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Economic and Environmental Impact Analysis of Innovative Peeling Methods in the Tomato Processing Industry

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Abstract: Peeling is a key step in the industrial production of canned peeled tomatoes, vital for optimizing efficiency, yield, product quality, waste reduction, and environmental impact. This study presents a comparative assessment of the economic and environmental impacts of adopting innovative peeling technologies, including infrared (IR), ohmic heating-assisted lye (OH-lye), and ultrasound-assisted lye (US-lye) peeling, relative to conventional steam and lye peeling methods. Focusing on a medium-sized Italian tomato processor, the impacts of these methods on productivity, water and energy consumption, wastewater generation, and environmental footprint using Life Cycle Assessment (LCA) methodology, were evaluated. Findings indicated that adopting IR, OH-lye, and US-lye methods enhanced peelability (ease of peeling > 4.5) and increased production capacity by 2.6–9.2%, while reducing solid waste by 16–52% compared to conventional steam and lye methods. LCA results showed IR as the most environmentally favorable method, followed by steam, OH-lye, and US-lye, with conventional lye peeling being the least sustainable. OH-lye and IR methods also significantly reduce water and energy use, while US-lye shows higher demands in these areas. Additionally, OH-lye and IR methods require little or no NaOH, minimizing chemical consumption and wastewater production, which offers notable environmental and cost advantages. Overall, this preliminary study underscores economic and environmental potential for novel peeling technologies, encouraging industry consideration for adoption.

Keywords: tomato processing; steam peeling; lye peeling; infrared peeling; ohmic heating peeling; ultrasound peeling; peeling loss; Life Cycle Assessment (LCA)

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1. Introduction

Peeling constitutes a fundamental unit operation in the industrial processing of fruits and vegetables like tomatoes, kiwi, pears, peaches, and apples, involving the removal of unwanted or inedible outer material [1]. This treatment offers numerous advantages, including enhancing palatability, accelerating osmotic dehydration or drying rates, and improving overall food quality while reducing pesticide residues. Consequently, peeling serves as a critical step prior to further processing and packaging, such as canning, freezing, dehydration, blanching, or cutting [1,2].

Given its pivotal role in the fruit and vegetable processing industry, the selection of appropriate peeling methods is paramount. Ineffective peeling operations can lead to physical damage, diminishing visual appeal and market value, and increasing the risk of flesh deterioration due to enzymatic changes, oxidative deterioration, and microbial contamination [1]. Furthermore, improper peeling techniques may result in substantial product loss, as the removal of edible portions along with the peel generates a large quantity of waste and reduces overall yield, thereby amplifying the environmental impact and undermining economic benefits [3]. Additionally, considerations regarding water and energy consumption, as well as environmental impact, are pivotal [4]. Therefore, the selection of the appropriate peeling method is critical for the industrial processing of high-quality and safe products with high yield, and for reducing environmental impact and production costs [1].

The tomato processing industry plays a pivotal role in the global food processing sector. In 2024, the worldwide production of processed tomatoes reached 50.9 million tons, with China (11.5 million tons), the United States (11.3 million tons), and Italy (5.3 million tons) emerging as the top producers [5]. Among tomato-based products, the global market for canned (whole, diced) peeled tomatoes was valued at $4 billion in 2022 and is projected to grow to $6.8 billion by 2032, reflecting a compound annual growth rate (CAGR) of 5.6% from 2023 to 2032 [6].

The production line of peeled tomatoes involves a multi-stage process where peeling follows initial washing and sorting phases, supplying peeled tomatoes for subsequent canning and sterilization steps [4].

Chemical peeling via lye solution and steam peeling methods have long been prevalent in the tomato processing industry [7]. These methods boast scalability and ease of operation [1]. Lye peeling typically involves immersing tomatoes in a hot solution of NaOH at various concentrations (8–25%) for a predefined time (15–60 s), effectively removing the outer peel through a synergistic combination of high temperature and chemical reaction [2,8]. This approach is favored in the fruits and vegetables industry due to its efficacy, versatility, and superior product quality [9]. However, the generation of wastewater with high pH and chemical oxygen demand (COD), along with potential chemical residue presence inside the fruits, poses environmental and food safety concerns [10].

During steam peeling, the tomatoes are rapidly heated in a scalder by pressurized steam (50–200 kPa) before undergoing vacuum cooling and mechanical skin removal [7,11]. The steam heats the outer layer of the fruit, causing the moisture beneath the skin to rapidly vaporize during the vacuum cooling stage. This buildup of vapor loosens the skin, creating cracks that make it easy to peel off [7,11,12]. Although steam peeling is a more eco-friendly alternative to lye peeling, it often results in softer fruit, reduced firmness, and greater peel loss [13]. Both methods, however, are energy- and water-intensive and produce substantial amounts of wastewater [14].

In response to these challenges, research is increasingly focusing on innovative and sustainable peeling techniques that reduce or eliminate chemical substances, minimize water and energy consumption, and improve yields and product quality. Among these approaches, unconventional technologies such as infrared radiation (IR) heating, ohmic heating (OH), ultrasound (US), and pulsed electric fields (PEF) are gaining significant attention [1,2,15]. These methods offer promising alternatives or complements to traditional peeling techniques, paving the way for sustainable and efficient fruit and vegetable processing.

In particular, IR peeling is an innovative and sustainable dry-peeling method that eliminates the need for chemicals and heating mediums like water or steam. By rapidly heating the surface of tomatoes using electric, ceramic, or catalytic IR generators, physical and biochemical changes occur in the peel, facilitating easy detachment while minimizing alterations to the inner fruit [16,17]. Tests at bench and pilot scales show that IR-peeled tomatoes have greater firmness and lower peeling loss compared to lye-peeling methods, with reduced energy consumption [7,13,18,19]. For example, Vidyarthi et al. [13] found that, compared to conventional lye peeling, IR dry-peeling produced up to 38.2% firmer peeled tomatoes and up to 12.2% lower peeling loss with a similar or greater ease of peeling and more desirable color of the peeled tomatoes.

Ohmic heating-assisted lye (OH-lye) peeling involves immersing tomatoes in an electroconductive solution with sodium hydroxide or sodium chloride, and then passing an alternating electric current through it to remove the skin [20,21]. This process combines thermal, chemical, physical, and electrical mechanisms to degrade the cuticle of tomato fruit and disrupt its substances, making peeling easier [2,3]. Using OH with a relatively low concentration (0.01–0.03% w/v) of NaCl solution can achieve high peeling scores

(4.5–5 out of 5) and shorten peeling times [22]. Furthermore, OH combined with lye peeling at lower concentrations (0.5–1% w/v) than the conventional method yields high-quality products, reduces losses and accelerates peeling by enhancing lye diffusion through electroporation [2,12,21]. For instance, Wongsa-Ngasri and Sastry [21] demonstrated that OH-lye peeling of tomatoes, conducted in a solution containing 0.01% NaCl and 0.5% NaOH at 2020 V/m, achieved a weight loss of 7.5%. In contrast, achieving comparable results with conventional lye peeling required a much higher NaOH concentration of 7%.

Ultrasound-assisted lye (US-lye) peeling utilizes high-frequency sound waves (20 to 100 kHz) to create cavitation, which helps break down the skin of tomatoes that have been pre-treated in a low-concentration (less than 10% w/v), high-temperature lye solution.

This process weakens the skin by breaking down structural carbohydrates, causing the epicarp to separate from the pericarp. The cavitation effect also produces free radicals that accelerate the chemical degradation of the cuticle's carbohydrates, enhancing peeling efficiency [8]. As a result, it was found that compared to conventional (10%) lye peeling, the combination of ultrasound (US) with a lower (4%) lye concentration significantly enhanced both the peeling yield and lycopene content in the peeled tomatoes [10].

However, there is a significant gap in the current research comparing innovative tomato peeling techniques with traditional methods. Existing studies vary in processing conditions, equipment, tomato variety, and the specific criteria used to evaluate the performance of peeling methods, such as peelability, peeling loss, ease of peeling, or product quality [2,9,19]. This diversity makes it challenging to make informed comparisons to identify the best peeling method. As per the literature survey, only a limited amount of data is available for comparing IR [19], OH [20], and US [10] peeling with conventional lye and steam peeling. These few available studies allow for a comparison of the relative impacts on production yield, resources (water and energy) consumption, and wastewater generation. Furthermore, to determine how the integration of novel peeling technologies might enhance the sustainability of the tomato processing industry, it is essential to evaluate the environmental impact and resource consumption throughout the product's entire life cycle [23]. Life Cycle Assessment (LCA), a widely recognized methodology, is instrumental in addressing these concerns and supporting the development of more environmentally friendly products [24].

This research seeks to address these gaps by offering a thorough comparison of innovative peeling methods, emphasizing their potential to optimize efficiency, reduce resource consumption, and promote sustainability in the tomato processing industry. The study includes a case analysis of a medium-sized Italian tomato processing company with an annual production capacity of 60,000 tons of whole-peeled tomatoes. The goal is to assess how different peeling techniques impact the economic and environmental sustainability of the tomato processing industry. Drawing on data from food processors and existing literature, a preliminary comparative assessment was conducted to evaluate the effects of conventional lye and steam peeling methods, alongside innovative techniques such as infrared (IR), ohmic heating (OH), and ultrasound-assisted lye peeling (OH-Lye and US-Lye). Key factors examined include productivity, consumption of resources (water, thermal energy, and electricity), wastewater generation, and the overall environmental and economic impacts of these methods. Additionally, the study includes an LCA to analyze how various midpoint environmental impact indicators are affected by both conventional and innovative peeling techniques in peeled tomato production.

2. Materials and Methods

2.1. Tomato Processing Facility for the Production of Peeled Tomatoes

A case study was carried out at a typical mid-sized tomato processing facility located in the province of Salerno, in southern Italy, which processes approximately 60,000 tons of tomatoes annually to produce peeled (whole) tomatoes. The facility operates continuously, with three eight-hour working shifts per day over a 90-day season from late July to early October. Under these conditions, the plant maintains a processing capacity of about 28 tons per hour. Around 65% of the tomatoes are processed into peeled tomatoes, while the remaining portion is used to produce puree, which is added to the tomato cans. The peeled tomato production line runs continuously, while the puree production line operates at 60% capacity throughout the processing season.

Figure 1 illustrates the typical steps involved in tomato processing at the facility, beginning with the reception of raw materials and concluding with the storage of the final products. Furthermore, the quantity (in tons per year) of each intermediate processing stream was calculated based on key input and output data, reflecting the process efficiency of the various conventional processing units as provided by the food processor, as well as using literature data on peeling performance and processing conditions for each innovative peeling method.

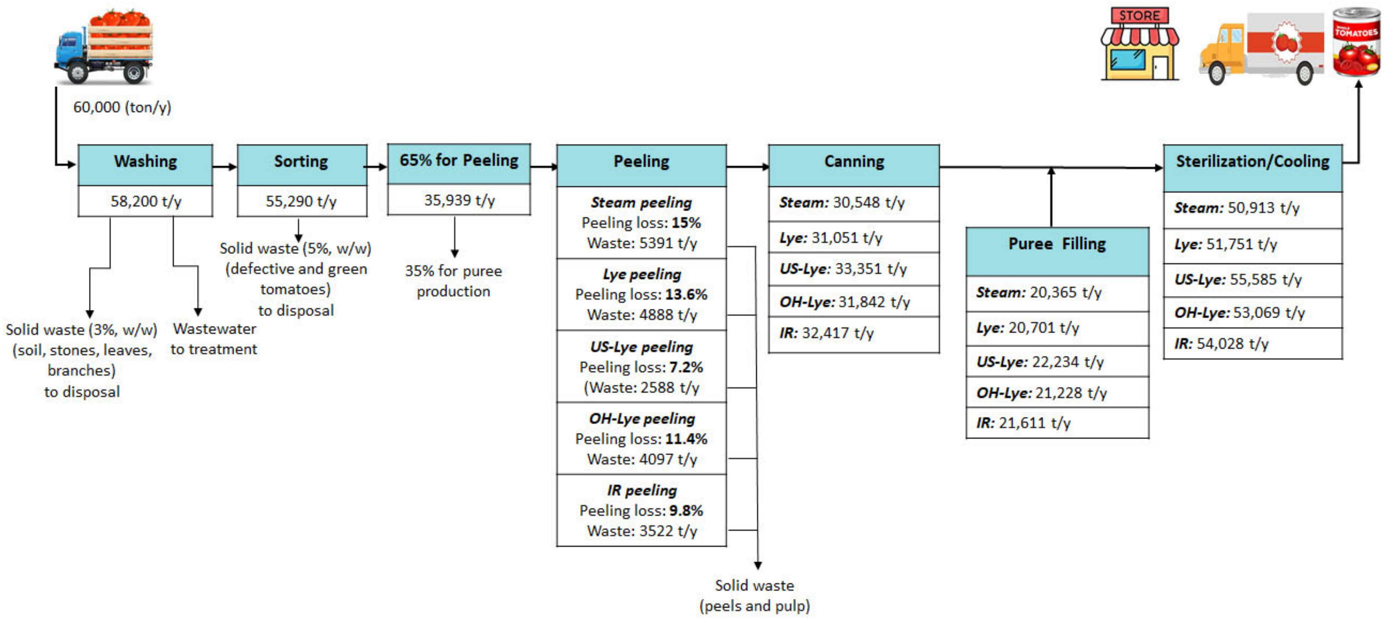

Figure 1. Current value stream map for a plant processing whole peeled tomatoes with a production capacity of 60,000 tons per season.

Tomato processing begins with the arrival of raw tomatoes via trucks at the offloading area of the plant. Subsequently, the tomatoes undergo washing and sorting within the flume network. This process consumes approximately 3–5 m^3 of water per hour for every 1 m^3 of tomatoes processed, aiding in the removal of foreign materials like leaves, branches, soil, and stones, which can constitute up to about 3–5% (w/w) of raw tomatoes [4]. Following washing, the tomatoes go through a combined manual and automated sorting process to remove defective fruits and any unwanted materials, including green tomatoes, which can make up to 5% of the incoming raw materials [4].

The cleaned and sorted tomatoes are then directed to the peeling operation. This study provides a comparative analysis of five peeling methods: traditional lye and steam peeling, as well as innovative techniques such as IR, OH-lye, and US-lye peeling. Detailed data on peeling performance and processing conditions for each method are presented in the following section.

After peeling, the tomatoes are packed into tinplate cans. During this process, a filling machine adds tomato puree with a dissolved solids concentration of approximately 8–9° Brix, ensuring an approximate 60:40 weight ratio of whole peeled tomatoes to puree.

The tomato puree is produced on a dedicated processing line, not shown in Figure 1 for clarity. In this process, cleaned and sorted tomatoes undergo crushing, hot break treatment, juice extraction, concentration, and pasteurization, as described in detail in previous research [4]. Once filled, the cans are sealed and conveyed to the sterilization unit, where they are heated by immersion in a hot water bath before undergoing a cooling process in water. Finally, the sterilized canned tomatoes proceed to an automatic palletizer for labeling and bulk storage before delivery to customers [4].

2.2. Tomato Peeling Operation

Table 1 provides a summary of the optimal processing conditions and performance indicators for the five peeling methods under investigation: lye, steam, US-ley, OH-lye, and IR peeling. Conventional lye and steam peeling were used as controls for innovative peeling methods.

Table 1. Operating conditions and performance indicators for conventional and innovative techniques of tomato peeling.

Peeling Method	Optimal Peeling Conditions	Peeling Easiness (Out of 5)	Peeling Loss (%)	References
Steam [(1)]	Pressurized steam: 120 kPa, (10–40 s) Vacuum step: 42 kPa	5.0	15	See Section 2.2.1
Lye [(2)]	10% (*w*/*v*) NaOH, Lye-to-tomato ratio: 5:1 (*v*/*w*) 95 °C, 75 s	4.8	13.6	[19]
US-lye [(3)]	Lye: 4% (*w*/*v*) NaOH, 97 °C, 30 s Lye-to-tomato ratio: 11:1 (*v*/*w*) US: P_v = 31.97 W/L, 70 °C for 50 s	5.0	7.2	[10]
OH-Lye [(4)]	Treatment medium: 0.01/0.5% NaCl/NaOH Medium-to-tomato ratio: 1:1 (*v*/*w*) OH: E = 1210 V/cm, 88 s	4.5	11.4	[20]
IR [(5)]	75 s, 90 mm emitter–tomato gap	4.8	9.8	[19]

[(1)] The steam peeling paraments include the steam pressure at the scalder inlet, the residence time, and the pressure during the vacuum step. [(2)] The parameters of conventional lye refer to the lye concentration expressed in weight/volume (*w*/*v*), the lye-to-tomato ratio in volume/weight (*v*/*w*), as well as the processing time and temperature. [(3)] Ultrasound (US) parameters encompass the ultrasound volumetric power (Pv), measured in Watts/Liter (W/L), processing temperature, and time. [(4)] Ohmic heating (OH) parameters refer to electric field strength (E, in Voltage/Centimeter (V/cm)) and heating time. [(5)] IR heating parameters include the exposure time to IR and the gap between the two catalytic IR emitters and the tomato.

The evaluation of the peeling performance of tomatoes is crucial to compare different peeling techniques, as well as for resolving mass and energy balances across the peeler (Figure 1). In this research, two performance indicators were used, namely peeling ease and peeling loss. The ease of peeling was assessed using a subjective quality scale ranging from 1 (unable to peel) to 5 (easy to peel) to describe the ease of peeling tomatoes subjected to different methods, as outlined in Table S1 of the Supplementary Materials. A score above 4 is deemed acceptable for peeling ease [19]. Peeling loss, expressed as the percentage weight change of tomatoes before and after peeling, indicates the amount of tomato removed as a by-product or waste. It is desirable to minimize peeling loss while achieving an acceptable level (>4) of peeling ease [19]. In this study, data on peeling performance and processing conditions of steam peeling were achieved from the Italian industrial tomato processor. In the absence of industrial-scale data on applying novel technologies in the tomato peeling phase, data were sourced from laboratory-scale studies in the literature [10,19,20,25]. Estimates for water, electricity, methane consumption, and peeling waste were derived from these studies and then scaled to match a target tomato processing facility with an annual capacity of 60,000 tons. These data were selected based on processing parameters that achieved a comparable ease of peeling score. Specifically, the optimal processing conditions for each peeling technique, as reported in Table 1, were identified as the minimal conditions required to achieve acceptable peeling ease (>4) with minimal peeling loss, while maintaining the firm and visually appealing surface integrity of the tomatoes. Further details are provided in the following subsections.

2.2.1. Steam Peeling

An Italian industrial tomato processor provided average data on steam peeling conditions and performance. During this process, cleaned tomatoes are fed into the scalder and exposed to pressurized steam at approximately 120 kPa for a brief period (10–40 s) before undergoing vacuum cooling at around 42 kPa. This method results in the highest tomato peel waste, roughly 15%, while achieving an optimal peeling quality score of 5 out of 5, indicating excellent efficiency in skin removal.

2.2.2. Lye Peeling

Conventional lye peeling was conducted by immersing tomatoes in a 10% (w/v) sodium hydroxide (NaOH) solution at 95 °C for 75 s, using a solution-to-tomato ratio of 5:1, as described by Pan et al. [19]. This method resulted in a peeling loss of 13.6%, representing the percentage of tomato mass lost during peeling. The peeling ease was rated 4.8 out of 5, demonstrating the high effectiveness of this technique, as most of the tomato skin separated from the flesh with minimal effort [19].

2.2.3. IR Peeling (IR)

IR peeling data were obtained from Pan et al. [19]. Tomato fruits were peeled using a heating system equipped with two catalytic IR emitters powered by natural gas and positioned 90 mm from the tomato fruits. The tomatoes were exposed to IR heating for 75 s, with product rotation to ensure uniform heating, which improved both quality and peeling performance. This process resulted in a peeling loss of 9.8%, and the ease of peeling was rated 4.8 out of 5 [19].

2.2.4. OH-Assisted Lye Peeling (OH-lye)

The OH-lye peeling method employed a system with an AC power supply (0–1000 V) and a controller connected to an ohmic heating unit consisting of two titanium electrodes, separated by an open Pyrex glass T-tube cylinder with a length of 0.201 m (electrode gap) and an inner diameter of 0.051 m, as detailed by Wongsa-Ngasri and Sastry [20]. This system processed tomatoes with NaCl/NaOH solutions. The ratio of solution to tomato was 1:1. Optimal results were achieved using 0.01/0.5% NaCl/NaOH at 1210 V/m for 81.8 s, which resulted in a peeling loss of 11.4% with a peeling ease score of 4.5 out of 5 [20].

2.2.5. US-Assisted Lye Peeling (US-lye)

Optimal data on US-lye peeling were obtained from Gao et al. [10]. The authors used a two-step tomato peeling method consisting of hot lye with the subsequent assistance of ultrasound. The tomatoes were initially immersed in a 4% (w/v) lye solution at 97 °C for 30 s with gentle agitation. The ratio of solution to tomato was 1:1. The tomatoes were then subjected to a 31.97 W/L ultrasound treatment at 70 °C for 50 s using a solution to tomato ratio of 11:1. This method achieved 100% peelability with a peeling loss of only 7.2% [10].

2.3. Life Cycle Assessment

Life cycle assessment (LCA) is a widely recognized methodology for evaluating the environmental impacts of a product or service throughout its entire life cycle. Standardized by ISO 14040 and 14044 (2006) [26,27], LCA facilitates the quantification, analysis, and interpretation of environmental impacts throughout the production, use, and disposal stages. In this study, SimaPro software (9.0.0.48) was utilized to assess the environmental impact associated with producing 1 kg of peeled tomatoes using various tomato peeling methods.

2.3.1. Boundaries and Assumptions

A few boundaries and assumptions were taken into consideration while evaluating and comparing the environmental impact of the peeled tomato production unit facility using different peeling methods. The boundaries analysis accounts for all relevant stages and activities in the product's life cycle to ensure the results are reliable, comparable, and useful for informed decision making [23]. One of the main aims of this research is to assess the environmental impact of conventional (lye, steam) and unconventional (US-ley, OH-lye, and IR) tomato peeling methods. These methods are supposed to be integrated into an industrial tomato facility processing 60,000 ton/year of tomatoes to produce canned whole peeled tomatoes, to identify the most environmentally friendly approach. The boundary limit considered is "gate-to-gate", focused exclusively on the tomato processing stages as depicted in Figure 1. The analysis includes tomatoes, water, electrical energy, methane, and chemical (NaOH) used during the processing phases all within the defined system boundaries. However, the system boundaries exclude stages such as downstream processes (e.g., product distribution and the end-of-life phase), other ingredients used in processing (e.g., salt), as well as packaging materials, and the biowaste or tomato waste generated during processing.

In LCA, the functional unit (FU) serves as a quantified measure of the performance of the product, service, or process under evaluation, providing a standardized reference for inventory data [26] and enabling comparisons across different products [27]. In the food industry, the FU is generally based on the unitary mass of the target product, with all associated inputs and outputs calculated accordingly [23]. For this study, the FU was defined as 1 kg of canned tomato, comprising 60% whole peeled tomatoes and 40% tomato puree.

2.3.2. Life Cycle Inventory (LCI) Data

The LCI phase is crucial in LCA, as it quantifies all inputs and outputs throughout a product's life cycle. The reliability of an LCA study largely depends on the quality of data collected during this phase [28]. As previously stated, data for steam peeling were provided directly by the tomato processor, while data for other peeling methods were sourced from existing literature, as summarized in Table 1. This information was normalized to represent the production of one kilogram of canned peeled tomatoes, as shown in Table 2. Specifically, to evaluate the impacts of innovative technologies in the peeling stage, data on water, electricity, methane, and chemical usage were gathered from multiple studies [10,19,20] (Table 2). For resource consumption data related to other tomato processing stages, such as washing, sorting, juice production, and packaging, information was sourced from Eslami et al. [25], who conducted a comprehensive evaluation of resource usage throughout the tomato processing steps.

Table 2. Life cycle inventory for producing one kg of canned peeled tomatoes through different methods.

Peeling Method	Tomato Input [(1)] (kg)	Fresh Water (m^3)	Electricity (kWh)	Thermal Energy [(2)] (kWh)	NaOH (kg)	References
Steam	1.490	0.007 (0.001)	0.048 (0.003)	0.205 (0.073)	0	[25]
Lye	1.478	0.010 (0.004)	0.045 (0)	0.465 (0.332)	0.347	[19,25]
US-lye	1.426	0.016 (0.010)	0.049 (0.005)	0.464 (0.332)	0.129	[10,25]
OH-Lye	1.459	0.007 (0.000)	0.106 (0.061)	0.132 (0)	0.002	[20,25]
IR	1.446	0.006 (0)	0.079 (0.034)	0.132 (0)	0	[19,25]

[(1)] Data were assessed by solving the mass balance across the processing line illustrated in Figure 1, based on a 1 kg output of canned peeled tomatoes, consisting of 60% whole peeled tomatoes and 40% tomato puree with a concentration of 8° Brix. [(2)] The values were calculated based on methane consumption per kilogram of product, using the lower calorific value of methane (13.1 kWh/m^3). The values in the brackets represent the contribution of the peeling stage alone for each peeling method. The actual water consumption for OH-Lye peeling was 0.0003 m^3, which rounds to zero.

2.3.3. Life Cycle Impact Assessment (LCIA)

According to the background data, information related to the production of electricity, methane, water, and sodium hydroxide was sourced from the Ecoinvent database (V3.5) [29]. The data used in this study primarily reflect the Italian context where available; however, in the absence of country-specific data, the study utilized information representative of the broader European context.

The CML-IA baseline method (V3.05) was employed to evaluate the environmental impact of processing operations for peeled tomatoes, developed by the Center for Environmental Science (CML) at Leiden University in the Netherlands [30]. This life cycle assessment (LCA) methodology includes 11 midpoint impact categories. Six of these categories, such as global warming potential (GWP100a), abiotic depletion (fossil fuels) (AD), ozone layer depletion (ODP), human toxicity (HT), acidification potential (AP), and eutrophication potential (EP) [30], were identified as the most relevant indicators, based on the specific characteristics of the processes analyzed in this study.

Specifically, GWP measures a product's or process's contribution to climate change through greenhouse gas (GHG) emissions. It is calculated over a 100-year timeframe (GWP100a) and expressed in carbon dioxide equivalents (CO_2-eq) [31].

ODP refers to the thinning of the ozone layer in the Earth's stratosphere, mainly caused by human-made chemicals such as chlorofluorocarbons (CFCs), halons, and other ozone-depleting substances. The ODP is measured in CFC-11 equivalents, which is a standard metric used to quantify how much a particular substance contributes to ozone depletion [32,33].

HT is a critical environmental impact commonly evaluated in life cycle assessment (LCA). It quantifies the potential harm that chemicals may pose to human health. This is quantified in kilograms of 1,4-DB-eq (1,4-dichlorobenzene equivalents), comparing the toxicity impact of various chemicals relative to the reference substance 1,4-dichlorobenzene. The assessment includes exposure to industrial chemicals, such as heavy metals (lead, mercury), pesticides, and solvents, which can enter the body through multiple pathways and potentially lead to severe health issues, including neurological damage and cancer. Additionally, air pollutants like particulate matter (PM), volatile organic compounds (VOCs), and nitrogen oxides (NO_x) contribute to respiratory diseases, while water contaminants, such as arsenic, mercury, and pharmaceutical residues, pose toxic risks, particularly impacting the nervous system and kidneys [34].

AD of fossil fuels refers to the depletion of non-renewable resources like coal, oil, and natural gas due to human activity. This depletion is measured in megajoules (MJ), representing the amount of energy extracted from Earth's finite reserves. In LCA, this concept evaluates the consumption of these finite resources, highlighting their eventual exhaustion. Fossil fuels serve as a primary energy source, and their depletion carries substantial environmental and economic consequences, especially since they are non-renewable within a human timescale, thus representing fossil energy used in production processes [33,35].

AP refers to the environmental impact of certain pollutant emissions, primarily sulfur dioxide (SO_2), nitrogen oxides (NO_x), and ammonia (NH_3), that react in the atmosphere to form acidic compounds. This process, often measured in kilograms of sulfur dioxide equivalent (kg SO_2-eq), leads to the deposition of acid on land and water through precipitation (acid rain), dry deposition, or fog. Acidification lowers ecosystem pH levels, adversely affecting soils, water bodies, and biodiversity by depleting soil nutrients and damaging aquatic life [36,37]. The acidification potential of each tomato peeling method was assessed for its contribution to acid rain formation and broader environmental consequences.

EP is a crucial environmental indicator related to water pollution, representing the risk of nutrient overload in water bodies due to excess nitrogen (N) and phosphorus (P). This nutrient excess, often stemming from agricultural runoff, wastewater, and industrial pollutants, promotes excessive algal and aquatic plant growth, which disrupts the natural balance of aquatic ecosystems. Measured in kilograms of phosphate equivalent (kg PO_4^{3-}-eq), EP quantifies a process's or product's contribution to nutrient pollution and its impact on water quality [37,38].

3. Results

3.1. Effect of Innovative Peeling Methods on Production Yield and Quality of Peeled Tomato

Figure 1 shows the process flow diagram for an industrial tomato processing line with a seasonal capacity of 60,000 tons, specifically designed for whole-peeled tomato production. The schematic compares the production yield of peeled tomatoes using conventional steam and lye peeling methods versus innovative OH-lye, US-lye, and IR peeling methods.

From the diagram, it is evident that before peeling, tomatoes undergo a washing phase, eliminating solid wastes (3%, w/w) such as soil, stones, leaves, and branches, along with wastewater generation. Subsequently, the washed tomatoes undergo manual and automatic sorting, during which about 5% (w/w) of the input raw material is assumed to be discarded due to defects, unwanted materials, and green tomatoes.

Approximately 65% of the washed and sorted tomatoes were subsequently subjected to different peeling operations using steam, lye, OH-lye, US-lye, and IR, following the optimal processing conditions outlined in Table 1. Furthermore, using data from both the tomato processor and existing literature, each peeling method was evaluated for its associated peeling losses corresponding to achieving similar peeling ease (>4), ensuring good peelability of the tomato fruits. In general, besides minimizing quality changes, water and energy consumption, and pollution loads, a sustainable peeling method should also aim to minimize product loss, thereby preserving economic benefits [9]. As indicated in Table 1, under the selected optimal processing conditions, steam peeling exhibited the highest peeling loss (15%) followed by lye peeling (13.6%), OH-lye (11.4%), IR (9.8%), and finally US-lye (7.2%). As a result, the quantities of tomatoes exiting the peeler differed across methods: 30,548 tons/year for steam peeling, 31,051 tons/year for lye peeling, 31,842 tons/year for OH-lye, 32,417 tons/year for IR, and 33,351 tons/year for US-lye peeling. Compared to conventional lye and steam peeling methods, US-lye, OH-lye, and IR techniques showed increased production capacities of 7.4–9.2%, 2.6–4.2%, and 4.4–6.1%, respectively. Consistently, as compared with lye and steam peeling, the lower peeling losses associated with OH-lye, US-lye, and IR peeling methods translate to decreased solid waste generation by 47–52%, 16–24%, and 28–35%, respectively, which comprises peels and pulp, thus reducing the environmental burden.

For puree production, about 35% of washed tomatoes were routed to the puree line, where they were crushed, heated to 95 °C, and refined to extract juice (~5° Brix) with a yield of approximately 95%, separating skins and seeds. The juice was then concentrated through evaporation to produce puree at 8° Brix.

Tomatoes peeled by the five methods were then packed into 400 g tinplate cans, with tomato puree (8° Brix) added at a 60:40 (w/w) ratio of whole peeled tomatoes to puree.

The total number of cans undergoing sterilization before labeling and storage reached $1.27 \cdot 10^8$ and $1.29 \cdot 10^8$ with conventional steam and lye peeling, respectively. In comparison, this number increased to $1.39 \cdot 10^8$ with US-lye, $1.35 \cdot 10^8$ with IR peeling, and $1.33 \cdot 10^8$ with OH-lye peeling (Table 3). These results demonstrate that the advanced US-lye, OH-lye, and IR peeling methods not only enhance production capacity but also reduce solid waste, contributing to the facility's economic and environmental sustainability. Further analysis will delve into these advantages in greater detail.

Moreover, the previous research demonstrated that under the processing parameters outlined in Table 1, the innovative peeling techniques produced peeled tomatoes with quality attributes comparable to or exceeding those of traditional methods. For instance, tomatoes processed using infrared (IR) peeling maintained a similar firmness (12.7 N) and color (Hue° = 30.8) to those peeled conventionally with lye (12.7 N, Hue° = 29.6) [19]. The combination of salt-lye and OH-assisted peeling also yielded improved product quality, especially with a firmer texture [1,20]. Additionally, a two-step process involving hot lye peeling followed by US assistance not only achieved 100% peelability with higher yields but also significantly enhanced the lycopene content (by an average of 86%) compared to traditional hot lye peeling [10].

Table 3. Effect of innovative peeling techniques of tomato fruits on the annual revenue of a tomato facility with a plant capacity of 60,000 ton/year.

Peeling Method	Total Cans $\cdot 10^6$	Gross Revenue (1) (MEUR)	Net Revenue (2) (MEUR)	Profit Margin (3) (MEUR)	Profit Margin (4) (MEUR)
Steam	127	53.46	10.69	-	-
Lye	129	54.34	10.87	-	-
US-Lye	139	58.36	11.67	0.98	0.81
OH-Lye	133	55.72	11.14	0.45	0.28
IR	135	56.73	11.35	0.65	0.48

(1) Calculated based on a gross selling price of 0.42EUR/can. (2) Calculated based on a net profit of 0.07EUR/can. (3) Calculated as net revenue (steam)–net revenue (IR, OH-Lye, and US-lye). (4) Calculated as net revenue (Lye)–net revenue (IR, OH-Lye, and US-lye).

3.2. Economic Impact of Innovative Peeling Methods

For the first time, an economic impact analysis was carried out to estimate the potential economic benefits of incorporating innovative peeling methods into a peeled tomato processing line, providing stakeholders with valuable insights.

In Table 3, the total amount of canned peeled tomatoes produced using the five different peeling methods under investigation (as depicted in Figure 1) was used to estimate the economic impact in terms of profitability associated with integrating innovative IR, US-lye, and OH-lye methods, compared to conventional lye and steam peeling.

First, the production capacity of each of the five peeling methods was evaluated to estimate the total number of 400 g tinplate cans of tomatoes achievable by the end of the season. This assessment involved analyzing the peeling efficiency of each technology to evaluate its output throughout the production period, ultimately allowing for a comparison of how these methods impact the total quantity of canned tomatoes produced. Then, based on this number of cans and an average selling price of EUR0.42 per can, as provided by the tomato processor, the gross revenue for each peeling method was determined. Furthermore, by assuming that the company earns 20% of the selling price, the annual net revenue for each peeling method was calculated, offering insights into the economic performance of each technology based on both gross and net revenues from production output and profit margins. Results showed that, compared to steam peeling, annual profits were notably higher with the alternative methods: US-lye generated EUR981,121, OH-lye produced EUR452,825, and IR yielded EUR654,081. Similarly, against traditional lye peeling, US-lye achieved EUR805,022, OH-lye brought in EUR276,726, and IR resulted in EUR477,982 in profits. Therefore, it is evident that integrating innovative peeling techniques such as US-lye, OH-lye, and IR can significantly boost annual profits by 2.5–7.4% compared to traditional lye peeling, and by 4.2–9.2% compared to steam peeling. However, it is important to note that this analysis does not account for the costs associated with the equipment required to implement these advanced peeling methods, such as IR, US-lye, and OH-lye peeling systems.

Figure 2 illustrates the total wastewater generated across the processing stages, from washing to peeling. The contributions of these two stages were evaluated by calculating the wastewater generated during the production of 1 kg of canned peeled tomatoes. This analysis considers the use of 3 m^3/h of water for washing each m^3 of raw tomatoes and accounts for the varying efficiencies of the peeling methods, as outlined in Table 1. Finally, the wastewater generated at each stage per kilogram of peeled tomatoes was scaled to reflect the annual processing capacity of 60,000 tons of raw tomatoes at the facility.

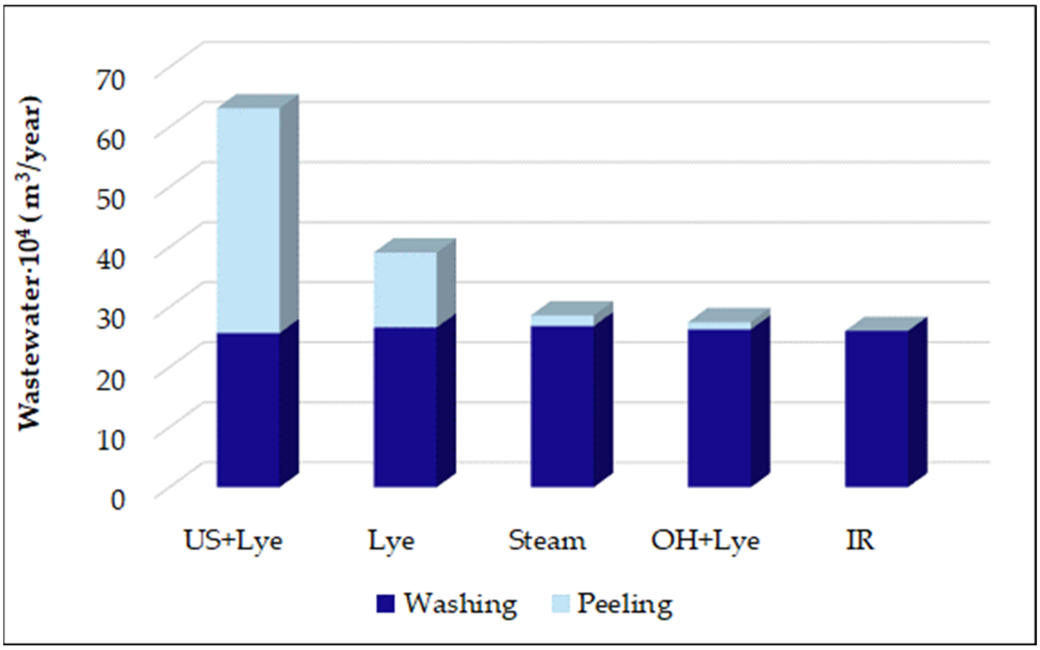

Figure 2. The total wastewater generated by the tomato processing company, with an annual capacity of 60,000 tons, across the washing, sorting, and peeling stages, utilizing both conventional and innovative methods in the peeling phase.

The results indicate that integrating US-lye peeling produces the highest total wastewater, followed by lye, steam, OH-lye, and IR peeling methods. However, the washing phase exhibited a different order (Steam > Lye > OH-lye > IR > US-lye), reflecting the varying efficiencies of the peeling methods (Table 1). Additionally, Figure 2 highlights the significant water demand associated with conventional lye peeling (10% NaOH) and US-lye peeling (4% NaOH). This is because both methods require high lye-to-tomato ratios, with lye peeling demanding a ratio of 5:1 (v/w) and US-lye peeling requiring a ratio of 11:1 (v/w). This intensive water consumption results in a large volume of wastewater characterized by high chemical oxygen demand (COD) and elevated pH levels, necessitating specialized treatment to meet environmental compliance standards. Consequently, these methods incur considerable disposal costs due to the extensive treatment required for wastewater management. Notably, combining lye with OH can mutually enhance the advantages of both methods, significantly reducing the concentration of NaOH to as low as 0.5%. This lower lye concentration in OH-lye peeling can be neutralized after processing, potentially by the natural acids present in tomatoes themselves [20]. Additionally, OH-lye peeling reduces wastewater volumes by up to five times compared to traditional lye peeling, due to its lower lye-to-tomato ratio (1:1, v/w), providing considerable economic and environmental advantages.

Physical peeling methods, such as steam and infrared (IR) dry-peeling, also significantly decrease wastewater volumes compared to lye-based methods. IR dry-peeling, in particular, proves effective for peeling tomatoes without chemicals or water during the peeling phase [19], thus generating minimal wastewater limited primarily to the washing and sorting stages.

3.3. Environmental Impact of Innovative Peeling Methods

3.3.1. Raw Material and Resource Usage

To illustrate the range of resource usage and environmental impacts associated with processing tomato fruits into 1 kg of canned peeled tomatoes using both conventional methods (steam and lye peeling) and innovative techniques (OH-lye, US-lye, and IR peeling), a gate-to-gate Life Cycle Assessment (LCA) was conducted employing the CML-IA baseline method.

In this context, the LCI analysis presented in Table 2 highlights significant differences in resource consumption across tomato processing facilities using various peeling methods. Pressurized steam and lye peeling methods demand a higher tomato input of 1.490 kg and 1.478 kg, respectively, for each unit of canned peeled tomatoes, compared to OH-lye (1.459 kg), IR (1.446 kg), and US-lye (1.426 kg) methods. This increased input is primarily due to the larger volume of tomato waste generated during steam (15%) and lye peeling (13.6%), whereas waste levels are considerably lower for US-lye (7.2%), OH-lye (11.4%), and IR (9.8%) methods.

The analysis also highlights notable differences in water, energy, and chemical consumption across tomato processing lines utilizing various peeling methods. Specifically, facilities employing US-lye (0.0164 m^3) and lye peeling (0.0097 m^3) require significantly higher water inputs per kilogram of canned peeled tomatoes, with 0.0104 m^3 and 0.0035 m^3, respectively, directly linked to the peeling phase. In contrast, OH-lye and steam peeling methods use 0.0065 m^3 (0.0003 m^3 for peeling) and 0.0067 m^3 (0.0005 m^3 for peeling) of water, respectively. IR peeling, as a dry process, demonstrates the lowest water consumption at 0.0061 m^3, primarily allocated for washing.

In terms of electrical energy, production lines using OH-lye (0.106 kWh) is the most energy-intensive methods. In comparison, IR (0.079 kWh), US-lye (0.049 kWh), steam (0.048 kWh), and lye peeling (0.045 kWh) are significantly more energy efficient.

Thermal energy in terms of steam generated through methane combustion, as outlined in Table 2, is applied across multiple processing stages, including hot break, evaporation, sterilization, and peeling (specifically when steam, lye, or US-lye peeling is utilized) [4]. The analysis shows that there are marked differences across peeling techniques. OH-lye and IR peeling exhibit the lowest thermal energy consumption (0.132 kWh each), as this energy primarily supports other thermal treatments unrelated to peeling itself. By contrast, steam peeling requires a moderate thermal energy input (0.205 kWh), partially due to steam usage in the scalder during peeling (0.073 kWh). Meanwhile, production lines employing lye peeling (0.465 kWh) and US-lye peeling (0.464 kWh) demonstrate the highest thermal energy demands, driven mainly by the heating requirements for the lye solution (0.332 kWh).

Lastly, sodium hydroxide usage is greatest in lye peeling (0.347 kg), followed by US-lye peeling (0.129 kg) and, to a much lesser extent, OH-lye peeling (0.002 kg). This underscores the resource-intensive nature of lye-based methods compared to alternative physical peeling techniques.

In conclusion, these results suggest that while novel tomato peeling techniques enhance productivity and reduce product waste, they may not always surpass conventional peeling methods in terms of freshwater consumption and energy efficiency.

Currently, the impact of novel peeling techniques on productivity and resource usage of tomato processing plants has been minimally explored, with previous research focusing primarily on conventional steam peeling [25] or its combination with PEF pre-treatment [7]. However, no studies have specifically addressed the novel peeling methods examined in this research. Nonetheless, their findings align with those of the present study. For instance, Eslami et al. [25] reported that washing and sorting stages for producing 1 kg of canned peeled tomatoes consume the majority of processing water (0.0034 m^3), the puree production stage requires the most electricity (0.061 kWh), and thermo-physical peeling (0.097 kWh/kg product) and tomato concentration (0.107 kWh/kg product) stages account for the highest thermal energy demands. Additionally, the industrial-scale integration of PEF technology to assist steam peeling of tomatoes demonstrated a 20% reduction in water and thermal energy consumption compared to conventional steam peeling [7], underscoring the potential of novel technologies to enhance the sustainability of tomato processing operations.

3.3.2. Midpoint Environmental Impact Indicators

The environmental impacts associated with producing one kilogram of canned peeled tomatoes using various peeling methods were assessed using multiple midpoint indicators. Figure 3 highlights the most relevant impact categories, including global warming potential (GWP100a), abiotic depletion (fossil fuels) (AD), ozone layer depletion (ODP), human toxicity (HT), acidification potential (AP), and eutrophication potential (EP), each examined in relation to the peeling methods used. These data illustrate the resource consumption and emissions tied to each method, providing a detailed view of their environmental footprints.

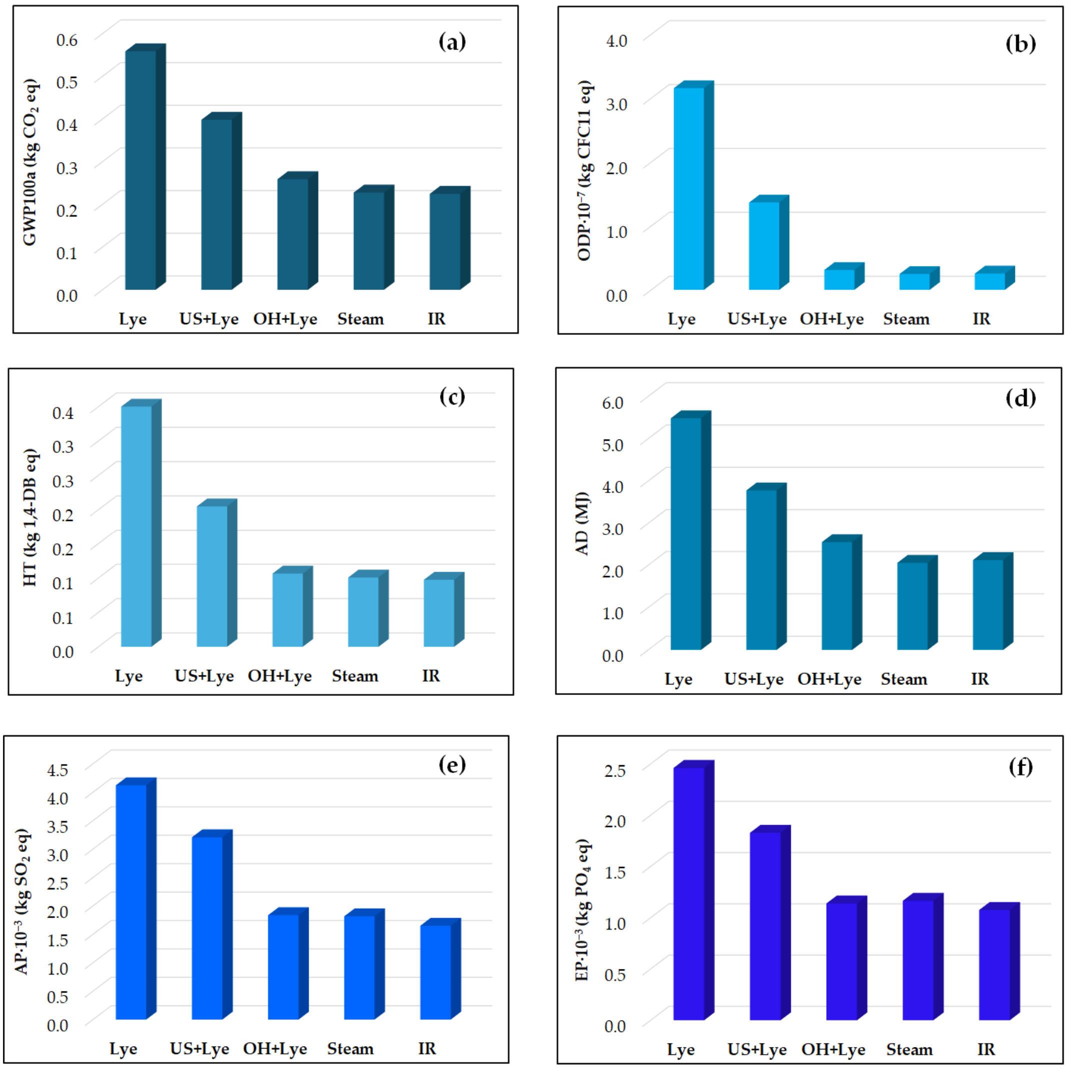

Figure 3. Environmental midpoint indicator impacts on the production of peeled tomatoes by different peeling methods. (**a**) Global warming potential (GWP100a), (**b**) ozone layer depletion (ODP), (**c**) human toxicity (HT), (**d**) abiotic depletion (fossil fuels) (AD), (**e**) acidification potential (AP), and (**f**) eutrophication potential (EP).

Generally, the results indicate that lye peeling consistently ranks as the least environmentally sustainable method, with the highest impacts across all analyzed categories, including GWP, ODP, HT, AP, and EP. In contrast, infrared (IR) peeling emerges as the most environmentally favorable method, followed by steam and OH-lye peeling.

Specifically, for global warming potential (GWP), conventional lye peeling has the highest value at 0.559 kg CO_2-eq per kilogram of peeled tomatoes. US-lye peeling reduces GWP by 29%, while OH-lye, steam, and IR peeling achieve more substantial reductions of

54%, 59%, and 60%, respectively. This positions IR peeling as the most sustainable option in this category.

A similar trend is observed in ozone depletion potential (ODP). Lye peeling exhibits the highest ODP at $3.16{\cdot}10^{-7}$ CFC-11-eq, while US-lye peeling reduces this by 57%. OH-lye peeling shows a remarkable 90% reduction, and both steam and IR peeling achieve reductions of approximately 92%, making them the most environmentally friendly methods in terms of ozone protection.

The analysis of human toxicity (HT) further underscores the environmental burden of lye peeling, which has the highest impact at 0.350 kg 1,4-DB-eq, due to the release of hazardous substances from high NaOH concentrations. US-lye peeling reduces HT by 42%, and OH-lye, steam and IR peeling achieve reductions of 70–72%, highlighting their potential to mitigate human health risks.

In terms of fossil fuel depletion, lye peeling consumes the most energy, at 5.48 MJ per kilogram of peeled tomatoes. US-lye and OH-lye peeling reduce energy use by 31% and 54%, respectively, while steam and IR peeling lower fossil fuel consumption by 63% and 61%, respectively.

The acidification potential (AP) results show lye peeling with the highest value at $4.12{\cdot}10^{-3}$ kg SO_2-eq, contributing significantly to acid rain formation. US-lye peeling achieves a modest reduction, while OH-lye, steam, and IR peeling show reductions of 55%, 56%, and 60%, respectively. These findings highlight the substantial environmental advantage of methods using lower concentrations of lye or physical processes.

For eutrophication potential (EP), conventional lye peeling has the highest impact at $2.46{\cdot}10^{-3}$ kg PO_4^{3-}-eq, contributing significantly to nutrient pollution. US-lye peeling reduces this by 25%, while OH-lye, steam and IR peeling achieve reductions of 53–56%, underscoring their sustainability benefits.

Overall, among all the tomato peeling methods examined, chemical techniques that utilize high concentrations of NaOH, specifically lye peeling (10% NaOH) and US-lye peeling (4% NaOH), exhibited the highest environmental impacts across all assessed categories. In contrast, OH-assisted lye peeling, which employs a relatively low NaOH concentration (0.5%), along with physical peeling methods such as steam and infrared peeling, demonstrated significantly lower environmental impacts and showed similar patterns of sustainability. These latter methods are regarded as the most environmentally friendly options among those analyzed.

The results also revealed that despite variations in total (electrical + thermal) energy consumption across different conventional and unconventional peeling methods, such as steam (0.253 kWh), lye (0.510 kWh), US-lye (0.584 kWh), OH-lye (0.286 kWh), and IR (0.211 kWh), methods involving sodium hydroxide (NaOH) consistently demonstrated the highest environmental impact. This trend suggests that the greater the consumption of NaOH, the higher the environmental impact. Although ultrasound-assisted lye peeling (US-lye) consumed more energy than traditional lye peeling, the latter still had the highest environmental impacts across all categories. This finding is likely due to the energy-intensive production process of NaOH, its thermal energy requirements during use, and the environmental burden from wastewater discharge, all contributing to a significant environmental footprint [39].

To the best of our knowledge, only a limited number of studies in the literature have examined the LCA of processing stages for canned peeled tomatoes, and these have predominantly focused on processing lines utilizing steam peeling, without specifically addressing plants that incorporate the novel peeling techniques analyzed in this study. For instance, Garofalo et al. [40] discussed the environmental impact of peeled tomato production, evaluating various impact categories and identifying juice production, pasteurization, and peeling as the stages with the highest environmental impact. Similar findings were reported by Eslami et al. [25], who determined that the total GWP for producing 1 kg of peeled tomatoes was $7.63{\cdot}10^{-2}$ kg CO_2-eq, aligning with the results obtained in this study (Figure 3a). Only one study has addressed the LCA of a processing line incorporating a novel peeling technique, specifically PEF technology, to enhance the efficiency of steam peeling [4]. The authors found that focusing solely on the steam peeling stage, all environmental indicators improved by 17% to 20% in terms of absolute values when PEF technology was integrated.

3.4. Disadvantages and Limitations of Tomato Peeling with Novel Technologies

Despite the evident economic and environmental benefits stemming from the adoption of IR, US-lye, and OH-lye peeling methods, several challenges persist. For instance, achieving optimal peeling performance and high-quality products with IR technology relies on critical parameters like the temperature of the infrared heater, the spacing between the product and the heater, and the heating time [13]. While exposing fruits or vegetables to high-intensity infrared radiation for extended periods can aid in peel removal, it may also lead to skin burns and the formation of a thick cooking ring, which is an undesirable outcome [1]. Moreover, the operation of IR heating for peeling may necessitate rotating the fruits and vegetables to mitigate the effects of uneven heating, which places higher demands on the equipment [19]. Therefore, careful optimization of process parameters and equipment design is crucial to fully capitalize on the potential benefits of IR peeling. In such cases, although the initial investment cost for IR peeling equipment is high, the long-term benefits may justify it.

A cascade approach that combines hot lye and ultrasound (US) has shown promising results, achieving satisfactory peelability with minimal peeling loss at low lye concentrations. However, scaling up ultrasound-assisted peeling presents significant challenges. The technique requires substantial energy input, which varies with the operational scale [4]. This energy demand must be carefully balanced against potential benefits, such as reduced chemical usage, improved product yield, and enhanced quality. Ultrasound's ability to penetrate and facilitate peeling is also limited, and variations in tomato characteristics, such as size, ripeness, and skin thickness, can contribute to uneven peeling [8]. Additionally, cavitation intensity decreases with distance from the acoustic electrode tip, potentially leading to uneven peeling in larger systems [1]. The process also requires a substantial water medium to effectively transmit sound waves, raising water consumption. Managing and recycling this water, often with high COD and BOD values, adds to operational costs and creates environmental concerns [2]. Overall, US-lye peeling shows promise for improving tomato processing efficiency, but further research is needed to address these limitations and optimize the method for large-scale applications [2,4,10,12].

On the other hand, the potential of OH-lye peeling for enhancing peeling performance, product yield, and quality requires the optimization of numerous factors, including the solid-to-liquid ratio, the size of fruits and vegetables, and parameters influencing electric field behavior such as ohmic heater geometry and electrical conductivity of the treated medium, all of which may complicate the large-scale application of this technology [1]. Furthermore, although OH enables marked reductions in the concentration of the salt solution or lye, the challenge of safely disposing the waste solution still remains [1,2]. Moreover, the unavoidable occurrence of electrochemical reactions at the electrode interface might represent a further challenge, especially when ohmic-peeling equipment is used for a long time. These reactions may involve electrode corrosion, fouling of the electrode, and electrolysis of water that may cause technological problems and product quality degradation [41]. Consequently, deploying OH on an industrial scale necessitates further research on engineering design, optimization of process parameters, economic considerations, and the scalability of the process [4,25,41].

In conclusion, scaling up and optimizing process parameters, along with refining equipment design for novel peeling technologies, are critical steps toward achieving efficient, high peelability with minimal water and energy use, while preserving the quality of the food product. By reducing dependence on traditional heating and chemical methods, these advancements contribute to more sustainable practices and support cleaner production.

4. Conclusions

This study conducted a comparative analysis of the economic and environmental impacts of conventional steam and lye peeling methods versus innovative peeling technologies, namely, ultrasound-assisted lye (US-lye), ohmic heating-assisted lye (OH-lye), and infrared (IR) peeling, in the tomato processing industry.

Findings from this preliminary research indicate that adopting innovative peeling techniques like US-lye, OH-lye, or IR, known for high peeling efficiency, can enhance production capacity by 2.6–9.2%, boosting revenue by a similar range (2.5–9.2%) and decreasing solid waste generation by 16–52% when compared to conventional peeling methods. However, while OH-lye and IR peeling significantly reduce water and energy usage, these advantages are not consistent across all innovative methods, with US-lye showing higher water and energy demands. Additionally, IR and OH-lye peeling methods either eliminate or significantly lower NaOH requirements, cutting chemical consumption and minimizing wastewater generation. This reduction in wastewater offers substantial environmental and economic advantages by easing the load and cost of wastewater treatment.

Life cycle assessment (LCA) results show that, beyond water and energy demands, chemical peeling methods using high NaOH concentrations, such as conventional lye and, to a lesser extent, US-lye, have a more significant environmental footprint compared to OH-lye and physical methods like steam and IR peeling, which use little to no NaOH. Across all considered environmental indicators, the implementation of innovative peeling methods yielded improvements of 22–57% for US-lye and 53–92% for steam, OH-lye, and IR peeling.

The potential benefits arising from the adoption of these novel peeling methods can motivate company management to explore opportunities for enhancing peeling efficiency and increasing the economic and environmental sustainability of the tomato processing industry. However, their implementation requires careful evaluation of initial costs, operational complexities, and long-term benefits. Further research is needed to optimize these technologies for large-scale industrial use, as scaling up may present challenges. In, particular, it is crucial to conduct engineering studies based on data validated at pilot and industrial scales to assess the technical and economic feasibility of each measure, comparing their costs with potential cost savings, and estimating the expected payback period.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su162411272/s1, Table S1: Definitions of peeling easiness (adapted from Pan et al. (2009) [19]).

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