmental implications associated with the production of Tahini and Halva, based on the production operations of MSFPS and LSFPS in Iran. Fig. 1 provides a visual representation of the stages included and excluded in the Tahini and Halva production chains of both MSFPS and LSFPS. Provisioning of raw materials and energy resources (green box), sesame cultivation, milling stone production and sesame processing plant (yellow box) and wastewater treatment (gray box) constitute the main stages of sesame-products' life cycles, evaluated in the present study. Conduction of mentioned stages entails generation of emissions (purple box) which is aimed to be identified and quantified as the main objective in the present study. It should be noted that storage, consumption, end-of-life of products and

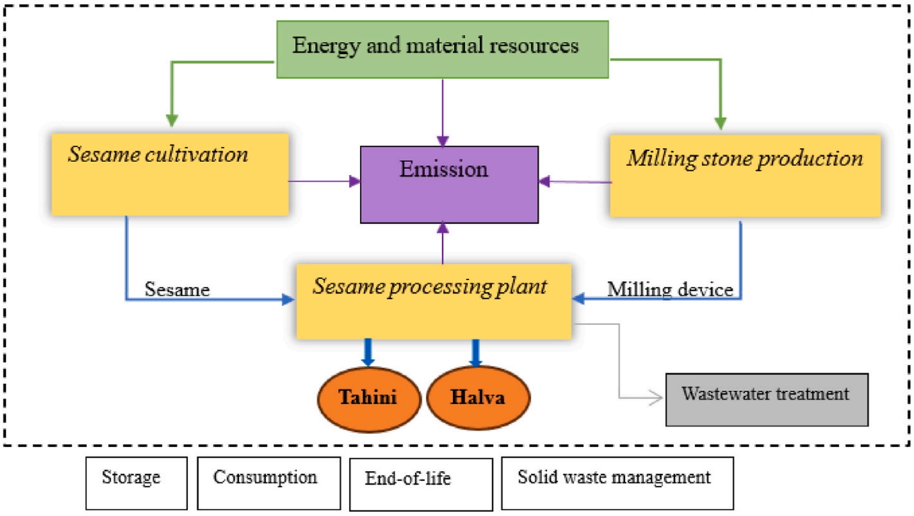

Fig. 1. The overall view of included (within the dotted box) and excluded (outside the dotted box) stages.

solid waste management practices are excluded. The LCA followed the guidelines outlined in ISO 14040, which entail defining the project's goals and scopes as the initial step, gathering inventory data, conducting a life cycle impact assessment, and then interpreting the results (ISO 14040, 2006). Environmental impacts calculation was performed by employing the CCaLC2 software, which serve as an environmental and economic appraisal tool based on the CML 2001 method. Developed by the university of Manchester in the UK, CCaLC2 software operates with Ecoinvent and CCaLC databases (CCaLC, 2013). Moreover, identification of the Energy flow pattern for each system was conducted manually.

3.2. *Goals and scopes*

The primary objective of this research is to shed light on the manufacturing processes of Halva and Tahini in Ardakan, a central hub for sesame product production in Iran, with a specific focus on energy consumption and environmental implications. To draw a clear picture in this regard, two distinct production systems, MSFPS and LSFPS, which represent traditional and modern methods of producing sesame-based products in the region, were studied. This study strives to promote sustainable practices among manufacturers of sesame-based products, particularly Tahini and Halva, by evaluating the environmental impact of well-established production systems in the region. The scope of this study encompasses the cultivation of sesame plants, the subsequent processing for final product manufacturing, and the production of milling stones. Notably, this research takes the initiative of determining the energy used and environmental impacts of Tahini and Halva production, by incorporating the energy and environmental footprints of

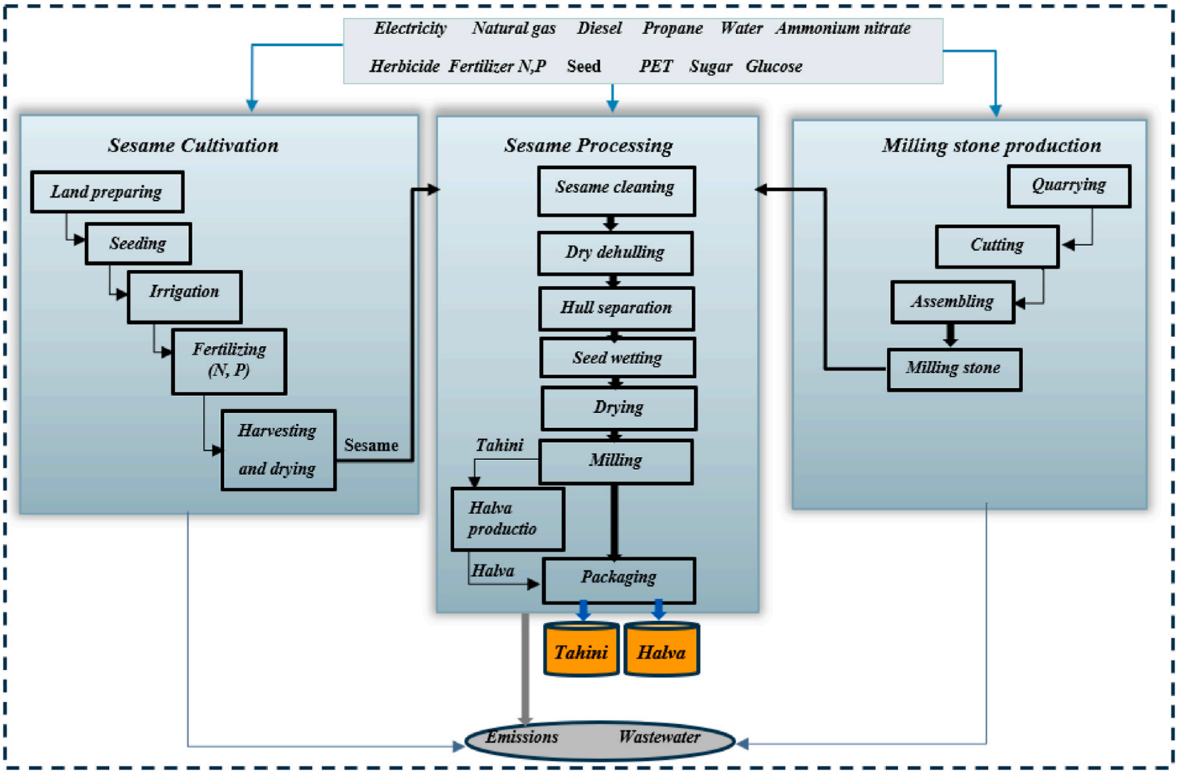

Fig. 2. The system boundary of MSFPS.

the milling stone production into the products life cycles. This innovative approach allows for a more accurate identification of the energy consumption and environmental burdens associated with each product. The detailed system boundaries for MSFPS and LSFPS are depicted in Figs. 2 and 3, respectively.

3.3. Case study

To model the operational processes of MSFPS and LSFPS, encompassing sesame cultivation, sesame processing, and milling stone production, representative subsystems that embody their production activities were chosen. In the cultivation subsystem of MSFPS, an organic sesame farm field was examined. For the sesame processing stage in the same system, a traditional Tahini and Halva production center using milling machines equipped with granite stones was considered. In contrast, LSFPS involved a sesame farm field using conventional cultivation methods and a commercial sesame processing factory employing sandstone-based milling machines for sesame seed pulverization. The modeling of granite milling stone production was based on the operational activities of a natural stone processing facility in the province of Yazd. The modeling of sandstone production relied on a study conducted elsewhere (University of Tennessee Center for Clean Products, 2009).

3.4. Data collection for model systems

For each of the production systems, foreground data collection involved gathering information on sesame cultivation, sesame processing, and milling stone production. Data pertaining to cultivation and processing stages were collected from representative production sites. As for the production of granite-based milling stone, data encompassing natural stone production, from primary quarrying to the final cutting, was obtained from a representative producer in the Yazd province. Information regarding the production of sandstone was sourced from the (University of Tennessee Center for Clean Products, 2009). It is worth noting that the assembly stage of grinding machines was excluded due to a lack of available data. However, transportation data of assembled milling stones from their respective manufacturing centers to the Tahini production sites was taken into consideration. Background data were sourced from the Ecoinvent database, CCaLC2 database, or relevant literature.

In this study, the investigation into the production processes of MSFPS and LSFPS was based on the manufacturing of 1 kg of Tahini and 1 kg of Halva as the functional units (referred to as FU_T and FU_H, respectively). To accurately evaluate the multi-output sesame processing stage in both systems, an allocation procedure was employed. The allocation coefficients for this stage were determined based on the proportion of sesame utilized for the production of Halva and Tahini, as per the provided production data from each processing site (excluding natural gas, which is used solely for Halva production). The allocation of emissions from milling stone manufacturing to the FU_T was based on Equation (1), which represent the proportion of milling stone required in the production of FU_T. In essence, it takes into account the reciprocal of the total Tahini that will be produced during the useful lifetime of the stone, multiplied by the weight of the stone, as an indicator of the required proportion of stone for meeting FU_T. As Tahini is integrated into the production of Halva, a ratio of 0.5:1, indicating that 0.5 kg of Tahini is consumed in the production of 1 kg of Halva, was employed to allocate the milling stone emission to the FU_H.

$$Cs = \left(\mathrm{Ws} \Big/ \sum \mathrm{Ti}\right) \tag{1}$$

Ws = The weight of milling stone (kg stone)

Ti = The amount of tahini produced during useful lifetime of stone (kg Tahini)

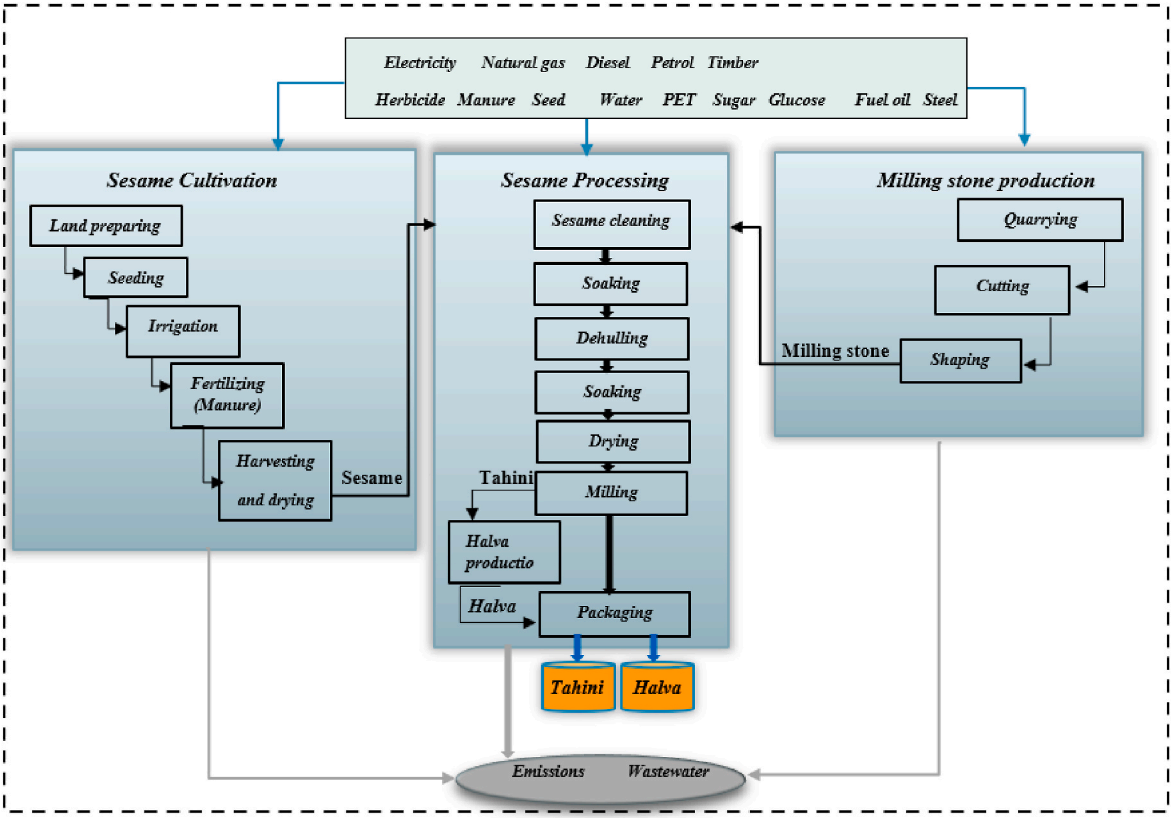

Fig. 3. The system boundary of LSFPS.

C_S = The coefficient for allocating the milling stone emission to the FU_T

3.5. Sesame seed cultivation

The cultivation area of 1 ha for each sesame farming systems was assumed. In terms of agricultural practices, organic and conventional methods for land preparation, seed planting, irrigation, plant maintenance and harvesting, were considered for MSFPS and LSFPS respectively. The comprehensive description of each farming system and relative inventories are provided in the Supplementary Material (section S1).

3.6. Sesame seed processing

Upon harvesting sesame and natural drying procedure, the seeds were transported to the processing sites. The sequential procedures during the processing stage for MSFPS and LSFPS are illustrated in Figs. 2 and 3, respectively. Despite variations in the processing methods of the systems under consideration, the primary steps in both systems involve cleaning sesame seeds, dehulling, milling seeds for Tahini production, and cooking sugar with Tahini and flavoring ingredients for Halva production. For a more detailed account of sesame processing in each production system, section S2 of the Supplementary Material provides additional information. In general, traditional methods rely heavily on labor activities as the primary workforce, while the other system places greater emphasis on machine operation throughout the production process.

3.7. Milling stone production

While different types of milling stones are employed in each production system, the fundamental process of transforming seeds into a soft paste using milling machines relies on a pair of stones; one stationary and the other rotating continuously, which result in the crushing of seeds and the production of Tahini. Specifically, granite stones and sandstone are used for undertaking stone milling process in MSFPS and LSFPS, respectively. The geological potential of Yazd province, enriched with a variety of marble, granite, and other stone mines, has facilitated the production of natural stone-based milling devices in the region. The production of both types of milling stones commenced with primary quarrying, involving the extraction of large stone blocks from the deposit site. Heavy machinery was employed for the removal and transportation of these blocks to the fabrication site for subsequent cutting and shaping, culminating in the attainment of the desired final diameter. For a more detailed account of the production of grinding stones and related inventories, please refer to the section S3 of the Supplementary Material.

3.8. Wastes of the sesame processing

During the manufacturing of Halva and Tahini, both direct and indirect waste streams were generated. The indirect waste stream primarily consisted of stone scraps produced at various stages of milling stone cutting, a common occurrence in both systems. On the other hand, one of the most significant direct waste streams resulted from sesame processing operations, encompassing liquid effluents primarily from washing sesame and the dehulling process, as well as solid waste resulting from the separation of sesame kernels and husks. In both production systems, husks were separated and collected for use in compost production. The dehulling process in sesame processing sites was found to generate various organic and inorganic wastes, along with a substantial amount of wastewater (Ngoie et al., 2020). Concerning wastewater management, LSFPS implemented on-site treatment of effluents, while MSFPS discharged wastewater into the urban sewer system, where it underwent treatment as necessary.

3.9. Emissions

The environmental life cycle modeling for MSFPS and LSFPS, which is based on the consumption of both direct and indirect energy and natural resources, was conducted using the CCaLC2 software. However, there were exceptions related to the use of manure and chemical fertilizers during the cultivation stage. In these cases, the calculation of N_2O emissions resulting from these activities was manually performed. This manual calculation was based on methodologies and emission factors provided by the Intergovernmental Panel on Climate Change (IPCC), as outlined in the (IPCC, 2006). For a comprehensive overview of all emission calculations related to fertilizer application, please refer to the Supplementary Material resource (section 1.1).

3.10. Energy flow pattern

In the present study, evaluation of the energy use pattern associated with the functional units is based on the concept of specific energy consumption, presented in Equation (2). In this regard, conversion of the input flows required for the manufacturing of Halva and Tahini in MSFPS and LSFPS to the equivalent energy value was conducted according to the coefficients of energy conversion depicted in Table 1.

$$SEC = E_{input} / M_{output} \tag{2}$$

Where

SEC = the specific energy consumption (MJ/kg)
E_{input} = the consumed energy in production (MJ)
M_{output} = the amount of product (kg)

4. Results and discussion

The energy consumption and environmental impacts resulting from the production of Halva and Tahini in the city of Ardakan, through the MSFPS and LSFPS production systems, are evaluated individually. Fig. 4 illustrates the evaluation steps, conducted for energy use and environmental impacts analysis. Initially, determining the energy used flow and specific energy consumption associated with the functional units are carried out. Subsequently, the environmental burdens of the functional units are assessed, and the contribution percentage of input flows to the total greenhouse gas (GHG) emissions of both MSFPS and LSFPS is determined.

Table 1
Energy equivalents of input flows utilized in the manufacturing of functional units.

Inputs	Unit	Ratio (MJ/unit)	Reference
Fertilizer N	kg	60.6	Singh (2002)
Fertilizer P	kg	11.1	Singh (2002)
Manure	kg	0.3	Singh (2002)
Sesame seed	kg	15.2	Akpınar et al. (2009)
Human labor	h	2.2	Pimentel and Pimentefl (1979)
Herbicide	kg	238	Erdal et al. (2007)
Diesel	L	47.8	Kitani (1999)
Electricity	kwh	11.93	Khanali et al. (2017)
Polyethylene (PET)	kg	46.3	Kittle (1993)
Sugar	kg	16.19	Khanali et al. (2020)
Glucose	kg	15.5	Zhu et al. (2014)
Natural gas	m^3	49.5	Kitani (1999)
Citric acid	kg	11.54	Kitani (1999)
Flavor[a]	L	11.67	Fereidani and Üçtuğ (2023)
Granite stone	m^3	13,770.5	Calculated
Sandstone	m^3	8835.4	Calculated

[a] Due to lack of energy data regarding cardamon extract, energy data of rose extract was used instead.

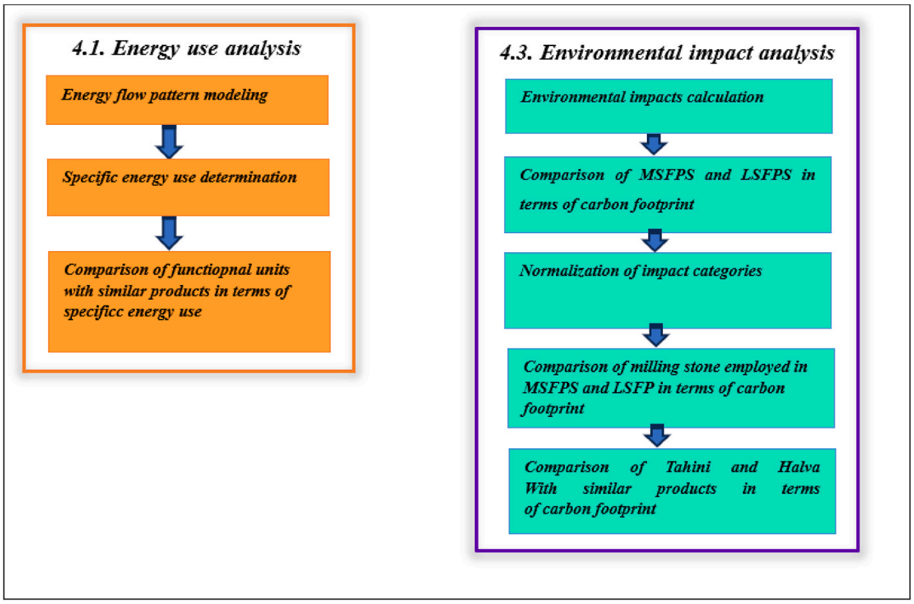

Fig. 4. The steps of energy use and environmental impact analysis.

4.1. Energy consumption

Energy values of inputs utilized for the manufacturing of functional units were calculated based on the energy conversion coefficients of each input and results are presented in Table 2. Following this conversion, the specific energy consumption of each functional unit was calculated, using Equation (2). This step aims to make these products comparable with similar food items in terms of their energy usage.

The Specific Energy Consumption (SEC) results for all products are presented in Table 3. Higher SEC results are observed for both Tahini and Halva production in MSFPS compared to results of the same products in LSFPS. Figs. 5 and 6 illustrate the contribution percentages of input resources to the total energy consumption of Tahini and Halva, respectively, according to MSFPS and LSFPS. In both functional units, a significant share of energy usage is attributed to milling stones, with granite and sandstone accounting for more than 59% and 55% of the energy used in Tahini production in MSFPS and LSFPS, respectively. In LSFPS, electricity consumption is the second major contributor to total energy consumption in both functional units, with a contribution of over 32% for Tahini production and 25% for Halva production in the same system. Notably, more than 95% of this contribution is linked to electricity consumption during the agricultural phase, while sesame processing accounts for a smaller portion of electricity usage.

Table 2
Energy values of input flows associated with the products of MSFPS and LSFPS.

Inputs	Energy used in MSFPS (MJ/FU)		Energy used in LSFPS (MJ/FU)	
	FU_T	FU_H	FU_T	FU_H
Fertilizer N	–	–	3.03	1.21
Fertilizer P	–	–	0.77	0.33
Manure	6.40	3	–	–
Sesame seed	0.07	0.03	0.07	0.03
Human labor	5.58	4.90	3	3.77
Herbicide	0.34	0.10	0.25	0.12
Diesel	7.25	3.70	1.24	0.66
Electricity	1.78	1.67	22.90	11.40
Polyethylene (PET)	1.62	2.31	1.62	2.31
Sugar	–	5.10	–	5.10
Glucose	–	0.02	–	0.02
Natural gas	–	9.40	–	1.90
Citric acid	–	–	–	0.30
Flavor	–	0.10	–	0.10
Granite stone	57.83	28.90	–	–
Sandstone	–	–	31.36	15.60
Diesel (transportation)	4.24	2	5.70	2.30
Total energy	85.11	61.23	69.94	45.15

Table 3
The specific energy consumption of functional units in MSFPS and LSFPS.

Parameter	Unit	MSFPS		LSFPS	
		FU_T	FU_H	FU_T	FU_H
SEC	MJ/kg	85.11	61.23	69.94	45.15

In the case of Tahini production in MSFPS, diesel and manure consumption during the agricultural stage represent the second and third highest contributors to energy usage, respectively. For Halva production in MSFPS, the consumption of natural gas and sugar during the processing stage, with contributions of 15.3% and 8.3%, respectively, are the major sources of energy consumption. Conversely, the lowest contribution to energy usage in the production of Tahini for both systems is attributed to sesame seeds during the cultivation stage, averaging only 0.075%. Additionally, glucose consumption in the production of Halva accounts for the lowest share of energy usage in both systems, with an average of 0.04%.

4.2. Comparison of tahini and halva with similar products in terms of energy consumption

Considering the various categories of food commodities, several studies have primarily focused on the evaluation of energy consumption associated with the production procedures. In this context, only a few studies have assessed confectionery and milled products in terms of energy consumption. It’s worth noting that the evaluation of energy usage in these studies is based on either energy auditing practices or the concepts of cumulative energy demand (CED) and primary energy demand (PED). Table 4 provides an overview of some studies in this regard.

Among selected studies, production of baklava (a Turkish snack) and chocolate was evaluated in (Özilgen, 2016), in terms of energy consumption. Author indicated that higher energy consumption for baklava is actually due to large number of ingredients required for production of this Turkish snack. Moreover, it was concluded that production of food

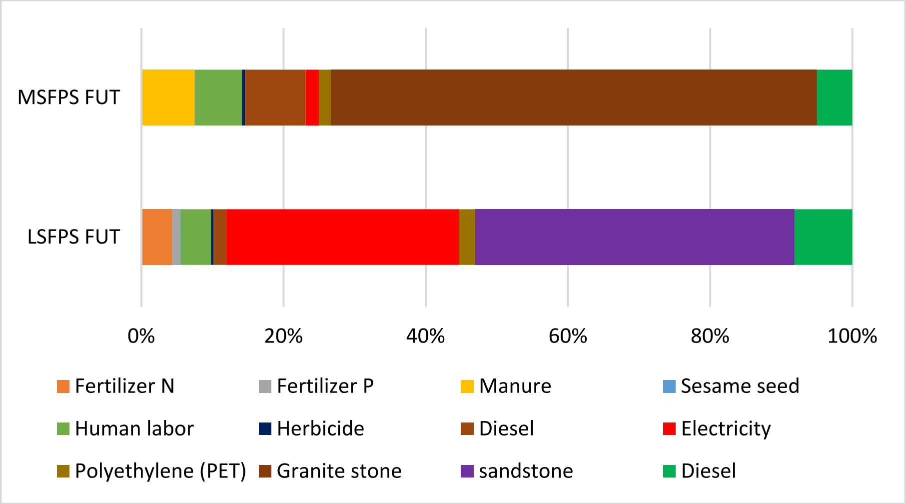

Fig. 5. Contribution of energy used in Tahini productions.

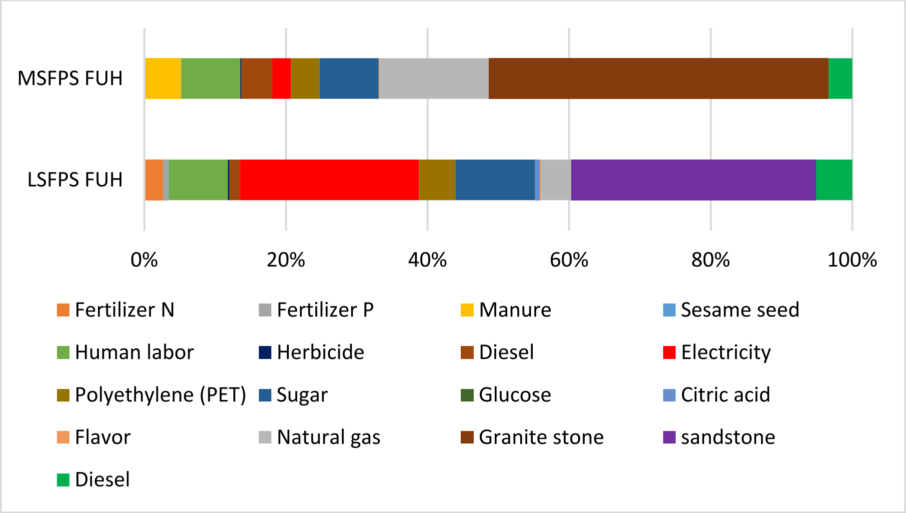

Fig. 6. Contribution of energy used in Halva productions.

items, contributed significantly (more than 81%) to the total energy used, surpassing other stages. In the case of chocolate production, energy consumption for two popular items of chocolate in bag (Konstantas et al., 2018) and dark chocolate (Recanati et al., 2018) was evaluated, where the primary energy used results of 40 and 33.75 MJ/kg were obtained for these products respectively. In terms of chocolate in bag production, authors attributed the major impacts to the manufacturing of raw material, specially milk powder production. In the case of dark chocolate, it was concluded that the production stage in the entire life cycle of chocolate is responsible for the majority of energy used, mainly as a result of consuming non-renewable sources. Considering different types of cakes in (Konstantas et al., 2019b), raw materials were found to be the main cause behind 40.4 and 17.5 MJ energy used in production of 1 kg of cheesecake and whole cake productions respectively. Moreover, manufacturing and packaging stages contributed the most to the ice cream production, accounting for 42 MJ/kg energy used (Konstantas et al., 2019a).

As far as confectionery products are concerned, the highest energy consumption was observed for the production of Halva in MSFPS, followed by the same product in LSFPS. This outcome was anticipated, given that the production of milling stones was factored into the determination of energy flows associated with the manufacturing of functional units in both production systems. As previously mentioned, milling stone production constituted the largest share of energy used for both Halva and Tahini production in the studied systems. Considering the entire life cycle of Halva production in terms of energy consumption, the manufacturing stage emerged as the primary hotspot, contributing to over 60% and 50% of the total energy used in MSFPS and LSFPS, respectively. For milled products, the energy used in Tahini production was compared with that of flour, rice, and sugar. In a study on flour production (Green et al., 2019), an energy audit was conducted based on manual, electrical, and thermal energy usage, with thermal energy being the most significant contributor to the total energy used. In another flour milling evaluation study based on energy audits (Aliu et al., 2018), the primary hotspot was found to be the energy consumption of roller milling equipment. Examining Table 4, the production of sugar cane exhibited the lowest energy consumption, with coal energy consumption being the primary contributor to the total energy used in this context (Gunawan et al., 2019). The highest energy usage in Table 4 was associated with Tahini production. Since, the energy consumption linked to the production of Halva and Tahini in this study encompasses both milling stone and food item productions collectively, it was expected to yield higher energy results compared to other studies.

Table 4
Energy used of confectionery and milled products.

Confectionery products	Energy used	Reference
Baklava	32,543 MJ/ton	Özilgen (2016)
Chocolate	25,747 MJ/ton	Özilgen (2016)
Chocolate in bag	40 MJ/kg (PED)	Konstantas et al. (2018)
Cheesecake	40.40 MJ/kg (PED)	Konstantas et al. (2019b)
Whole cake	17.5 MJ/kg (PED)	Konstantas et al. (2019b)
Dark chocolate	33.75 MJ/kg (CED)	Recanati et al. (2018)
Ice cream (vanilla regular)	42 MJ/kg (PED)	Konstantas et al. (2019a)
Halva (produced in MSFPS)	61.23 MJ/kg	Present study
Halva (produced in LSFPS)	45.15 MJ/kg	Present study
Milled products		
Flour	1.03 MJ/kg (SEC)	Aliu et al. (2018)
Wheat flour	1.40 GJ/tone (Energy productivity)	Green et al. (2019)
Milled Rice	Input energy = 68178.31 MJ TIP-1 Output energy = 11894.64 MJ TIP-1	Nabavi-Pelesaraei et al. (2019)
Sugar cane	116.56 MJ/tone	Gunawan et al. (2019)
Tahini (produced in MSFPS)	85.11 MJ/kg	Present study
Tahini (produced in LSFPS)	69.94 MJ/kg	Present study

4.3. Life cycle assessment

The life cycle environmental impacts of Halva and Tahini production in MSFPS and LSFPS were assessed using CCaLC2 software, focusing on the following midpoint impacts: acidification potential (AP), eutrophication potential (EP), carbon footprint (CF), photochemical smog potential (POCP), ozone layer depletion potential (ODP), and human toxicity potential (HTP). The modeling of each system in CCaLC2 software encompassed both the raw material acquisition stage and the production stage. The former involved the provision of inputs to unit processes, while the latter included agricultural production and downstream processing stages. Additionally, the transportation of raw materials to the agricultural and processing stages was considered. Regarding CF results, MSFPS exhibited higher emission levels compared to the other system for all products. Specifically, Tahini production in MSFPS resulted in the highest carbon emissions, at 12.4 kg CO$_2$eq, surpassing other products. Conversely, the lowest emissions were observed for Halva production in LSFPS, with 5.44 kg CO$_2$eq. In terms of AP, the highest emission result was associated with Tahini produced in LSFPS, amounting to 73.1 g SO$_2$eq. The production of sandstone-made milling stones contributed the most to this impact category, accounting for more than 87% of the total emissions. For Tahini production in MSFPS, a similar factor influenced AP results, with emissions of 34.8 g SO2eq. The lowest AP result in this category was attributed to Halva in MSFPS, with 19 g SO2eq. Concerning EP and HTP, the highest results were associated with Tahini produced in MSFPS. Specifically, Tahini in MSFPS exhibited results of 11.8 g PO$_4$eq for EP and 2.24 kg DCBeq for HTP. However, for POCP category, the highest result was observed for Tahini production in both LSFPS and MSFPS, with 1.74 g C$_2$H$_4$eq. Considering ODP category, production of Tahini in LSFPS with 0.735 mg R11eq demonstrated the highest result. It's noteworthy that the production of milling stones was the primary contributor to all impact categories in both production systems. In terms of tahini production's life cycle in MSFPS, raw material acquisition stage contributed the most to EP, AP and POCP categories, followed by transportation of inputs to the unit processes. However, for other impact categories, the highest impacts were primarily due to raw material and production stages respectively. In contrast, the contribution trend for the same product in LSFPS was slightly different, where the highest to the lowest share of CF, AP, POCP and HTP was attributed to the following stages respectively: raw material acquisition stage, production stage and transportation. For the remaining impact categories, the highest to the lowest share of emissions was due to the raw material, transportation and production stages respectively. Overall, traditionally produced Tahini exhibited considerable environmental impacts compared to other products, except POCP category where commercially produced Tahini demonstrated higher result. Conversely, commercially produced Halva demonstrated better environmental compatibility profile compared to others. Considering all products, the highest to the lowest share of emissions in all impact categories stemmed from the raw material, production and transportation stages, except in EP results of MSFPS, in which production stage held the highest share of impact category.

It should be mentioned that while storage and use stages are not included in our system boundaries, they appear in the legends in Figs. 7–10 is due to the fact that CCaLC2 software automatically includes them as fixed stages.

4.4. Comparison of MSFPS and LSFPS in terms of carbon footprint

In LCA modeling of products in MSFPS and LSFP, the raw material acquisition, production stage including agricultural and processing activities and transportation stage were considered. Regarding CF results of Tahini and Halva production in MSFPS, approximately 3.37% and 12.7% of contributions to this category were associated with the processing stage of considered products respectively. Moreover, processing Tahini and Halva in LSFPS, resulted in contributions of 5.25% and 8.08% to the total CF of products respectively. On the other hand, considering the cultivation stage of products in MSFPS, the contributions of approximately 23.9% and 10.25% to the total CF of Tahini and Halva were linked to production activities of this stage respectively. In LSFPS, the contribution of the cultivation stage to the CF of the same products was around 11.9% and 10.1%, respectively. Tables 5 and 6 illustrate the detailed contribution percentages of input flows for each functional unit, including the utilized resources in raw material stage, energy consumption, direct emissions associated with agricultural activities in production stage, as well as the transportation of inputs to each unit process. According to the results, milling stone is the predominant contributor to the CF results of both products in MSFPS and LSFPS. Considering Tahini production, granite-based milling stone with 69.11% contribution and sandstone-based milling stone with 57.96% contribution were the major CF hotspots in MSFPS and LSFPS respectively. In terms of Halva production, contributions of relative milling stones in MSFPS and LSFPS were 56.67% and 49.21% respectively. The second-highest contribution to the CF results was attributed to water consumption during sesame cultivation stage, except for Halva production in MSFPS, where consumption of natural gas preceded with 8.83% contribution. Regarding Tahini and Halva productions in LSFPS, a considerable CF impact was also observed for the electricity consumption (11.25% and 10.45% respectively), which is mainly associated with the sesame cultivation stage. Conversely, applying herbicide had the lowest contribution to the CF category for all products. In terms of transportation, higher CF results were associated with productions of Tahini and Halva in LSFPS, compared to the manufacturing of the same products in MSFPS.

4.5. Normalization

In order to express the environmental impact results in a standard scale, quantifying the contributions associated with the product systems to the impact categories was conducted to provide normalized results. In this regard, the CML characterization factors were extracted from (Sleeswijk et al., 2008), concerning global impact values. Accordingly, the category indicator results for each product were divided by the

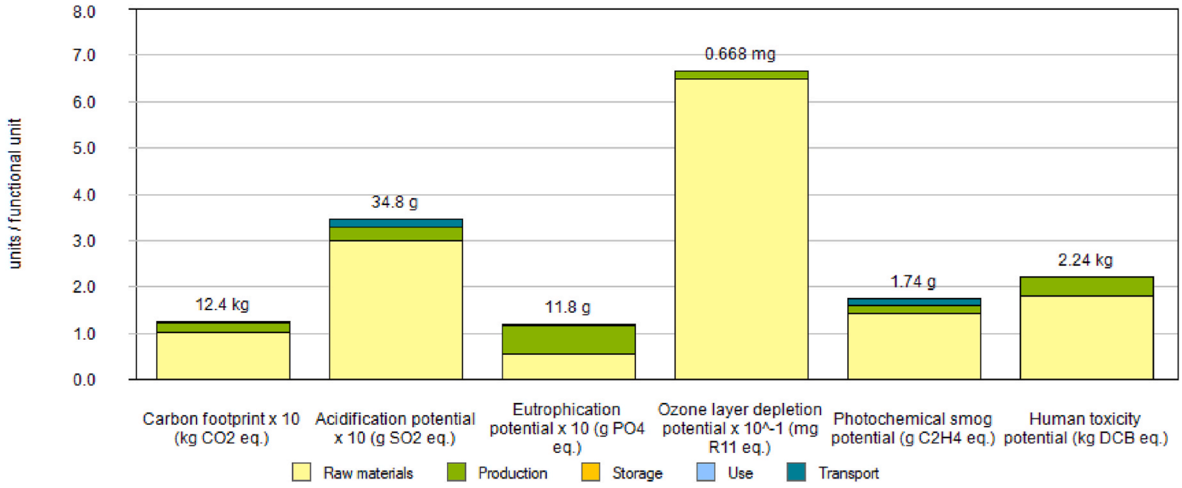

Fig. 7. The environmental impacts of Tahini production in MSFPS.

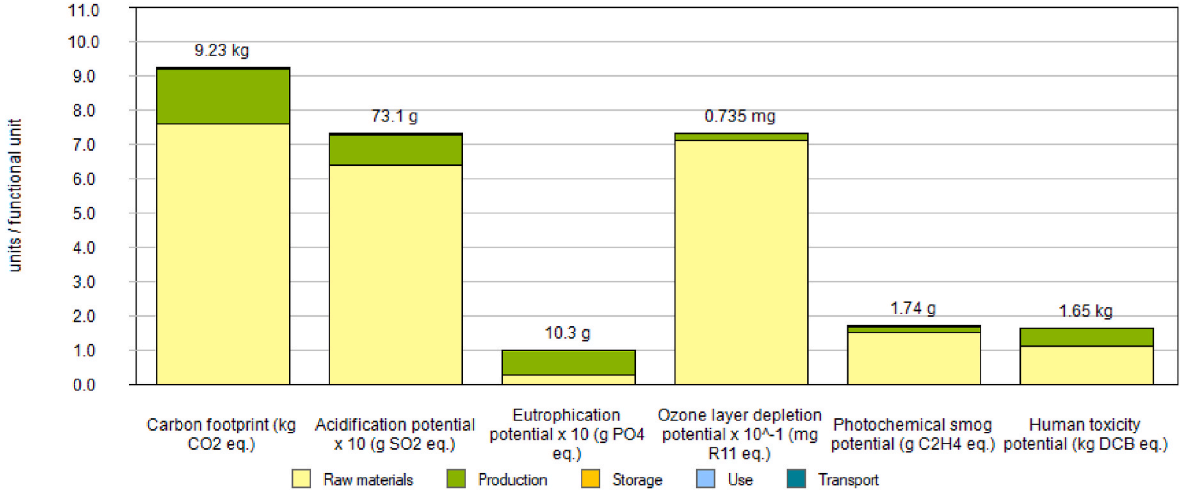

Fig. 8. The environmental impacts of Tahini production in LSFP.

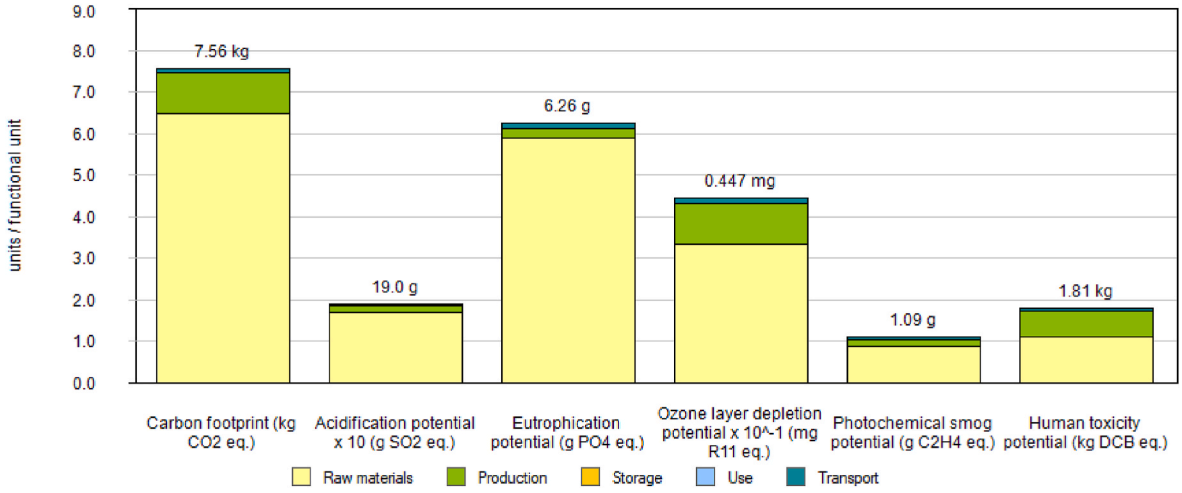

Fig. 9. The environmental impacts of Halva production in MSFPS.

characterization factors to provide the outcomes of impact categories on the same base (ISO, 2006). Results are depicted in Table 7. According to results, the highest normalized values for Tahini and Halva production of MSFPS were associated with GWP category, while for the same products of LSFPS, AP category demonstrated the highest results. In terms of the second most affected category, opposite result was obtained

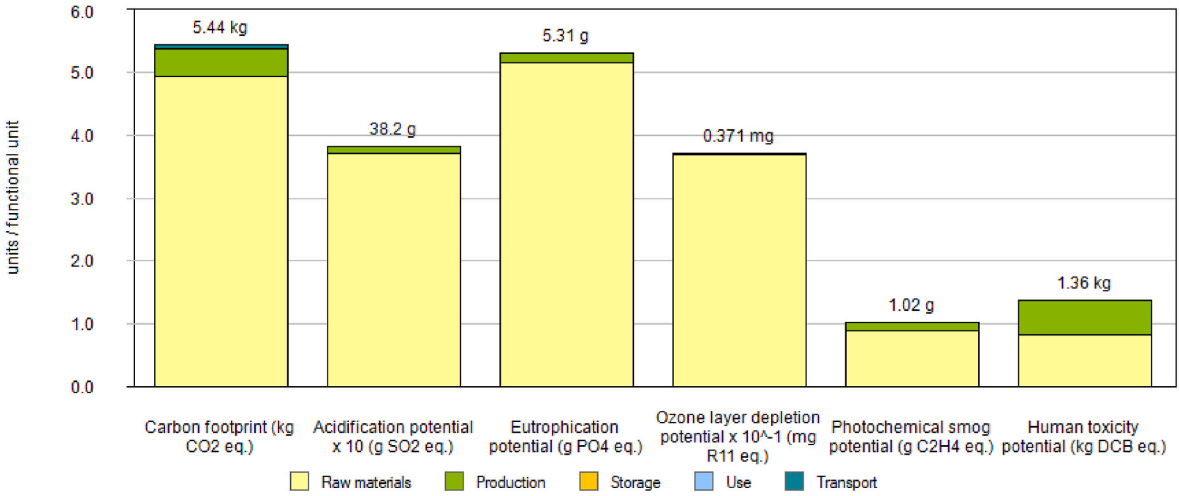

Fig. 10. The environmental impacts of Halva production in LSFPS.

Table 5
CF contribution of inputs associated with Tahini production in MSFPS and LSFPS.

Inputs	MSFPS	LSFPS
Water (cultivation)	9.75%	14.19%
Direct emission (Cultivation)	9.04%	0.72%
PET	1.32%	1.77%
Water (processing)	2.87%	4.68%
Fertilizer (P)	–	1.57%
Fertilizer (N)	–	3.82%
Animal manure	0.67%	–
Herbicide	0.11%	0.12%
Granite	69.11%	–
Sandstone	–	57.96%
Electricity	0.60%	11.25%
Diesel (farm machinery)	3.33%	1.1%
Wastewater treatment	1.05%	2.37%
Transportation	2.150%	0.45%

Table 6
CF contribution of inputs associated with Halva production in MSFPS and LSFPS.

Inputs	MSFPS	LSFPS
Water (cultivation)	7.99%	12.05%
Direct emission (Cultivation)	7.41%	0.61%
PET	1.08%	1.5%
Water (processing)	1.25%	6%
Fertilizer (P)	–	1.33%
Fertilizer (N)	–	3.20%
Animal manure	0.54%	–
Herbicide	0.09%	0.10%
Granite	56.67%	–
Sandstone	–	49.21%
Electricity	1%	10.45%
Natural gas	8.83%	2.42%
Diesel (farm machinery)	2.73%	0.93%
Transportation	3.10%	1.64%
Sugar	1.74%	2.42%
Glucose	0.87%	1.20%
Wastewater treatment	1.18%	2.01%

Table 7
Normalized results of impact categories associated with products of MSFPS and LSFPS.

Impact category	MSFPS		LSFPS	
	FU_T	FU_H	FU_T	FU_H
GWP	2.9e-13	1.8e-13	2.2e-13	1.3e-13
AP	1.4e-13	7.9e-14	3e-13	1.5e-13
EP	7.5e-14	3.9e-14	6.3e-14	3.3e-14
POCP	3.2e-14	2e-14	3.2e-14	1.8e-14
HTP	5.8e-14	4.7e-14	4.2e-14	3.5e-14
ODP	2.9e-15	1.9e-15	3.2e-15	1.6e-15

where the second highest results were observed for GWP and AP categories for products of LSFPS and MSFPS respectively. Considering the high AP results of products in LSFPS and at lower extent in MSFPS, potential social and economic hazards as a result of regional damages caused by soil acidification such as infertility in the long term could be looming. On the other hand, ODP category was the least affected category for all products in MSFPS and LSFPS. The percentage contributions of inputs to the normalized impact categories are presented in Figs. 11–14. According to the results milling stone was responsible for a major share of impact categories results in both systems. In terms of Tahini production in both systems, wastewater treatment demonstrated the second highest contribution to the EP category. Beyond milling stone, the contribution of electricity consumption to the majority of impact categories in LSFPS was considerable, specially for POCP and HTP categories with 20% and 22% contribution for Tahini production and 19% and 18% contribution for Halva production respectively.

4.6. Comparison of milling stones employed in MSFPS and LSFPS in terms of carbon footprint

Fig. 15 reveals the environmental impacts of sandstone and granite-based milling stones, utilized in LSFPS and MSFPS respectively. As previously mentioned, the modeling of the former milling stone was based on quarrying, cutting and transportation to the sesame processing site; while, the production of granite-made milling stone was modeled based on the natural stone extraction, cutting and shaping process, required in manufacturing milling stone and transportation to the sesame processing plant. According to Fig. 15, the highest emission results in CF, HTP and EP were associated with production of granite-based milling stone. On the other hand, the production of sandstone demonstrated higher emission results in AP, ODP and POCP. The detailed breakdown of the contribution of input flows associated with life cycle of milling stones to CF category is provided in Fig. 16. In case of the granite-stone milling device, the hotspot was the water usage, followed by the consumption of diesel. Conversely, for the sandstone milling device, diesel consumption contributed the most the CF category, followed closely by consumption of water. The lowest CF contribution results in the manufacturing of sandstone milling device were related to the fuel oil (0.001%), timber (0.2%) and ammonium nitrate (0.15%)

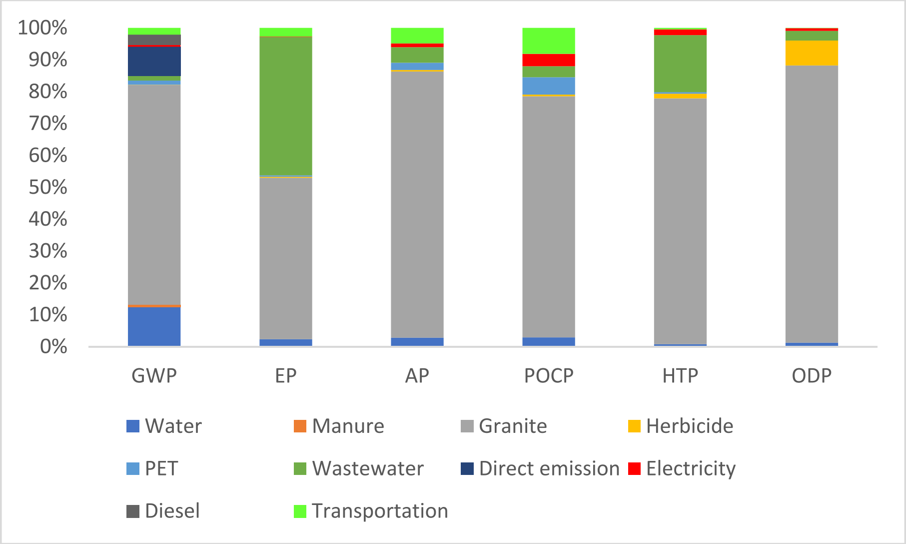

Fig. 11. Contributions of inputs to the normalized impact categories associated with Tahini production in MSFPS.

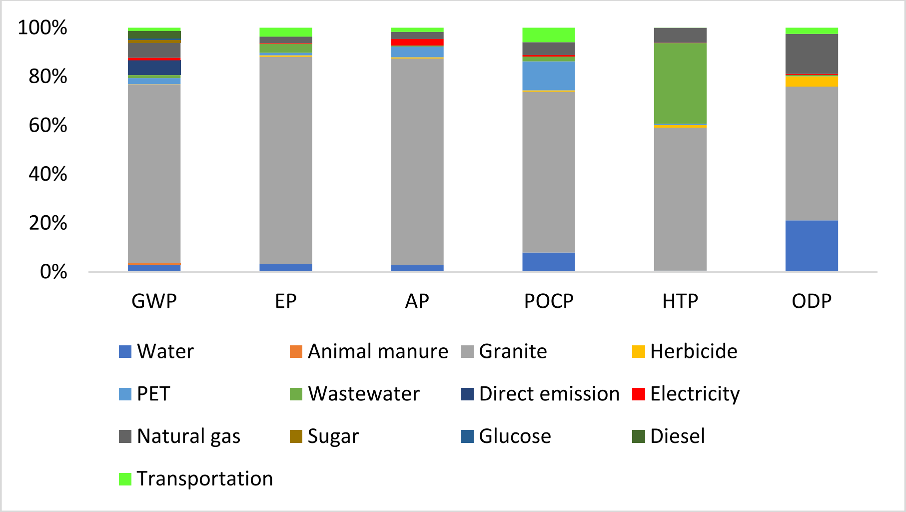

Fig. 12. Contributions of inputs to the normalized impact categories associated with Halva production in MSFPS.

respectively. Regarding granite milling stone, the lowest CF results were attributed to the fuel oil and polyurethane with 0.000052% and 0.01% contributions respectively.

4.7. Comparison of tahini and halva with similar products in terms of carbon footprint

Table 8 depicted the CF results for various confectionery and milled products, including Tahini and Halva produced in MSFPS and LSFPS. In terms of confectionery products, the highest CF results are attributed to Halva produced in MSFPS and LSFPS, with 7.56 and 5.44 kg CO_2eq per functional unit respectively. In contrast, the lowest result was reported for chocolate production in (Özilgen, 2016) with 0.98 kg CO_2eq/kg chocolate. Examining baklava and chocolate production in (Özilgen, 2016), the highest share of emissions for both products was attributed to the production processing. Additionally, an environmental impacts evaluation of the cheesecake and whole cake production in (Konstantas et al., 2019b) revealed 4.83 and 2.04 kg CO_2eq per 1 kg of these products respectively, with the main hotspot found to be the raw material stage. Similar trends were observed in production of ice cream (Konstantas et al., 2019a), where the raw material stage was identified as the main hotspot. In the case of dark chocolate production, the coco bean cultivation and transportation, followed by energy provisioning at the processing plant were identified as the main environmental contributors (Recanati et al., 2018). On the other hand, authors in (Deng et al., 2013) indicated that the life cycle hotspots of wheat gluten powder are associated with cultivation and drying of gluten; while, consumption of coal in boiler was regarded the main hotspot in Carrageenan flour life cycle (Zuhria, 2022). Natural gas combustion in the milling factories was one of the main environmental hotspots in the life cycle of milled rice, evaluated in (Nabavi-Pelesaraei et al., 2019). Considering the Halva and Tahini production in MSFPS and LSFPS in this study, the higher emission results compared to other similar products were expected, as environmental footprint of milling stone, with an intensive emission profile was included in the system boundary of the evaluated products.

4.8. Alternative scenarios

To ameliorate the energy used and carbon emission profiles of Tahini and Halva production in MSFPS and LSFPS, two scenarios as the proactive strategies for delivering sustainability objectives were designed. In this context, the energy used and environmental hotspots of

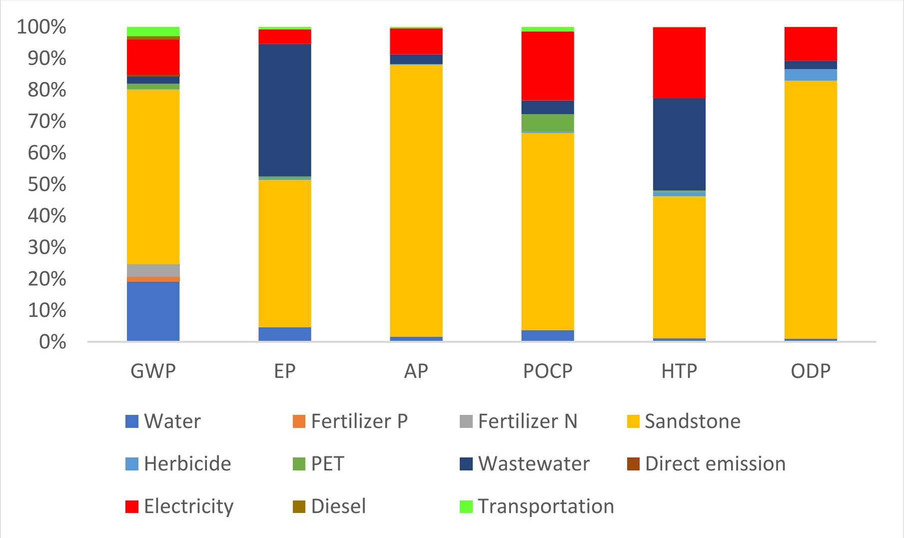

Fig. 13. Contributions of inputs to the normalized impact categories associated with Tahini production in LSFPS.

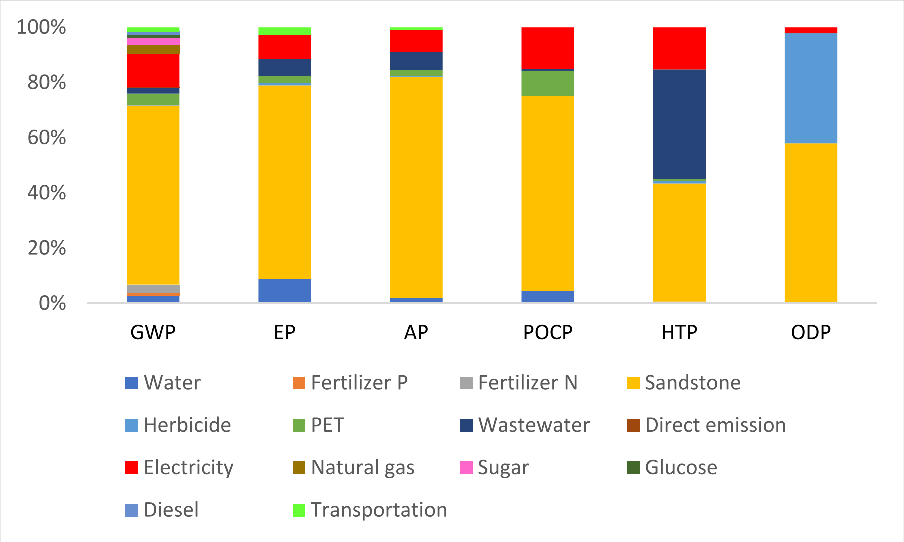

Fig. 14. Contributions of inputs to the normalized impact categories associated with Halva production in LSFPS.

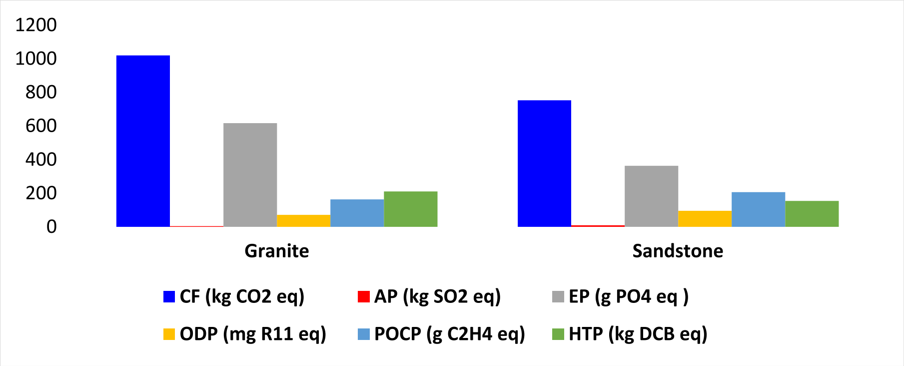

Fig. 15. The environmental impacts of sandstone and granite productions (emissions per m^3 of stone).

production systems were targeted in the development of the alternative scenarios.

I. Agrivoltaics System (AVS) integration: One of the major energy-intensive stages identified in the production systems was electricity consumption during sesame cultivation in LSFPS. The first scenario

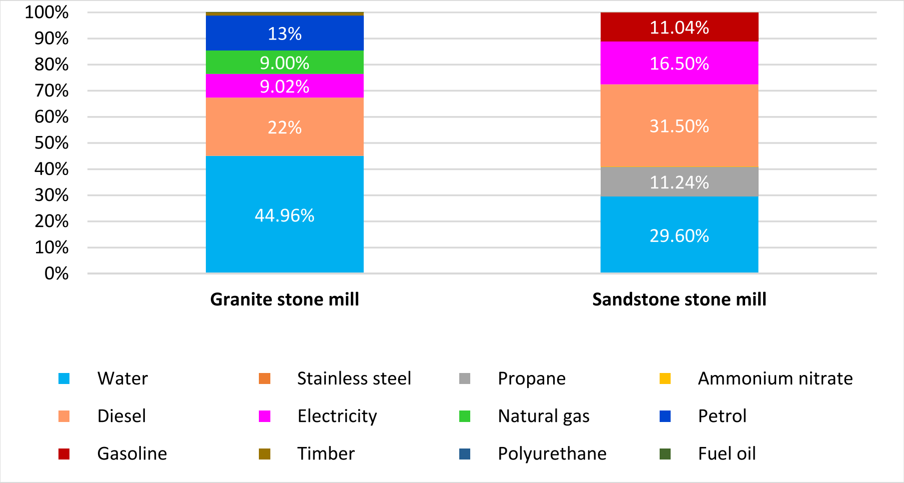

Fig. 16. Breakdown of CF contribution of inputs in sandstone and granite productions.

Table 8
Comparison of milled products and confectioneries in terms of CF.

Product	CF quantity	Reference
Confectionery items		
Baklava	2.05 kg CO_2eq/kg baklava	Özilgen (2016)
Chocolate	0.98 kg CO_2eq/kg chocolate	Özilgen (2016)
Chocolate in bag	4.15 kg CO_2eq/kg chocolate	Konstantas et al. (2018)
Cheesecake	4.83 kg CO_2eq/kg cheesecake	Konstantas et al. (2019b)
Whole cake	2.04 kg CO_2eq/kg whole cake	Konstantas et al. (2019b)
Dark chocolate	2.62 kg CO_2eq/kg dark chocolate	Recanati et al. (2018)
Ice cream (vanilla regular)	3.75 kg CO_2eq/kg ice cream	Konstantas et al. (2019a)
Halva (produced in MSFPS)	7.56 kg CO_2eq/kg Halva	Present study
Halva (produced in LSFPS)	5.44 kg CO_2eq/kg Halva	Present study
Milled items		
Wheat gluten powder	1550.7 g CO_2eq/kg gluten powder	Deng et al. (2013)
Carrageenan flour	47.73 kg CO_2eq/kg carrageenan flour	Zuhria (2022)
Milled rice	8.41 kg CO_2eq/kg milled rice	Nabavi-Pelesaraei et al. (2019)
Tahini (produced in MSFPS)	12.4 kg CO_2eq/kg Tahini	Present study
Tahini (produced in LSFPS)	9.23 kg CO_2eq/kg Tahini	Present study

focused on integrating a solar energy harvesting system with agricultural production, knowing as an agrivoltaics system (AVS). This approach aimed to reduce the reliance on fossil-based electricity by switching to the green energy harvesting from solar panels. The feasibility of the sesame-based agrivoltaic system has been evaluated in (Kim et al., 2021), where authors concluded that growing sesame under 21.3% shade result only in 7% yield loss. It was anticipated that consideration of AVS in this study could enhance the carbon footprint associated with electricity consumption during sesame cultivation.

II. Circular Economy approach for milling stone: The energy flow and environmental impact analyses in this study indicated that the highest environmental impacts were associated with the production of Tahini and Halva in MSFPS, with milling stone production being a significant contributor. The second scenario was designed to enhance the emission profile of the milling stones used in MSFPS, aligning with the principles of the circular economy. This scenario was based on the concept of the French Buhr milestone, which was a prominent milling stone used for producing finely milled products during the early 18th century (Hockensmith, 2019). The scenario aimed to improve the sustainability of the grinding instrument used in MSFPS. Figs. 17 and 18 provide schematic views of the proposed Agrivoltaics System (AVS) and the French Buhr stone concept, respectively, as part of these sustainability scenarios.

The polylithic structure of French Buhr milling stone, composed of segmented stone pieces, is the main characteristic that segregate this type of stone from modern monolithic grinding stone. While modern grinding stones are typically crafted from a single stone block, French Buhr stones were assembled from several polygonal-shaped stone pieces cemented together. Production of composite milling stone, according to the circular economy concept, is the main consideration for the scenario B. In another word, its assumed that stone pieces are recovered from the disposal of a dismantled granite stone-based object. Moreover, the required cutting and assembly of the polygon-shaped pieces, based on the French Buhr milling concept are also considered in the scenario B. In order to evaluate the environmental impacts of implementing scenario B comprehensively, the dismantling of a retaining wall, cladded with granite tilts, has been considered in the system modeling of the scenario B. The ultimate drive behind this scenario is the elimination of the energy-intensive quarrying, stone cutting and transportation procedures, by repurposing dismantled stone-based objects for reuse or

Fig. 17. AVS system (Toledo and Scognamiglio, 2021).

Fig. 18. French buhr milling stone (Hannibal, 2019).

recycling. Ultimately, the following assumptions regarding the scenarios A and B are considered for LSFPS and MSFPS respectively:

Scenario A: Installation of AVS over sesame farming field, in order to meet energy needs of the cultivation stage.

Scenario B: Crafting a composite milestone, based on the concept of French Buhr, by collecting discarded granite stones from a demolished stone-made wall.

For the purpose of implementing the first scenario, a static PV array configuration over the sesame field is adopted. The size of AVS in scenario A is assumed to be in accordance with the energy needs of the field. Details of the AVS system for the sesame field and the relative inventory are presented in the Supplementary Material (section S4). In terms of the second scenario, the stages considered for the production of alternative milling stone are illustrated in Fig. 19. In this context, the demolition practice of the stone-based wall is considered to be manually. Moreover, it is assumed that the stone debris from the building site are relocated to a landfill. The production practices considered for the composite grinding stone, after the collection and transportation of stone pieces from the landfill, include cutting stones into the desired polygon-shaped pieces, roughening high spots and assembling the pieces to create the final milling stone, using cement and steel band. Section S5 in the Supplementary Material provides more details regarding the scenario B. While, it could have been simplified by considering the landfill as the initial stage of the stone's life cycle, delving into the entire roadmap of the scenario and accounting for all stages, from original quarrying to the final assembly stage, in the emission calculation of final product were perceived for this scenario. In line with the inclusion of primary stages before landfill, the avoided stages as a result of linking the life cycle of a stone-cladded wall with that of milling stone, have also been taken into consideration.

Adoption of both scenarios was evaluated in terms of their environmental impacts and results are depicted in Figs. 20–25. According to the environmental impacts results, the scenario B offers the highest emissions reduction potential. Regarding CF, deployment of scenario A led to carbon reductions of almost 0.9 and 0.42 kg CO_2eq per FU_T and FU_H respectively. In contrast, greater reductions of 8.3 kg CO_2eq per FU_T and 4.1 kg CO_2eq per FU_H were obtained in manufacturing of the same products based on the scenario B. The limited effectiveness of scenario A, can be attributed to the counterbalancing emissions of PV panels and supporting structure of AVS, entailing emission-intensive components, thereby offsetting some of the environmental benefits of solar-based

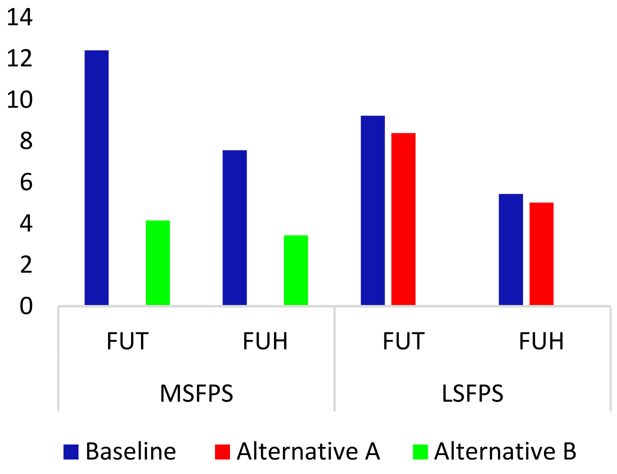

Fig. 20. CF results of different scenarios (kg CO_2eq/FU).

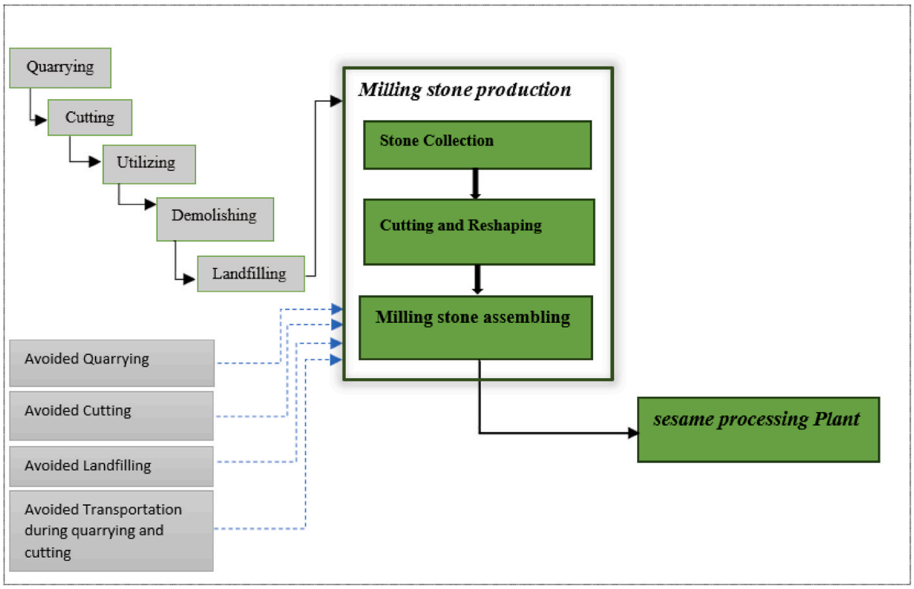

Fig. 19. The milling stone production chain according to the scenario B.

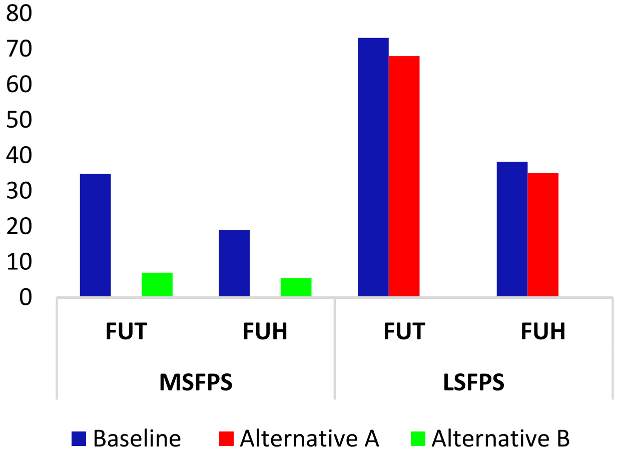

Fig. 21. AP results of different scenarios (gSO_2eq/FU).

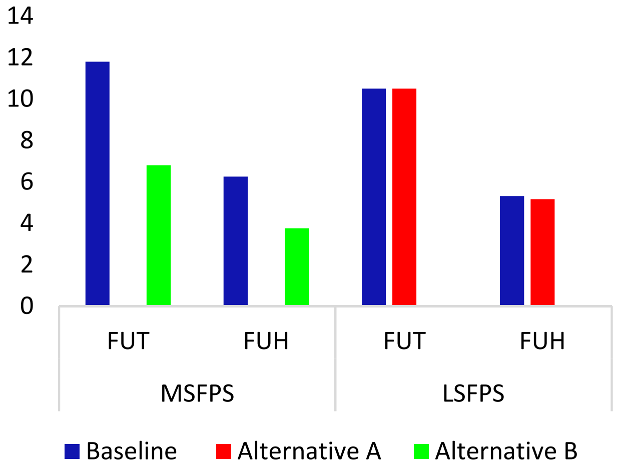

Fig. 22. EP results of different scenarios (g PO_4eq/FU).

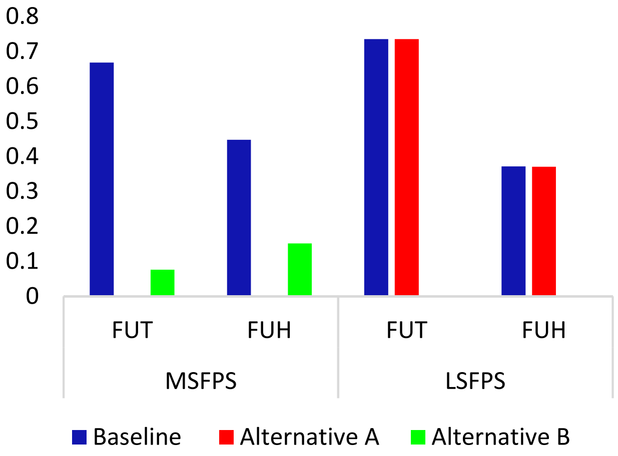

Fig. 23. ODP results of different scenarios (mg R11eq/FU).

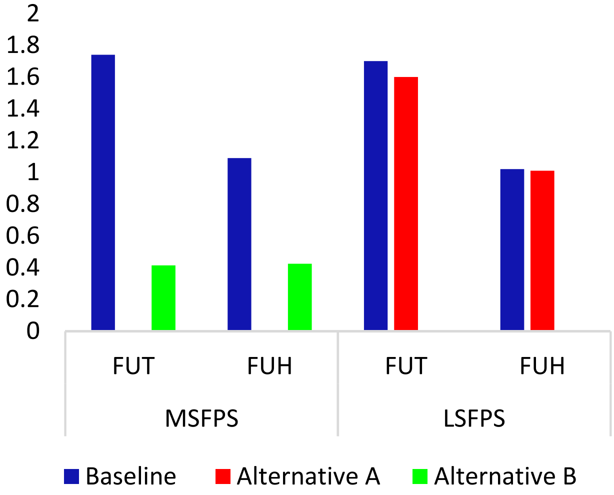

Fig. 24. POCP results of different scenarios (g C_2H_4eq/FU).

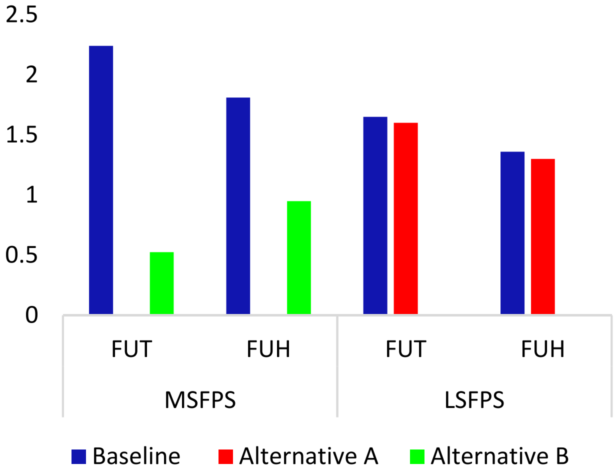

Fig. 25. HTP results of different scenarios (kg DCBeq/FU).

electricity generation.

In terms of AP, a considerable reduction occurred when substituting the milling stone in MSFPS with the French buhr-based device for Tahini production (340 g SO_2eq/FU_T). However, the AP reduction potential of the scenario A for both products in LSFPS was less significant (averaging around 4 g SO_2eq/FU_H). Same reduction trends are observed in EP, PODP, ODP and HTP, with scenario B yielding the highest reductions and scenario A the lowest. The superior emission results achieved with the deployment of the scenario B basically derived from its circular economy-based approach, which aimed to enhance the energy-intensive stone querying, transportation and cutting blocks with merging the end-of-life stage of one product with the manufacturing stage of another. Taking the baseline scenario in MSFPS into account, consumptions of water and electricity during the primary stone processing stage were identified as the major hotspots, which were eliminated in the scenario B. However, as the predominant contributions to all impact categories of both systems, were due to the milling stone production, therefore, the lower effectiveness of implementing AVS compared to enhancing milling stone production was expected.

5. Implications

In the majority of LCA studies, specially in the realm of food items, the scope of evaluation is limited to the production activities related to the primary agricultural stage, downstream processing, distribution and end of life stage. Thus, the major hotspots of the products' environmental impacts fall into either of the mentioned life cycle stages. Manufacturing the technological elements relevant to a product's supply chain, including various instruments and machinery has been investigated less frequently from LCA perspective. However, the outcome of the present study reveals that the manufacturing of instruments that are operating within a product supply chain, is indeed a predominant source of emissions, influencing the environmental profile of products remarkably. In fact, the substantial share of environmental impacts in the production of Tahini and Halva has been associated with the manufacturing of milling stone utilized in the processing of sesame. Based on this result, the eco-efficient solution that enhance milling stone production was developed to simultaneously enhance the sesame-products' environmental impacts. In another word, exclusion of instrument manufacturing from the LCA of products could influence the results significantly, leading to less attention to the major sources of emission in the products' supply chain.

What stands out in this context is environmentally remarkable, as it enables development of pragmatic solutions with high potential in improving the resource use patterns in the productions of both food products and processing instruments. In pursuit of a sustainable production model within the food production supply chain, the finding of present study can contribute significantly, as it informs eco-efficient decision making in the consumption of resources. Given that, applying LCA methodology with inclusion of instrument production within the mainstream evaluation, can truly be a game-changing practice, leading to a deeper understanding of what is environmentally at stake and how to handle it effectively.

From an academic perspective, the novel environmental impact evaluation framework of the present study can serve as a benchmark for evaluation of other food or even non-food products manufacturing, especially those with intensive resource consumption profile.

6. Conclusion

A comprehensive investigation of the energy flow patterns and environmental impacts associated with the manufacturing of two popular sesame products, Tahini and Halva in Iran was conducted using Life Cycle Assessment (LCA) methodology. The production processes of two predominant manufacturing systems in the province of Ardakan, MFSPS or Medium-Scale Food Production System and LSFPS or Large-Scale Food Production System were modeled in this context, considering the primary sesame cultivation and processing stages. In this study, the modeled MSFPS and LSFPS were the representatives of the traditional and modern production systems respectively. Moreover, the production of milling stone as the main instrument in the sesame seed grinding process has been evaluated for each production system, based on the energy use and environmental burdens. The following highlights the findings of present study, in terms of energy use and environmental impacts evaluations.

- Energy consumption outcomes: According to the energy flow results, the highest energy resources consumption was observed in the production of both Tahini and Halva in MSFPS. The specific energy use of Tahini for both production systems was higher than Halva, with 89.31 and 74.54 MJ per 1 kg Tahini and 63.63 and 47.80 MJ per 1 kg Halva in MSFPS and LSFSP respectively. The study highlighted milling stones as the predominant hotspot, contributing to over 50% of the total energy consumption in the production of Tahini and Halva in both systems. Additionally, electricity consumption in the production of both products in LSFPS, and diesel and natural gas consumption for Tahini and Halva production in MSFPS, were the second-highest contributors to total energy consumption, respectively. In comparison with the similar products, higher energy use patterns were observed for Tahini and Halva productions in the present study, which mainly derive from the milling stone manufacturing of evaluated production systems. Therefore, enhancing the energy efficiency of milling stone manufacturing specially though integration of renewable sources of energy could be a viable strategy for ameliorating the energy use pattern of Tahini and Halva production.
- Environmental impact outcomes: Regarding the environmental impacts, it was found that the highest emission results in the majority of impact categories were attributable to both products in MSFPS, compared to their counterparts in LSFPS. Tahini produced in MSFPS had the highest Carbon Footprint (CF) result with 12.4 kg CO_2eq per FU_T, while Halva produced in LSFPS had the lowest CF with 5.44 kg CO_2eq per FU_H. Regarding Acidification potential and Ozone layer depletion potential categories, Tahini produced in LSFPS demonstrated the highest results, mainly due to the production of sandstone-made milling stone. In addition to the CF category, traditionally produced Tahini demonstrated the highest results in Eutrophication potential and Human toxicity potential categories as well. Similar to the energy use analyze, the milling stone production was noticeably the primary contributor to the environmental impacts of functional units. The carbon footprint contribution of inputs related to Tahini production of MSFPS and LSFPS demonstrated that milling stone of these systems held 59.11% and 57.96% of total contribution respectively. In terms of Halva production, carbon footprint contributions of 56.67 % and 49.21% were associated with milling stone utilized in MSFPS and LSFPS respectively. In this context, the resource intensity of milling stone production in both systems specially in terms of diesel and water consumption was the pivotal factor behind the environmental consequences of Tahini and Halva production. Specifically, the higher resource use pattern in the milling stone manufacturing was associated with the production of granite-based device in MSFPS, leading to the higher emissions of sesame products in the same system. The normalization process was performed for all products, which demonstrated that the major categories with the highest normalized values are global warming potential and acidification potential for products of MSFPS and LSFPS respectively. Moreover, acidification potential category was the second most affected category for Tahini and Halva production in MSFPS. Therefore, regional consequences associated with high acidification potential of sesame products manufacturing in the studied region which cause infertility of farming land could trigger social and economic barriers in a long-term for manufacturers linked to MSFPS and LSFPS. Considering the latter system, contribution of electricity consumption to the majority of impact categories was also considerable, especially in terms of photochemical smog potential and human toxicity potential categories. Comparison of Tahini and Halva with similar food products in terms of carbon footprint results revealed that higher emission results were associated with the production of Tahini and Halva (in both systems), which has been mainly due to the milling stone manufacturing.
- Alternative scenario outcomes: To enhance the sustainability profile of Tahini and Halva production, two alternative scenarios were proposed based on the identified hotspots of the energy flow patterns and environmental impacts. The first scenario which involved harvesting solar energy for agricultural activities based on the Agrivoltaic System was suggested for LSFPS, while the second scenario focused on the production of alternative milling stone for MSFPS, based on the circular economy principle and the French Buhr milling stone concept. The viability of both scenarios in reducing all impact categories of carbon footprint, acidification potential, eutrophication potential, human toxicity potential, photochemical smog and ozone layer depletion potential, compared to the baseline scenario was

demonstrated. However, employing the second scenario which eliminate the energy-intensive stone quarrying, showed better emission reduction results. Given the predominance of the sesame market by MSFPS in the studied region, the incorporation of eco-friendly milling device based on a French buhr stone into the sesame production chain can preserve this long-lasting tradition in a sustainable manner.

This study underscores that while production methods and scale influence the energy flow patterns and environmental impacts of products, they should not be regarded as the sole determinants of environmental consequences. In contrast to the prevailing consensus suggesting that traditional production methods result in higher emissions, our study revealed that industrial manufacturing of sesame products resulted in higher emissions compared to the same products in the traditional system. In fact, the contribution of the production stage to the CF of Tahini and Halva manufacturing was 12.7% and 23.1% in MSFPS, and 17.9% and 23.6% in LSFPS, respectively. Furthermore, our findings highlight that the choice of machinery and equipment used in product manufacturing can have a significantly higher environmental impact than agricultural or processing activities, thereby representing a substantial portion of the products' overall environmental impacts. Consequently, assessing the environmental implications of production machinery and equipment within the product supply chain should be prioritized in future LCA studies when evaluating the environmental consequences of products.

However, it is inevitable that certain limitations were encountered during the implementation of the research methodology. As is the case with many LCA studies, a major limitation was the lack of data, especially regarding the manufacturing of sandstone-based milling devices. Moreover, the production processes of MSFPS and LSFPS in this study were modeled based on the operational activities of only two representative sesame production entities, which may not fully meet the quality standards of LCA data (Adsal et al., 2020). Nonetheless, collecting data from multiple production sites in this context could provide a more comprehensive and detailed understanding, offering greater opportunities for enhancing the sustainability of sesame production systems.

The environmental impact assessment framework employed in this study provides valuable insights into the advantages and disadvantages of pursuing modern and traditional sesame production pathways and identifies opportunities for transitioning toward eco-friendly sesame production models. Given the significant role of sesame seed processing in Iran, the findings of this study are of paramount importance for guiding decisions aimed at aligning the resource consumption patterns of companies involved in the sesame production chains, particularly the manufacturers of milling devices, with sustainability goals. To foster effective improvements in resource utilization within the sesame production chain, we recommend further investigation into the social and economic aspects associated with the current production systems in the region. Furthermore, in line with the outcomes of this study, which underscore the technological aspects of products' life cycles, there is a compelling call for the development of additional solutions that enhance the environmental profile of modern technologies and their production processes.

CRediT authorship contribution statement

Bahar M. Fereidani: Data curation, Methodology, Resources, Software, Writing – original draft. **Fehmi Görkem Üçtuğ:** Conceptualization, Formal analysis, Investigation, Project administration, Supervision, Validation, Writing – review & editing.

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

I shared data in the supplementary file

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.clrc.2023.100166.

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