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Review

Enhancing resource efficiency and sustainability in tomato processing: A comprehensive review

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ABSTRACT

The increasing global demand for water and energy resources, coupled with the scarcity of freshwater and fossil fuels, highlights the urgent need for efficient resource utilization and sustainable practices across industries. Industrial tomato processing, a prominent segment within the food processing industry, consumes substantial amounts of water and energy which are interconnected each other through various processing stages.

A systematic approach characterizing the water and energy flows and their link in tomato processing helps to understand how these resources are used in tomato processing and what opportunities exist for improving efficiency. This enable decision makers to implement tailored strategies for water and energy conservation, and waste management enabling to enhance both efficiency and sustainability in tomato processing.

This review provides a comprehensive description of the processing lines involved in tomato processing, with a specific focus on the key steps impacting water and energy consumption as well as waste generation. Furthermore, it proposes a quantitative methodological approach based on water-energy nexus (WEN) assessment, which establishes baselines and identifies opportunities for improving resource efficiency. The review also explores a range of conventional and novel measures and technologies for water conservation, energy recovery, and efficiency across the various stages of tomato processing. It delves into their advantages and limitations, offering insights into their applicability within the industry. By examining these approaches, the review aims to provide valuable guidance for stakeholders in the tomato processing industry seeking to optimize resource utilization, reduce environmental impact, and improve overall sustainability.

1. Introduction

The growing need for water and energy, coupled with the limited availability of freshwater and fossil fuels, the alarming climate fluctuations, and environmental concerns, urgently demand for efficient resource utilization and the adoption of sustainable and optimized industrial practices.

Industries of the food and beverage sector are among the most energy-intensive industries that use huge amounts of fresh water for various processes (Islam and Karim, 2019). According to the United Nations, globally about 72% of water resources are used for agriculture and irrigation, 16% is consumed by municipalities, and 12% goes toward industrial uses (UN-Water, 2021), with 56% of it being consumed by the food and beverages industry (Bhatt et al., 2022). Among them, the most water-intensive sectors include soft drinks and bottled water, dairy products, brewing, wine and spirits, as well as meat and fruits and vegetable processing (Mekonnen and Gerbens-Leenes, 2020; Peterson et al., 2022). In these sectors, water of potable quality is commonly employed as an ingredient, for cleaning, heating, cooling, transportation, and other essential processes (Maxime et al., 2006). Unfortunately, while significant strides have been taken to enhance water use efficiency in agriculture using modern technologies like the Internet of Things (IoT), drones, and satellites, as well as innovative methods such as smart farming (Abdul Rajak, 2022), there is still limited effort from the food and beverages industry to reduce freshwater consumption during the processing of raw materials. Moreover, around 70% of the freshwater used being discharged as effluent containing high levels of biological oxygen demand (BOD) and chemical oxygen demand (COD) (Meneses et al., 2019; Ölmez, 2013). Hence, the management of water resources within the food industry remains less than optimal (Meneses et al., 2019). This is despite wastewater treatment facilities progressively integrating state-of-the-art technologies to meet increasingly

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stringent legal discharge constraints as well as to enhance reclamation efficiency (Borzooei et al., 2020).

In terms of energy requirements, the global food sector consumes approximately 200 EJ per year (FAO, 2017; Mead, 2017), with processing and distribution activities contributing to about 45% of this total (FAO, 2011; Sims et al., 2015). It is also worth noticing that electricity consumption, accounts for one-third of the overall energy consumption in the sector. These substantial energy demands significantly impact production costs in food manufacturing and contributes to air pollution and greenhouse gas emissions (GHGEs) (FAO, 2017). However, it's worth noting that there exists a noteworthy potential for energy savings in the domain of food production (Panepinto et al., 2014).

Therefore, there is an urgent need to rationalize the use of these resources, as well as redesign and optimize existing food processing plants by implementing tailored strategies for water and energy conservation, waste management, and the utilization of conventional or advanced technological solutions and renewable energy sources. Such measures aim to significantly improve the efficiency and sustainability of the food manufacturing industry (Grinberga-Zalite and Zvirbule, 2022; Ringler et al., 2016).

Within this context, it's essential to highlight the interconnected nature of water and energy involved in food processing. Energy (thermal end electrical) is required to transport, heat, and cool water. Further, water in the form of steam can be harnessed to produce energy through turbines (Amón et al., 2017). These relationships are termed the water energy nexus (WEN). In recent years there is growing awareness that understanding the WEN across many industrial sectors is important for characterizing water and energy use through the different stages of processing. Moreover, it facilitates the identification of specific processing areas where water conservation and energy efficiency efforts can have the greatest impact (Amón et al., 2017; Peterson et al., 2022).

The WEN holds particular significance in the context of food processing, a sector known for its substantial consumption of both water and energy resources (Amón et al., 2017). In this context, with a global production exceeding 40 million metric tons annually, the processing of tomatoes represents a significant segment within the food processing industry and an intriguing case study. The United States is the leading producer, followed by China and Italy (De Meo et al., 2022). Tomato processing involves a multi-stage process to produce peeled tomatoes and tomato concentrate, which contributes substantially to water consumption and thermal and electrical energy expenses. The extent of these impacts depends on factors such as the final product, technological solutions, and processing practices (Latini et al., 2017). Furthermore, tomato processing generates two primary wastes that require valorization and reutilization. Wastewater is produced during the raw product fluming and washing stages, with an estimated production ranging from 1.5 to 7.5 m^3 per ton of processed tomatoes (Behzadian et al., 2015; Latini et al., 2017). Additionally, tomato pomace, consisting of skins and seeds, is generated during juice extraction, constituting approximately 2–5% of the total weight of processed fruits (Eslami et al., 2023; Pataro et al., 2020). Currently, it is utilized in low-value applications such as animal feed or compost or is sent directly to landfills (Rossini et al., 2013; Strati and Oreopoulou, 2014). However, this by-product contains valuable components such as natural carotenoids with antioxidant properties, as well as oil, pectin, cutin, and proteins. Exploring methods to recover these components bring significant economic and environmental benefits (Eslami et al., 2023; Pataro et al., 2020). Additionally, residual biomass could be used as a renewable source to obtain energy, in order to reduce both greenhouse gas emissions and reliance on fossil fuels (Grinberga-Zalite and Zvirbule, 2022; Panepinto et al., 2014).

To address these challenges, it is crucial to adopt a holistic approach that optimizes water and energy utilization while efficiently managing waste in the tomato processing industry. This entails adopting state-of-the-art monitoring systems as well as the adoption of conventional measures and cutting-edge technologies to minimize the environmental impact and achieve the highest level of economic and environmental sustainability in the industry.

A comprehensive review of current literature, which was conducted predominantly through the Scopus and Science Direct databases, along with the retrieval of open access project reports, unveiled a collection of publications focusing on the efficient use of resource and sustainability within the food industry and, specifically, in tomato processing sector. These previous works, using different methodological approaches such as WEN assessment, Life Cyle Assessment (LCA) and Current Value Steam Mapping (CVSM), underscore the pivotal significance of quantifying water and energy flows within tomato processing facilities. Such quantification forms the foundation for propelling improvements in efficiency and sustainability. Notably, these previous works have highlighted substantial opportunities for savings electrical energy, peak demand, natural gas consumption, and water usage within tomato processing facilities (Amón and Simmons, 2017; Trueblood et al., 2013).

Moreover, these investigations were primarily addressed at examining specific tomato processing lines of varying sizes, tailored to the production of particular products like peeled or paste. Their main focus revolved around thermal and electric energy-related aspects, striving to uncover opportunities for augmenting efficiency within the domain of industrial tomato processing (Amón et al., 2013; Amón and Simmons, 2017; Trueblood et al., 2013). The emphasis on elucidating the WEN was comparatively limited in these studies even though the use of water and energy are inherently linked and thus important for overall process efficiency (Amón et al., 2013, 2017). Additional explorations have delved into the environmental impact of tomato production (Brodt et al., 2013; Folinas et al., 2017; Garofalo et al., 2017; Manfredi and Vignali, 2014), and the application of innovative technologies aimed at improving process efficiency and product quality (Arnal et al., 2018; Vidyarthi et al., 2019).

This review work is the first attempt to gather, standardize, and critically analyse data achieved from different research groups in different processing plant and employing different methodological approaches. The primary goal is to equip readers, especially decision-makers, with a valuable instrument that facilitates the implementation of tailor-made strategies enabling to enhance both efficiency and sustainability in tomato processing.

Specifically, this review provides a comprehensive description of the processing lines involved in tomato processing, with a specific focus on the key steps impacting water and energy (thermal and electrical) consumption as well as waste generation. Furthermore, it also addresses a methodological approach based on the water-energy nexus (WEN) assessment for setting up the baselines of water and energy consumption and identifying opportunities for improving the efficiency of resource usage. Finally, the review also explores a range of conventional and novel measures and technologies for water conservation, energy recovery, and efficiency across the various stages of tomato processing. It delves into their advantages and limitations, offering insights into their applicability within the industry. By examining these approaches, the review aims to provide valuable guidance for stakeholders in the tomato processing industry seeking to optimize resource utilization, reduce environmental impact, and improve overall sustainability.

2. Tomato processing

Tomato processing facilities operate continuously during a specific period, usually spanning from late July to early October, with processing seasons typically lasting around 90–100 days (equivalent to approximately 2,300 h per year) (Trueblood et al., 2013). The majority of processed tomatoes are utilized in the production of peeled tomatoes (whole, diced, and sliced) as well as tomato concentrates, such as puree and tomato paste. Tomato puree has a natural total soluble solids content ranging from 6 to 9°Brix, while tomato paste ranges between 22 and 36°Brix. In addition to fresh tomatoes, the production of these tomato-based products involves various materials, including packaging containers, fresh water, natural gas, and electricity (Behzadian et al., 2015).

Fig. 1 illustrates the typical steps involved in tomato processing lines for the production of either tomato puree/paste or peeled tomatoes, starting from the reception of raw materials and up to the storage of the final products. It should be noticed that in this schematics, “in-container processing” is considered instead of “aseptic processing”, which involves the cooking, sterilization, and cooling stages prior to packaging (Trueblood et al., 2013). Furthermore, key stages that consume significant amounts of water and energy and generate substantial waste are highlighted with kaizen burst icons, indicating areas that require improvement.

The processing of tomatoes, regardless of the final products, begins with the arrival of raw tomatoes in trucks at the plant’s offloading area. From there, they are transported to a hydraulic flume where they undergo washing and sorting before being taken to the processing line. The washing process takes place within the flume network, where a continuous supply of fresh and recirculated water is used to move and wash the tomatoes, removing foreign materials such as leaves, branches, soil, and stones, which can make up to 3–5% (w/w) of raw tomatoes (Eslami et al., 2023). This stage is highly water-intensive, requiring approximately 3–5 m^3 of water per hour for every 1 m^3 of tomatoes processed (Latini et al., 2017). Consequently, a significant amount of wastewater is generated, which is then pumped to the wastewater treatment unit. After washing, the tomatoes go through a grading and sorting station, where manual and automated sorting processes remove defective fruits and unwanted materials, including green tomatoes. Overall, the sorting process results in the removal of up to 5% of the incoming raw materials (Reyes-de-corcuera et al., 2014), which are collected on a reject conveyor and stored for disposal.

The cleaned and sorted tomatoes then undergo thermal treatments, the specifics of which depend on the desired final product.

For puree and paste production, suitable tomatoes are sent to crushing machines, which convert them into coarse pulp. The crushed tomatoes are subsequently subjected to steam heating within a heat exchanger, raising their temperatures to a range of 65–75 °C for Cold Break (CB) treatment or 85–95 °C for Hot Break (HB) treatment. The temperature choice depends on the desired consistency of the finished product and aims to partially or totally inactivate pectolytic enzymes (Latini et al., 2017). The heated tomato pulp is subsequently pumped to a series of refiners that extract the juice (~5°Brix) with a yield of approximately 95%, removing skins and seeds (Giagnacovo et al., 2016). The extracted juice is conveyed to a large holding tank, which supplies the evaporation step. In this step, a significant amount of water is removed using steam heating, resulting in the formation of tomato puree (6–9°Brix) or tomato paste at different concentrations (>18°Brix), namely double (28°Brix) or triple concentrate paste (36°Brix) (Latini et al., 2017). The concentration step occurs under vacuum conditions and at low temperatures, typically ranging from 50 to 85 °C (Latini et al., 2017). This stage is one of the most energy-intensive in the entire production line, with the main operating cost attributed to the steam generated by a boiler (Giagnacovo et al., 2016; Meneses et al., 2019). The tomato concentrate is then sent to the sterilization/packaging stage.

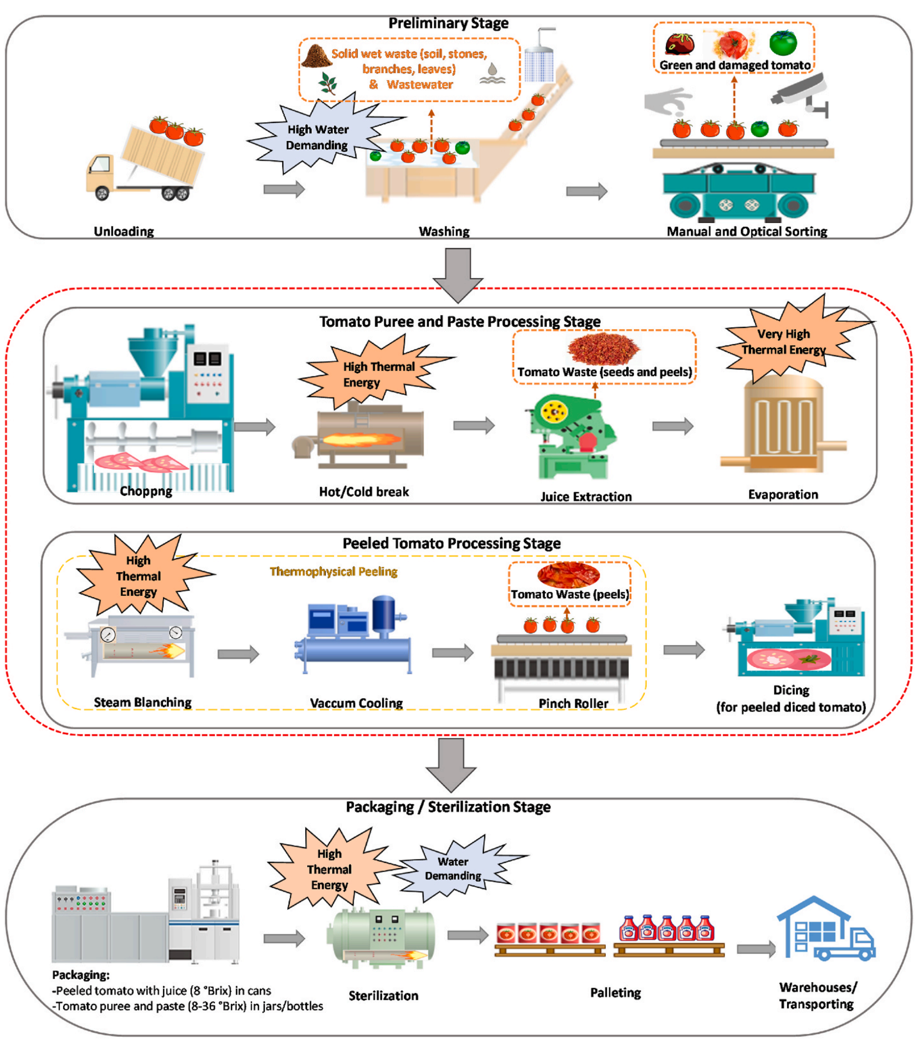


Fig. 1. Schematic of tomato puree/paste and peeled tomato production lines.

Depending on the method chosen, cooking, sterilization, and cooling stages can occur either before (aseptic in-line sterilization) or after (in-container sterilization) the packaging process in glass bottles and plastic bags or jars containers (Trueblood et al., 2013). During in-container sterilization, containers filled with tomato concentrate are sealed and heated in tunnel spray sterilizer with hot water or steam before being cooled to room temperature with water spray. Alternatively, for aseptic in-line sterilization, the tomato paste, or puree undergoes cooking and sterilization through direct steam injection or tubular heat exchangers using overheated water. The sterilized tomato is rapidly cooled in tube-in-tube cooling systems before aseptic packaging.

In the production of peeled (whole, diced, and sliced) tomatoes, the washed and sorted fruits are routed to the peeling operation, where the tomato peel is typically removed using chemical or steam methods (Arnal et al., 2018; Kohli et al., 2021; Rock et al., 2012) Peeling typically occurs via chemical or thermal methods, which are very water and energy-demanding, and waste-generating and whose performance significantly impacts the overall process efficiency and quality of the end product (Rock et al., 2012; Zhou et al., 2022). Following peeling, the peeled tomatoes undergo manual and optical sorting to eliminate fruits that do not meet commercial standards in terms of size, color, or the presence of black spots or scars on the surface.

A portion of the whole peeled tomatoes may also be sent to dicers to produce diced or sliced tomatoes. Subsequently, the peeled tomatoes (whole, diced, sliced) are filled into tinplate cans and jars of various sizes (ranging from 0.5 to 3 kg). The containers then pass through a filler where tomato juice or a very thin purée is added before removing the air to create a vacuum and mechanically or thermally sealing the package (Trueblood et al., 2013). The ratio of peeled tomatoes to purée is approximately 60:40 (w/w). The sealed packages are then conveyed to the in-container sterilization unit, where the cans are heated by immersion in a hot water bath before being cooled in water.

The exact sterilization temperatures and durations depend on the product's pH and the package's geometry.

Finally, containers of canned or aseptically sealed tomato products, as well as canned peeled tomatoes, undergo cleaning processes using hot water, steam, or blasts of pressurized air (Trueblood et al., 2013). They are then placed in an automatic palletizer for labeling, packaging, and subsequent storage in ambient temperature warehouses until they are ready to be delivered to clients upon request (Manfredi and Vignali, 2014).

3. The tomato industrial processing Water-Energy Nexus (WEN)

3.1. Water-Energy Nexus assessment framework

The food processing industry typically uses substantial quantities of water and energy, which are often linked to each other, given that energy is required to transport, heat, and cool water, and water in the form of steam can be used to generate thermal energy (Amón et al., 2017; Liu et al., 2019). This interdependence is defined as water-energy nexus (WEN) (Hamidov and Helming, 2020). Concerning the tomato processing industry, it typically uses great volumes of water for tasks such as unloading, sorting, transportation, and heating of tomatoes. Thermal and electrical energy is imparted to this water during each processing step primarily by pumps, fans, and boilers to form the tomato processing WEN (Amón et al., 2017).

To gain a comprehensive understanding of the water and energy usage throughout the tomato processing facility, a WEN assessment is essential. This evaluation provides a quantitative foundation that holds utmost importance for the industry's pursuit of enhancing resource efficiency (Amón et al., 2017; Peterson et al., 2022). WEN assessment should systematically account for water consumption and the energy required to process water at each stage of industrial tomato processing. In the frame of the European project AccelWater (Project ID: 958266), a real scenario of an Italian tomato processing industry was evaluated using an integrated WEN assessment approach. Data gathered from installed sensors and monitoring systems, simulation software, thermal properties, and interviews with plant operators and technicians were utilized for this purpose (AccelWater, 2020). A similar approach has been also applied in assessing the WEN at an industrial tomato paste processing plant in California, USA, resulting in the development of a map of water and associated energy use at each processing step (Amón et al., 2017). Furthermore, it was utilized to appraise the potential for recuperating waste heat from condensate and utilizing that energy for process heating, thereby reducing the use of steam and, as a result, decreasing the consumption of natural gas in boilers (Amón et al., 2015). Notably, this methodology has also demonstrated its effectiveness in various other food processing sectors, such as small breweries, where a systematic approach to analyzing water and energy flows has identified opportunities for enhancing efficiency by reducing waste (Peterson et al., 2022).

In general, a WEN assessment involves the development of a WEN map that specifically considers unit operations in which water streams are directly involved in transforming tomato fruits into bulk concentrate or peeled tomatoes while taking into account the different ways in which electrical and thermal energy are embedded in the process water (Amón et al., 2017). These specific unit operations, where water and energy interact during tomato processing, are referred to as WEN points. Fig. 2 provides a general schematic of the WEN map for a tomato processing facility, in which certain WEN points are grouped as general operations where energy is embedded in water during processing. At these points, measurement or estimation of water and energy demands is necessary to quantify the WEN. A detailed description of the WEN points is also reported in Table 1.

As shown in Fig. 2, all fresh water used for tomato processing generally originated from on-site wells. Groundwater may undergo purification in mechanical separators to remove grit before being used in various processes (Amón et al., 2017).

The treated well water is mainly pumped to pre-processing units to unload, wash, sort, and convey tomatoes as they enter the facility. The flume water is then processed by electric rotary separators to remove solid waste (e.g., leaves, branches, soil, and stones) and partially recirculated to the washing channel. Wastewater leaving the washing phase is sent to wastewater treatment.

A portion of the treated well water is allocated to supply vacuum pumps and hose systems for cleaning flume debris separators and facility surfaces (Amón et al., 2017). Another portion is delivered to both the single pass cooling section of the sterilization units and sprayed into evaporator condensers to promote condensation and maintain vacuum (Amón et al., 2017). The spent water from these units is typically sent to cooling towers to dissipate waste heat before being recycled to other processing units. Excess water may be directly sent to wastewater treatment.

For certain applications, treated well water may undergo further purification through reverse osmosis (RO). The resulting permeate is typically deaerated and utilized as boiler feed water (Amón et al., 2017). Steam is employed in different thermal units such as hot/cold break, evaporators, peelers, and sterilizers (Fig. 1). Indirect steam heating is used in hot/cold break units, as well as rotary coil and shell-and-tube heat exchangers in sterilization and evaporation units. Most of the steam condensate from these units is recovered and recycled as boiler feed water. However, condensate from steam supplied to thermal units relying on direct steam heating, such as steam injection systems for paste sterilization and tomato peelers, along with tomato water condensate, namely the water vapor removed from tomato juice in the evaporators to form tomato concentrate, cannot be recycled due to their impurities. These condensate streams are typically directed to cooling towers to dissipate waste heat before being recycled in other units, such as the preliminary washing phase. Excess condensate is sent directly to wastewater processing (Amón et al., 2017).

Wastewater primarily consists of process water from flumes, and to a

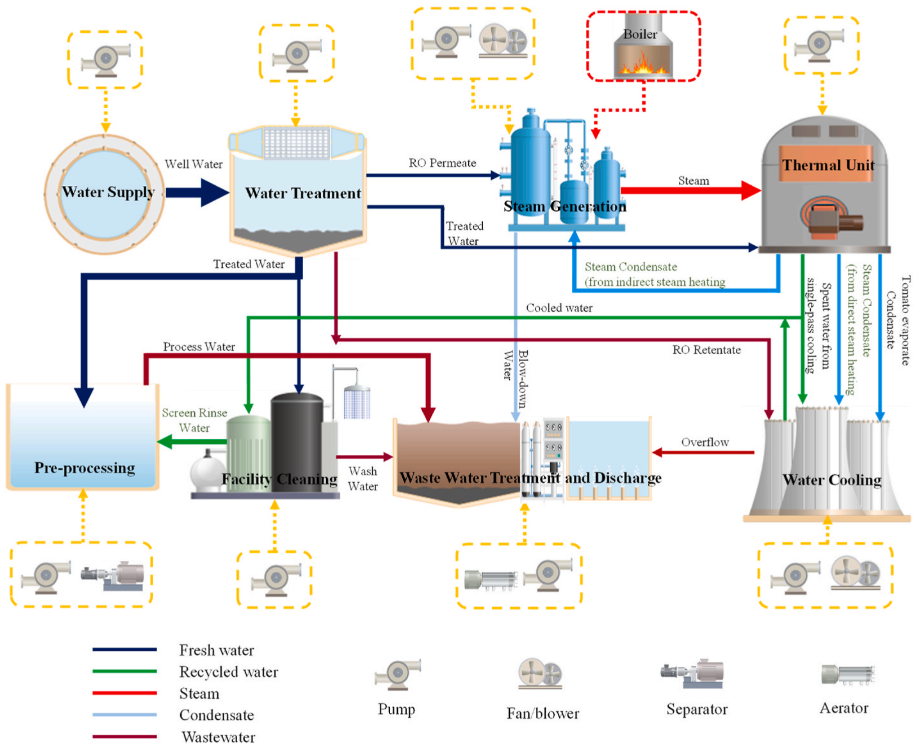


Fig. 2. Simplified schematic of the Water-Energy Nexus (WEN) map and the primary WEN points in a tomato processing facility. Equipment involved in embedding either electrical or thermal energy in water is depicted within boxes outlined by dashed and dotted lines, respectively. The dashed and dotted arrows represent energy inputs, with gold dashed lines indicating electrical energy and red dotted lines representing thermal energy. Arrow width serves as a qualitative indicator of the magnitude of water/steam mass being transferred. The abbreviation "RO" corresponds to reverse osmosis. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

lesser extent, blowdown water from the boiler system, cooling tower overflow, retentate from the reverse osmosis system, and water used for facility cleaning (Amón et al., 2017). Flume water is usually pumped to a sedimentation pond to remove solids and then transferred to aerated lagoons to facilitate the aerobic microbial degradation of organic matter. It is subsequently routed to a sump collector along with wastewater from the steam system and cooling tower before being discharged into the municipal sewer or used for various purposes such as aquifer recharge, irrigation, and truck washing, in accordance with local regulations (Meneses et al., 2019).

3.2. Water, electrical, and thermal energy use assessment

The data collected from the WEN assessment of water, thermal, and electrical energy usage is essential for identifying inefficiencies within unit operations and determining the processing operations that consume the most resources. This data serves as a baseline for identifying opportunities to improve resource efficiency by adjusting water loads on equipment (Peterson et al., 2022). It also helps in developing specific strategies for conserving and recovering water and energy, as well as managing waste effectively throughout the various stages of tomato processing (Amón et al., 2015).

3.2.1. Water use assessment

The assessment of water usage during tomato processing, both at the facility level and within each unit operation, can start from the known seasonal quantity of water pumped from on-site wells. Additionally, water usage specifications provided by equipment manufacturers or measured flow rate data from pumps supplying water to specific operations can be utilized to estimate the water demand for those particular operations. To improve data precision and facilitate real-time monitoring, it is advantageous to incorporate water flow rate meter sensors like innovative electromagnetic or Clamp-on Doppler or Transit-time Ultrasonic flow meters (DiGiacomo, 2011; Hauptmann et al., 2002; Peterson et al., 2022; Xu et al., 2019) along with monitoring systems at WEN points where such installations are feasible.

Moreover, certain water flow rates, such as those associated with the mass of evaporated tomato condensate, can be calculated using facility metrics such as throughput and the solids content of tomato juice (~5°Brix) and tomato concentrate (8–36°Brix) (Amón et al., 2017). In cases where direct flow measurement is not possible for certain streams, but sufficient data is available for related streams within the same operation, process simulation tools can be utilized to solve water mass balances and estimate flow rates accurately.

3.2.2. Thermal energy use assessment

The steam generation system used in the tomato processing facility typically consists of fire tube boilers fuelled by natural gas. These boilers produce steam at a gauge pressure ranging from 10 to 30 bar. Standard fire tube boilers, without economizers, generally achieve an 80% conversion efficiency rate from input to output energy (Trueblood et al., 2013). The steam generated by these boilers is then directed to collectors located near different thermal units. These collectors are equipped with pressure-reducing valves to ensure that the steam is delivered at the required pressure for specific operations.

By examining utility provider records for the amount of natural gas consumed throughout the processing season and considering its thermophysical properties, it is possible to determine the steam generation rate and the total thermal energy associated with steam production. This evaluation involves solving mass and energy balances at the boiler, using input data such as the boiler's capacity, operating conditions, efficiency, heat loss, natural gas supply conditions, boiler makeup water usage and temperature, flow rate and temperature of condensate recycled as boiler feed water from indirect heating operations, annual

Table 1
Overview of the WEN points (processes and equipment) of the tomato processing industry where energy (electrical and/or thermal) is embedded with water during the process.

WEN point	Equipment	Description	Electric/ Thermal energy	Source of energy
Water supply	Pumps	Pumping of fresh water from on-site wells	Electric	Electricity
Water treatment	Mechanical separators Membrane separators Pumps	Removal of grit from groundwater. Reverse osmosis to soften water for pump sealing and boiler makeup.	Electric	Electricity
Non-thermal processes	Flume systems Water pumps Sorting machine Mechanical separators	Unloading, conveying, washing, and sorting of tomatoes in flume systems. Removal of solids from flume water and subsequent recirculation. Sealing of pump shafts.	Electric	Electricity
Steam generation	Fire-tube Boilers Pumps Blower	Pumping and deaeration of boiler make-up water. Supplying of air to boiler furnaces. Blower of combustion air. Steam generation by boilers.	Electric and thermal	Electricity Fuel (Natural gas)
Thermal unit	Cold/Hot break Evaporators Peelers Cookers/ Sterilizers Coolers Pumps	Use of steam to heat products for enzyme inactivation, peeling, tomato water evaporation, and sterilization processes. Use of water for: a) condensation of evaporated tomato water and maintaining the vacuum in the evaporators and b) products cooling after the sterilization stage. Pumping of condensates and exhaust water.	Thermal and Electric	Steam Electricity
Water cooling	Pumps Fans	Pumping of water and circulation of air in cooling towers to promote water evaporation	Electric	Electricity
Facility cleaning	Pumps	Pumping water to rinse facility surfaces and equipment	Electric	Electricity
Wastewater treatment and discharge	Solid separators Pumps	Screening of wastewater for solid waste removal. Pumping to collect and discharge wastewater. Blowers	Electric	Electricity
Aeration of wastewater lagoons.				

operating hours, and steam pressure (Amón et al., 2017).

Likewise, the steam usage in each relevant thermal unit can be estimated by solving local mass and energy balances. This estimation takes into account input data like local steam pressure, heat transfer coefficient, heat transfer area, flow rate, and inlet and outlet temperatures of the processed product. Alternatively, for a more precise evaluation of boiler steam generation and steam usage at each relevant processing step, the installation of appropriate steam flow meters such as orifice, vortex, and in-line ultrasonic flow meters (Murakawa et al., 2021; Steven and Hall, 2009; Zhoua et al., 2018) and thermal energy meters can be implemented (Amón et al., 2017; Peterson et al., 2022).

3.2.3. Electricity use assessment

The assessment of electrical energy usage in WEN primarily involves the pumps responsible for distributing and recirculating water within and between units. It also includes other equipment motors, such as fans used for air supply to boiler furnaces and water evaporation in the cooling tower, mechanical separators for removing solids from flume water, and blowers used in lagoons for aerobic wastewater treatment (Amón et al., 2017). However, the electrical power consumption of additional machinery and equipment, like belt conveyors, packing units, pinch peelers, choppers, juice, and product circulation pumps, etc., is not considered in the WEN analysis since they are not directly involved with process water (Amón et al., 2017).

The obtain information about the electrical motors' characteristics, such as voltage, amperage, and power, one can use one can refer to equipment nameplates, and manufacturers' data sheets, or measure directly using power meters and data loggers (Peterson et al., 2022). Furthermore, it is advisable to determine a coefficient of usage for each equipment motor, ranging from 0 to 1, which represents the actual fraction of time the motors operate during the processing season. This can be achieved through a comprehensive review of operational records, including data logged by sensors, and by conducting interviews with facility personnel responsible for operating specific equipment (Amón et al., 2017).

Using these data, the seasonal energy usage of the equipment (measured in kWh) can be calculated as the product of the power delivered to the equipment motors (in kW), the coefficient of usage, and the number of operating hours.

3.2.4. Water and energy usage in the tomato processing industry

To enhance efficiency in tomato processing, the initial step involves identifying the operations that have the highest water and energy demands. Several authors have employed various methodological approaches, such as WEN assessment, Life Cycle Assessment (LCA), and Current Value Stream Mapping (CVSM), to estimate water and energy usage data in the most significant processing steps of tomato facilities. Table 2 presents a comprehensive overview of the findings, highlighting the key processing steps that consume water, electrical and thermal energy in the production of concentrate (puree/paste) and/or peeled tomatoes.

In general, comparing data from different processing plants and

Table 2
Summary of water, electric, and thermal energy consumption in the main processing steps of industrial tomato facility for the production of peeled and/or tomato concentrate.

Water

Tomato Product	Pre-processing	Processing (thermal)	Processing (non-thermal)	References
Paste (29°Brix)/diced tomato	67%	24%	9%	Amón et al. (2017)
Puree (8°Brix)	88%	12%	N/A	Manfredi and Vignali (2014)
Peeled tomato	20%	80%	N/A	Arnal et al. (2018)

Thermal energy

Tomato Product	Evaporation	CB/HB	Sterilization	Steam Peeling	References
Paste (36°Brix)	76.2%	15.2%	8.6%	N/A	Giagnacovo et al. (2016)
Paste (30°Brix)	63.4%	30.9%	5.7%	N/A	Folinas et al. (2017)
Puree (8°Brix)	44.2%	37.8%	18.0%	N/A	Manfredi and Vignali (2014)
Peeled tomato	N/A	49%	32%	19%	Garofalo et al. (2017)
Peeled tomato	N/A	39%	61%	N/A	Arnal et al. (2018)

Electrical energy

Tomato Product	Pre-processing	Processing (thermal)	Processing (non-thermal)	Packaging	Other usages	References
Paste (36°Brix)	7.9%	45.2%	31.0%	6.9%	9.0%	Giagnacovo et al. (2016)
Paste (30°Brix)	5.2%	9.8%	79.2%	5.8%	N/A	Folinas et al. (2017)
Paste (24–39°Brix)/diced tomatoes	6%	45%	33%	4%	12%	Trueblood et al. (2013)
Puree (8°Brix)	4.5%	(47.4%)[a]	(47.4%)[a]	22.8%	25.3%	Manfredi and Vignali (2014)
Paste (29°Brix)/diced tomato	29%	30%	16%	19%	7%	Amón et al. (2017)
Peeled tomato	4.5%	(47.5%)[a]	(47.5%)[a]	22.8%	25.3%	Garofalo et al. (2017)
Peeled tomato	21%	30%	N/A	49%	N/A	Arnal et al. (2018)

Pre-processing: unloading, washing, and sorting.
Processing (thermal): steam peeling, evaporation, CB/HB, sterilization, and boilers.
Processing (non-thermal): chopping, optical sorting, juice extraction, holding, refinement, filtration, pump sealing, cooling tower, and facility cleaning.
Packaging: filling and closing, labeling, and palletizing.
Other usage: lighting, water treatment, and auxiliary process.
N/A means Not Available.
[a] It includes both thermal and non-thermal processing data.

using different methodologies is challenging. However, based on the results presented in Table 2, it can be observed that the quantity and distribution of water, thermal and electrical energy usage in the tomato processing facility primarily depend on the type of final product (peeled or concentrate tomato). After the initial washing and sorting stages, the processing lines for these products differ significantly, as illustrated in Fig. 1.

Specifically, the use of water is unevenly distributed across the processing units. The majority of the water is pumped to the pre-processing steps, such as unloading, washing, sorting, and conveying tomatoes into the facility. The remaining portion of the total water is primarily used as steam in thermal processes and for cooling after sterilization treatment.

For instance, Amón et al. (2017) conducted a study on water consumption in a tomato facility using the WEN approach. The facility processed approximately 90% of the tomatoes into the paste and the remaining into diced tomatoes. According to their findings, around 8.3 metric tonnes of water were used per metric tonne of product. Out of this water, the majority (67%) was directed to flumes for unloading, washing, sorting, and conveying tomatoes, while 24% was used in the steam utilization system. The remaining 9% of the water was allocated to pump sealing, boiler make-up water, and facility cleaning. Similar results were reported by Manfredi and Vignali (2014), who assessed water usage in the processing phases of a tomato puree production line using the LCA methodology. They found that the most water-consuming stage was unloading and washing (88%), followed by evaporation, juice pasteurization, and bottle pasteurization (12%).

On the other hand, the tomato processing industry extensively utilizes steam, primarily in various thermal processing stages such as evaporation, sterilization, CB/HB, and peeling. The distribution of steam depends on factors such as raw material characteristics, the type and quantity of the end products, equipment type, and operational conditions. Approximately half of the total steam generated is directed to closed-system, indirect heating operations (e.g., cold or hot break and evaporators, tube-in-tube heat exchangers), enabling the recovery and reuse of approximately 95% of the condensate in the boilers (Trueblood et al., 2013). Among thermal operations, evaporation and CB/HB are the most energy-intensive stages during tomato concentrate production, while steam peeling and sterilization consume the largest amount of thermal energy in peeled tomato production. For instance, in the study by Giagnacovo et al. (2016), the energy-intensive stages of a triple concentrate tomato paste processing plant were identified. Evaporation, CB/HB, and sterilization accounted for 76.2%, 15.2%, and 8.6% of the total thermal energy, respectively. Similarly, Folinas et al. (2017) found that in the production of canned double-concentrate tomato paste, the majority of steam consumption occurred during evaporation (63.4%), CB/HB (30.9%), and sterilization (5.7%). The slight variation in distribution observed in the results achieved compared to Giagnacovo et al. (2016), can be likely attributed to the lower concentration of solids in the tomato paste product.

Regarding the production of peeled tomatoes, Garofalo et al. (2017) evaluated the distribution of thermal energy in the production line of canned peeled tomatoes mixed with tomato sauce using the LCA methodology. Their results indicated that 49% of the total thermal energy was consumed during the evaporation stage for sauce production, followed by 32.4% in the sterilization stage and 18.6% in the peeling stage. Using the same methodology, Arnal et al. (2018) assessed the thermal energy consumption in the production of peeled tomatoes, excluding energy requirements for tomato sauce production. They found that thermal energy was primarily used in two main steps: steam peeling (61%) and sterilization (39%).

While the major energy requirements in large-scale tomato processing plants are thermal, electricity consumption also plays a significant role (Latini et al., 2017). Generally, electrical energy is more evenly distributed throughout the production line compared to water and thermal energy. However, certain thermal and non-thermal processes consume more electrical energy than others (Table 2). For example, when Giagnacovo et al. (2016) evaluated the electricity distribution in a triple concentrate tomato paste processing plant, they found that the evaporation stage accounted for approximately one-third (34%) of the total electrical energy, followed by juice extraction (16%) and chopping (15%) steps. Trueblood et al. (2013) examined electricity consumption in different stages of a tomato paste/puree processing plant and identified the cooling tower, evaporation, and HB as the most electricity-demanding stages, consuming 17%, 13%, and 13% of the total electrical energy, respectively. This was primarily attributed to the recirculation of paste/puree in the evaporators and product cooling. Other significant consumers included steam boiler combustion blowers (7%), boiler feedwater pumps (7%), facility lighting (2%), and air compressors (5%). Regarding the electricity usage distribution in peeled tomato processing, Garofalo et al. (2017) found that the in-container processing stage consumed the highest amount of energy, accounting for 67% of the total electricity usage. The remaining electricity was distributed to a lesser extent between thermal units (23%) and preliminary stages (10%). Arnal et al. (2018) also investigated the electrical energy consumption in the production of peeled tomatoes and reported that the canning stage consumed the most electricity (49%), followed by washing (21%), sterilization (21%), and peeling (9%). These findings are consistent with the results reported by Garofalo et al. (2017). Amón et al. (2017) conducted a systematic study on the distribution of electricity usage in a processing line producing paste and diced tomatoes. They found that approximately 53% of the overall electricity used at the facility was consumed in processing water (WEN points), amounting to 4.4 million kWh. The remaining electrical energy was utilized in non-WEN points for activities such as facility lighting, climate control, compressed air generation, juice extraction, pumping tomato juice and paste, and aseptic packing. Pumping operations accounted for the majority of electrical WEN usage (approximately 81%), while the remaining energy was allocated to power fans, separators, and aerators. Among the non-pumping electrical demands, cooling tower fans required the highest energy consumption at approximately 12.5% of the total electrical WEN for the season, followed by boiler furnace fans (5.7%), and to a lesser extent, aerators, and separators (0.8%).

3.3. Key Performance Indicators (KPIs) for water and energy consumption in the tomato processing industry

The assessment of water and energy usage in industrial tomato processing enables the identification of key processes necessary for establishing baselines for water and energy consumption. These baselines are crucial for conducting benchmarking analyses and developing relevant Key Performance Indicators (KPIs) (Latini et al., 2017; Peterson et al., 2022).

In the specific subsector of tomato processing, average KPIs can be simply derived from the water, gas, and electricity bills, normalized by the total production per tomato season (Giagnacovo et al., 2016; Latini et al., 2017). Furthermore, to elucidate the intricate relationship between energy and water across diverse process zones (WEN points), a local water-energy intensity KPI can be calculated. This involves dividing the energy consumption by the specific amount of water that traverses a given WEN point. This metric contributes to contextualizing each WEN point within the overall process, as it offers insight into how energy is being embedded into the water flowing through a given WEN point (Peterson et al., 2022). It must be underlined that the water-energy intensity KPI cannot be calculated for non-WEN processes because although these processes consume either water or energy, energy is not being embedded into the water (Peterson et al., 2022).

These indicators facilitate the comparison of performance between different tomato processing lines or analogous lines within separate facilities. Moreover, their computation assumes pivotal importance in quantifying efficiency enhancements over time within the same processing plant.

In this review, average KPIs were determined through a comprehensive literature review and, when necessary, estimated based on information and data gathered during energy audits conducted in Italian tomato facilities of similar capacity as part of the EU "AccelWater (ID: 958266)" project. The results, presented in Table 3, highlight the average KPIs for water, thermal, and electrical energy consumption per ton of final products in triple tomato paste, tomato puree, and peeled tomato production lines.

It is evident that triple tomato paste processing consumes more energy and water compared to tomato puree and peeled tomato production. This can be primarily attributed to the high water and energy intensity of the thermal processes involved in triple tomato paste production, particularly the evaporation step used to concentrate tomato juice from approximately 5°Brix to 36–40°Brix. LCA studies have estimated the thermal and electrical energy footprints of processing tomato paste and diced tomatoes. For instance, Brodt et al. (2013) found that tomato paste processing required more energy per unit mass of final products compared to diced tomatoes (approximately 8 and 2 MJ/kg, respectively). This difference is mainly due to the energy-intensive evaporation step in paste production (Karakaya and Özilgen, 2011), which requires significant energy due to the high specific heat capacity and latent heat of vaporization of water (Amón and Simmons, 2017).

These findings strongly emphasize the need to identify the main water and energy-consuming stages during tomato processing to establish local average KPIs for highly demanding water and energy unit operations. Improving efficiency in these stages can lead to significant benefits (Amón and Simmons, 2017; Latini et al., 2017).

4. Opportunities for water conservation and energy efficiency in the tomato processing industry

As described in the previous sections, tomato processing facilities consist of inherently water and energy-intensive processes and are extremely production-oriented, with tomato processors that typically do not have time to optimize the performance of their equipment during the short harvest season for tomatoes (Giagnacovo et al., 2016; Trueblood et al., 2013). However, there are numerous opportunities for water conservation and energy efficiency, which are crucial for enhancing the profitability of tomato processors in the global market and promoting the environmental sustainability of tomato processing (Trueblood et al., 2013).

This section provides an overview of recommended conventional and unconventional practices and technologies that can be employed to achieve water conservation, energy recovery, and efficiency improvements across various stages of tomato processing facilities. These approaches encompass strategies such as maintaining and enhancing the efficiency of existing systems, implementing water recycling and waste

Table 3
KPIs in triple tomato concentrate and peeled tomato production lines.

KPI name	Average KPIs values			References
	Peeled tomato	Tomato puree (8 °Brix)	Tomato paste (36–40 °Brix)	
Thermal energy consumption per ton of tomato products (kWh/ton)	355	710	2340	(Amón et al., 2017; Arnal et al., 2018; Giagnacovo et al., 2016; Latini et al., 2017)
Electrical energy consumption per ton of tomato products (kWh/ton)	36	43	103	(Amón et al., 2017; Arnal et al., 2018; Giagnacovo et al., 2016; Latini et al., 2017)
Water consumption per ton of tomato products (m^3/ton)	4.6	2.0	8.3	(Amón et al., 2017; Arnal et al., 2018; Behzadian et al., 2015)

heat recovery, and adopting innovative processing unit operations and waste management practices.

4.1. Conventional water conservation and energy efficiency measures

Table 4 provides a comprehensive summary of various conventional measures that can potentially be implemented in tomato processing facilities. These measures are evaluated based on their relative impact in terms of water, thermal, and electrical energy savings, as well as the reduction in wastewater generation and associated discharge costs. It is important to note that, in some cases, due to the inherent link between water and energy, implementing water conservation measures can also lead to energy savings, and vice versa. The potential benefits resulting from the implementation of these measures can serve as a motivation for company management to explore opportunities for water and energy conservation. However, it is crucial to conduct engineering studies to assess the technical and economic feasibility of each measure, comparing their costs with the potential cost savings and estimating the expected payback period (Amón et al., 2013; Trueblood et al., 2013) (see Table 5).

4.1.1. Water conservation measures

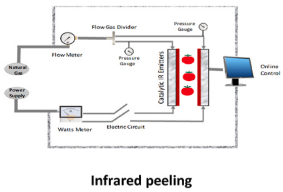
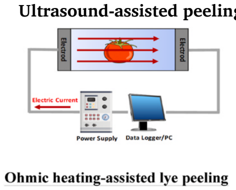
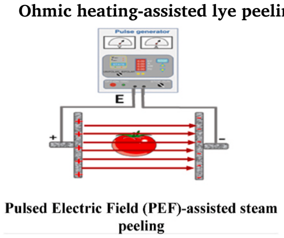
Tomato processing facilities are known to consume substantial amounts of water, which is typically pumped from aquifers, used

Table 4
Summary of typical water and energy conservation measures in tomato processing facilities, including their impact on freshwater, thermal and electrical energy savings, and wastewater generation.

Recourse	Measure description	Impact after implementation				References
		Freshwater	Electricity	Fuel	Discharge cost	
Water	Repairing water leaks	Reduced consumption	Reduced pumping well water	–	Reduced wastewater generation	Trueblood et al. (2013)
	Preventing overflow of cooling tower water	Reduced consumption	Reduced pumping well water	–	Reduced wastewater generation	Trueblood et al. (2013)
	Reusing flume water in former stages	Reduced fresh makeup water in the flume	Reduced pumping well water	–	Reduced wastewater generation	Trueblood et al. (2013)
	Reusing single-pass cooling water	Reduced fresh makeup water in the flume	Reduced pumping well water	–	Reduced wastewater generation	Trueblood et al. (2013)
	Recycling steam condensate from indirect heat exchangers	Reduced boiler makeup water and blow down loss	Reduced pumping well water and cooling tower fans use	Reduced fuel use	Reduced wastewater generation	(Behzadian et al., 2015; Trueblood et al., 2013)
	Recycling of tomato water condensate	Reduced usage of fresh makeup water in the flume, seal water pump floor, washing	Reduced pumping of well water and wastewater, and cooling tower fan use	Reduced fuel use	Reduced wastewater generation	(Amón et al., 2013; Trueblood et al., 2013)
Natural gas (Steam)	Repairing steam leaks	Reduced boiler makeup water and blow down loss	Reduced use of the RO system Reduced pumping and blower use	Reduced fuel use	Reduced wastewater generation	Trueblood et al. (2013)
	Reducing the operating pressure of the boilers	–	–	Reduced fuel use	–	Trueblood et al. (2013)
	Returning condensate from thermal units	Reduced consumption	Reduced pumping and cooling tower fan use	Reduced fuel use	Reduced wastewater generation	(Amón et al., 2017; Trueblood et al., 2013)
	Installing economizers, blowdown heat exchangers, and improving combustion efficiency	–	–	Reduced fuel use	–	(Amón et al., 2017; Trueblood et al., 2013)
	Controlling fouling on heat exchangers	Reduced boiler makeup water and blow down loss	Reduced pumping and blower use	Reduced fuel use	Reduced wastewater generation, and product wastage	Balasubramanian and Puri (2009)
	Insulation of equipment, condensate tanks, steam, and condensate pipelines	Reduced boiler makeup water and blow down loss	Reduced pumping and blower use	Reduced fuel use	–	Trueblood et al. (2013)
	Waste heat recovery from condensate effluent (tomato water condensate)	Reduced boiler makeup water and blow down loss	Reduced pumping of well water and wastewater, and cooling tower fan use	Reduced fuel use	Reduced wastewater generation	(Amón et al., 2013; Amón et al., 2015)
	Installing mechanical vapor recompression (MVR) systems or additional evaporation stages	Reduced boiler makeup water and blow down loss	Reduced pumping of well water and wastewater, and cooling tower fan use	Reduced fuel use	Reduced wastewater generation	Latini et al. (2017)
Electricity	Assessing pumping efficiency Repair and replace pumps to improve energy efficiency	–	Reduced consumption	–	–	(Amón et al., 2017; Amón and Simmons, 2017)
	Installing VFDs on pumps	–	Reduced consumption and peak demand	–	–	Trueblood et al. (2013)
	Repairing air leaks	–	Reduced consumption	–	–	Trueblood et al. (2013)
	Substituting compressed air with blower air	–	Reduced consumption	–	–	Trueblood et al. (2013)
	Installing VFDs on blowers and fans	–	Reduced consumption and peak demand	–	–	Trueblood et al. (2013)
	Installing high-efficiency lighting and motion sensors	–	Reduced consumption and peak demand	–	–	Trueblood et al. (2013)
All	Keeping input/output balancing and operating at the highest capacity	Reduced consumption	Reduced consumption	Reduced consumption	Reduced wastewater generation waste of fresh tomatoes	Latini et al. (2017)

VFDs is the abbreviation of Variable Frequency Drives.

Table 5
Advantages and disadvantages of tomato peeling by advanced technologies.

Method	Pros	Cons	References
 **Infrared peeling**	• Fast heating and shallow penetration depth • No chemicals • No heating medium (water, steam) • High peelability • Lower peeling loss • Firmer product texture • High quality product • Less environmental impact	• Non uniform heating • High investment cost • Training of workers	(Li et al., 2014a, 2014b; Vidyarthi et al., 2019)
 **Ultrasound-assisted peeling**	• High peelability • Reduced peeling loss • Reduced peeling time • Reduced lye concentration • High-quality product • Increased lycopene content • Less environmental impact	• Scale-up • Reactor design complexity • Univen peeling in the up-scaled units • Disposal of waste effluent • High investment cost • Training of workers	(Gao et al., 2018; Kohli et al., 2021; Rock et al., 2010, 2012)
 **Ohmic heating-assisted lye peeling**	• Fast heating • Reduced peeling time • Accelerated lye diffusion • Reduced lye concentration • High peelability • Reduced peeling loss • High-quality product • Less environmental impact	• Electrode corrosion • Complexity in design and process control • Need of process optimization • Disposal of waste effluent • High investment cost • Training of workers	(Gavahian and Sastry, 2020; Pataro et al., 2014; Rock et al., 2012; Wongsa-Ngasri and Sastry, 2016a, 2016b)
 **Pulsed Electric Field (PEF)-assisted steam peeling**	• Mild processing conditions • Easy integration in e processing plant • High peelability • Reduced peeling loss • High-quality product • Reduced water and energy consumption • Less environmental impact	• Long term reliability of PEF generator • Electrode corrosion • High investment cost • Training of workers	(Arnal et al., 2018; Giancaterino and Jaeger, 2023; Pataro and Ferrari, 2020)

internally, and then discharged as treated wastewater into sewer systems or for land application (Trueblood et al., 2013). As highlighted in Table 4, there are various opportunities for water conservation at different stages of tomato processing.

For instance, simple and cost-effective measures like repairing water leaks from valves, hoses, and storage tanks, as well as installing a level control system for cooling tower makeup water pumps to prevent overflow can significantly reduce total freshwater consumption (Trueblood et al., 2013). The adoption of water conservation measures in closed-loop systems such as the recovery and filtration of flume water from the final stage and its reuse in earlier stages can also contribute to substantial reductions in freshwater usage. Additionally, water used to cool down the temperature of tomato products after sterilization can be redirected to the cooling tower or flumes to offset the need for fresh makeup water (Trueblood et al., 2013). Implementing all the above-recommended measures could potentially reduce freshwater usage by 16% in the industry (Trueblood et al., 2013).

The return and reuse of condensate in boilers, particularly from indirect heat exchangers, can save freshwater and reduce boiler makeup water treatment costs, blowdown losses, and fuel consumption due to thermal energy recovery (Behzadian et al., 2015; Trueblood et al., 2013).

The large volume of tomato water condensate generated during paste production has the potential not only for waste heat recovery, as will be discussed later, but also for water recovery and reuse in applications like cooling towers, flumes, seal water pumps, and floor washing (Amón et al., 2013; Trueblood et al., 2013). A WEN assessment estimated that a facility with a capacity of 7000 tons of tomatoes per day could theoretically produce 129,232,774 gallons of tomato water per season, of which around 70 million gallons could be technically recovered. This recovery had the potential to reduce electricity consumption for well water and wastewater pumping systems, as well as cooling tower fans, by 442,600 kWh and generate over 40,000 MMBtu of energy (Amón et al., 2013). This is because each cubic meter of recovered tomato water corresponds to one less cubic meter pumped from wells, cooled in cooling towers, or discharged as wastewater. However, engineering studies are necessary to assess the technical and economic feasibility of recycling and utilizing tomato water in new applications.

4.1.2. Thermal energy conservation and efficiency improvement measures

Tomato processing facilities rely heavily on thermal energy for various direct and indirect heat exchange processes. Therefore, there are several opportunities outlined in Table 4 to improve energy efficiency, conserve energy, and recover waste heat from boilers and thermal processing units.

Typically, boilers produce steam at much higher pressures (>10 bar) than required by the thermal processes in a tomato facility. Therefore, simple measures like adjusting boiler pressure set points can reduce natural gas consumption (Trueblood et al., 2013). Another significant saving in natural gas can be achieved through conventional waste heat recovery methods for boilers. These methods include returning condensate from indirect heat exchangers, installing economizers and blowdown heat exchangers to pre-heat feed water, and improving combustion efficiencies (Amón et al., 2017; Trueblood et al., 2013).

Furthermore, controlling fouling on heat exchanger surfaces is crucial for enhancing energy efficiency and reducing the need for frequent cleaning, which can cause process interruptions. The use of low-friction, food-grade coatings specifically designed for heat exchangers can effectively minimize fouling and its negative impact (Balasubramanian and Puri, 2009).

Addressing steam leaks is a highly cost-effective method for achieving substantial energy conservation. This is because the water lost through a steam leak necessitates the introduction of new treated water, leading to additional electrical energy usage in the RO (Reverse Osmosis) system and increased fuel consumption in the boiler (Peterson et al., 2022; Trueblood et al., 2013).

Furthermore, given the extensive use of steam in tomato processing, applying insulation materials such as fiberglass blankets to uncovered surfaces of equipment, product, and condensate tanks, as well as steam and condensate pipelines can result in additional natural gas savings for steam boilers (Trueblood et al., 2013).

Waste heat can be also recovered from various process effluents other than those recycled to boilers from indirect heat exchangers. However, the feasibility of heat recovery from these streams depends on factors such as temperature, quantity, purity, and availability of waste heat-containing streams, as well as the associated recovery costs (Amón and Simmons, 2017). In tomato processing, a significant source of waste heat is tomato water condensate, which exits the evaporator at temperatures ranging from 55 to 85 °C (Meneses et al., 2019). Typically, this low-grade waste heat is dissipated in cooling towers before being discharged (Amón et al., 2015). However, due to the relatively clean nature of this effluent, it can be considered for reuse in other parts of the processing facility, such as in flumes, once appropriately cooled (Amón et al., 2013; Amón et al., 2015). Researchers have explored heat recovery from tomato water condensate, by pre-heating crushed tomatoes entering the hot break stage, achieving substantial energy savings, accounting for approximately 3.7% of the total seasonal energy usage. The majority of the savings (over 95%) resulted from reduced natural gas usage at the boiler, while the remaining portion came from a reduced load on cooling towers, groundwater pumps, and wastewater processes (Amón et al., 2015). It is worth noting that the technical and economic feasibility of this measure should consider the costs associated with using an additional heat exchanger upstream of the one used for the steam-heated hot break, making it a capital-intensive measure.

Installing mechanical vapor recompression (MVR) systems or additional evaporation stages on the evaporator is another opportunity for waste heat recovery and reducing natural gas consumption (Latini et al., 2017). The MVR evaporator is the most efficient and capital-intensive, which recompresses steam from the evaporated tomato paste and redirects it to earlier stages in the evaporator (Trueblood et al., 2013). The steam economy of MVR systems can reach up to 20 units of water evaporated from tomatoes for every unit of steam input. Implementing additional effects in the evaporator, usually 2 to 5 effects in a multiple-effect evaporator design, is also a capital-intensive measure. In this design, each effect operates at a lower pressure than the previous stage, allowing the evaporated water from tomatoes to serve as a thermal energy source for the next effect (Latini et al., 2017; Trueblood et al., 2013). These approaches can lead to significant energy savings, with the ideal steam economies for a multiple n-effects evaporator ranging from one unit of steam boiler evaporating n units of water from tomatoes (Trueblood et al., 2013).

4.1.3. Electrical energy conservation measures

Tomato processors are large consumers of electrical energy with a very high electrical peak demand concentrated in a short period. However, there are numerous opportunities to save energy throughout the tomato processing stages.

The primary use of electrical energy in tomato processing is for powering pumps, which rely on electric motors to convey products and transport water (Amón et al., 2017). Therefore, improving pumping efficiency is crucial for reducing electricity consumption in tomato processing. Factors such as flow rate, head, and the condition of pumping systems can significantly impact efficiency (Amón et al., 2017; Amón and Simmons, 2017). A comprehensive assessment of water pumping systems conducted at an industrial tomato processing facility revealed an overall efficiency of 53.6%, lower than the expected efficiency of well-functioning centrifugal pumps, which should be at least 65% (Amón et al., 2013) These findings highlight the importance of assessing pump efficiency for individual facilities and taking steps such as repairing and replacing pumps to improve energy efficiency. Additionally, many pumps are oversized and throttled or bypassed to control flow and pressure. Installing Variable Frequency Drives (VFDs) and pressure or level sensors on these pumps can yield significant electrical energy savings (up to about 80%) and reduce peak demand (Trueblood et al., 2013).

Electricity also powers compressors that are used to provide compressed air for various operations in tomato processing, including driving diaphragm pumps, controlling valves, operating pneumatic tools, and handling aspects of packaging and labeling (Amón and Simmons, 2017). Assessments of several industrial tomato processing facilities have identified energy efficiency opportunities in compressed air systems (Amón et al., 2013). For example, implementing cost-effective measures such as reducing compressed air pressure to the minimum required and establishing a regular repair program for air leaks can enhance efficiency and significantly reduce compressor energy consumption up to 10% (Trueblood et al., 2013). Furthermore, replacing compressed air with blower air in specific applications, such as package flattening, drying, or mechanical conveyance, where high-pressure blower air is a viable and efficient alternative, can further reduce energy usage (Trueblood et al., 2013).

Electricity also powers motors in boiler furnaces blowers and cooling tower fans. Similar to pumps, installing VFDs on blowers and fans can yield substantial energy savings. Studies have demonstrated that implementing this measure can save 33%–44% of combustion blower energy consumption, and 42%–63% of cooling tower fan energy consumption (Trueblood et al., 2013).

Finally, replacing inefficient lamps with energy-efficient lighting and using motion and daylight sensors in unoccupied areas contribute to energy savings and peak demand reduction (Trueblood et al., 2013).

4.1.4. Other practices to save water and energy and reduce waste generation in tomato processing industry

To reduce water and energy consumption, as well as waste generation in a medium to medium-large tomato processing plant handling hundreds of tons of fresh tomatoes daily, it is crucial to maintain a continuous operation of the processing lines and avoid operating below the maximum capacity or intermittently (Latini et al., 2017). Processing equipment, in fact, operates most efficiently when it can run continuously with minimal starts and stops (Brodt et al., 2013). For this reason, effective management of fruit harvesting and delivery is essential to ensure a consistent and uninterrupted supply of fresh tomatoes at maximum capacity throughout the processing season (Latini et al., 2017).

Furthermore, it is important to minimize unplanned manufacturing process stops caused by events such as motor failures, material issues, operator shortages, or unscheduled maintenance (Giagnacovo et al., 2016). Every time the tomato processing line is shut down, machines need to be thoroughly cleaned, resulting in the loss of several working hours, significant water and energy consumption, and waste of fresh tomatoes waiting in trucks outside the facility at temperatures that can exceed 30 °C, or tomatoes at various stages of processing, particularly in the evaporators.

4.2. Unconventional water conservation and energy efficiency technologies

The tomato processing industry is currently focused on reducing water usage, improving energy efficiency, and preserving the quality and health benefits of fresh tomatoes. In addition to conventional measures and technologies, advanced thermal and non-thermal technologies are being explored as sustainable and innovative alternatives for tomato processing. These technologies include high-pressure processing (HPP), pulsed electric field (PEF), infrared radiation (IR), ohmic heating (OH), and ultrasound (US), among others. They have gained attention from researchers and food processors as they offer promising solutions for saving energy in evaporation, enzyme and microbial inactivation processes, and peeling operations while maintaining tomato quality and health properties. The following sections will provide examples of how these novel technologies can be applied at different stages of tomato processing.

4.2.1. Innovative technologies for enzyme and microbial inactivation

Thermal processes used in tomato processing, such as CB/HB and sterilization, consume a significant amount of water and energy and can have a negative impact on product quality. As a result, there has been a growing interest in the past two decades to explore advanced technologies that offer water and energy savings and improved product quality compared to traditional thermal processes (Pereira and Vicente, 2010). HPP, PEF, US, and OH are among the technologies that have shown great promise as mild and energy-efficient alternatives for producing safe and high-quality tomato products (Pereira and Vicente, 2010; Rathnakumar et al., 2023). For example, HPP utilizes intense hydrostatic pressures (100–1000 MPa) to denature proteins and induce microbial death. Studies have demonstrated successful sterilization of tomato purée using HPP at 700 MPa and 20 °C, resulting in a reduction of viable microorganisms to undetectable levels (Krebbers et al., 2003).

PEF involves subjecting a food product placed in contact with two conductive electrodes to a series of short (1–10 μs) electric pulses of high intensity (10–40 kV/cm) and energy input (50–150 kJ/kg), which results in the permeabilization of the cell membrane by electroporation, as well as disruption of intramolecular protein interactions, leading to microbial and enzyme inactivation (Raso et al., 2016; Shams et al., 2023). The technique has been employed to inhibit pectin methylesterase extracted from tomatoes, achieving a 93.8% reduction in enzyme activity (Giner et al., 2000). Subsequently, commercial-scale demonstrations have showcased the potential of replacing traditional thermal hot break processes with PEF treatment (Jayathunge et al., 2019).

US treatment has also shown significant potential for microbial and enzyme inactivation in foods (Lauteri et al., 2023). By applying pressure waves (16–100 kHz) to the food material, cavitation and turbulence are generated, which disrupt microorganisms and enzymes (Rathnakumar et al., 2023). Many studies have demonstrated that ultrasound processing can effectively reduce pectin-degrading enzyme activity in tomato juice, comparable to or even exceeding thermal hot break methods (Terefe et al., 2009; Wu et al., 2008). Ultrasonic treatment has also achieved a 5-log reduction in viable yeast in tomato juice (Adekunte et al., 2010). These studies highlight the potential to decrease or eliminate the need for heating during hot or cold break processes, as well as sterilization.

OH is an alternative to traditional indirect thermal methods for evaporating, blanching, and sterilizing food products (Guida et al., 2013; Pataro et al., 2011). It involves passing alternating electrical current (50 Hz - 100 kHz) through food placed between two electrodes generating internal heat due to the food's electrical resistance (Junqua et al., 2021). OH offers rapid and uniform heating of materials, including viscous and particulate foods, and it ensures efficient energy transfer (Pereira et al., 2016). It also prevents fouling of heat exchanger surfaces, increasing energy efficiency (Pereira and Vicente, 2010). Tomato paste, with its high conductivity, is well-suited for ohmic heating (Darvishi et al., 2012) allowing for effective moisture removal (Torkian Boldaji et al., 2015), and enzyme inactivation (Yildiz and Baysal, 2006). Studies have shown that OH can also inactivate harmful microorganisms in tomato juice (Lee et al., 2012; Somavat et al., 2013; Yildiz and Baysal, 2006).

Incorporating advanced energy-efficient technologies in tomato processing can improve product quality (Amón and Simmons, 2017). Traditional thermal processes can lead to the loss of essential antioxidants like lycopene and β-carotene (Seybold et al., 2004). To preserve these crucial nutrients, mild and energy-efficient processes can be integrated at specific stages of tomato processing. For example, tomato purée processed with HPP exhibited higher retention of anti-radical power, ascorbic acid, and total carotenoids compared to thermally processed one. HPP-treated tomato purée also had higher levels of carotenoids compared to unprocessed tomatoes (Patras et al., 2009). Similarly, using PEF for processing tomato juice resulted in enhanced availability of certain nutrients, such as carotenoids, in the final products (Odriozola-Serrano et al., 2009).

Further research is necessary to scale up and accurately assess the water and energy-saving potential of specific emerging technologies in tomato processing. Additionally, a careful optimization of process parameters and equipment design is necessary in order to ensure the desired degree of microbial or enzymes with the minimum expenditure of energy without overprocessing the food product. The final objective is to minimize or replace traditional heating methods while also ensuring that these emerging technologies do not compromise, and ideally enhance, the quality of the final products compared to conventional thermal methods.

4.2.2. Innovative methods for tomato peeling

Peeling is a crucial process in food processing to efficiently produce high-quality products (Kohli et al., 2021). The performance of peeling methods is assessed based on factors like peelability, peeling loss, ease of peeling, and product quality (Li et al., 2014a; Pan et al., 2009). Concerns regarding water and energy consumption as well as environmental impact are also important considerations (Arnal et al., 2018).

Chemical and steam peeling methods have been widely used in the tomato processing industry. Chemical peeling involves immersing tomatoes in a hot caustic solution (usually sodium hydroxide, 8%–25%, at temperatures of 85–100 °C for 15–60 s), which effectively removes the skin, but poses challenges such as high water and energy consumption and disposal of peeling effluent (Arnal et al., 2018; Pan et al., 2009; Rock et al., 2012). Steam peeling weakens the tomato skin using pressurized steam (50–200 kPa, for 10–60 s), but it may result in inferior peelability, higher peeling loss, and reduced firmness compared to chemical peeling, while it is also water and energy-intensive (Arnal et al., 2018; Rock et al., 2012).

To address these issues, sustainable and non-chemical peeling alternatives using innovative technologies like IR heating, OH, US, and PEF, have been developed (Andreou et al., 2020; Gao et al., 2018; Gavahian and Sastry, 2020; Giancaterino and Jaeger, 2023; Kohli et al., 2021; Li et al., 2014a, 2014b; Rock et al., 2012; Vidyarthi et al., 2019). However, their industrial implementation has been limited so far due to high investment costs and low processing capacities, among others.

4.2.2.1. Infrared (IR) peeling. IR peeling is an innovative and sustainable dry-peeling method that eliminates the need for chemicals and heating mediums like water or steam in the peeling process. It effectively reduces product loss and maintains product quality (Li and Pan, 2014a, 2014b; Pan et al., 2009; Vidyarthi, 2017; Vidyarthi et al., 2019). By rapidly heating the surface of tomatoes using electric, ceramic or the more advanced catalytic IR generator, physical and biochemical changes occur in the peel, facilitating easy detachment (Li et al., 2014a; Qu et al., 2022; Vidyarthi et al., 2019). IR radiation has a shallow penetration depth, resulting in minimal alterations to the texture and nutrient content of the inner part of the fruit (Vidyarthi et al., 2019). Tests conducted both at the bench scale and pilot scale have shown that tomatoes peeled using IR technology have greater firmness and lower peeling loss compared to lye peeling methods while consuming less energy (Li et al., 2014a, 2014b; Vidyarthi et al., 2019).

However, achieving optimal peeling performance with IR technology depends on crucial parameters like tomato surface temperature and heating rate (Vidyarthi et al., 2019). Uniform heating can be a challenge, and careful optimization of process parameters and equipment design is necessary (Pan et al., 2009). The initial investment cost for IR peeling equipment is high, but the long-term benefits may justify it.

4.2.2.2. Ultrasound (US)-assisted peeling. US-assisted peeling utilizes high-intensity sound waves (20–100 kHz) to generate a cavitation effect, leading to the degradation of the tomato skin and structural carbohydrates. This weakens the skin, resulting in the separation of the epicarp from the pericarp. The cavitation also generates free radicals aiding in the chemical breakdown of carbohydrates and facilitating the peeling process (Rock et al., 2012).

Initial studies have demonstrated that using power US in hot water yields better peeling performance compared to conventional lye peeling. Higher temperatures combined with ultrasound provide better peeling scores and lower losses. Applying US directly in the lye solution further minimizes peeling losses while reducing the lye concentration (Rock et al., 2012). A cascade approach combining hot lye and US has been also found to reduce the concentration and processing time of hot lye while increasing the yield and lycopene content of peeled tomatoes (Gao et al., 2018).

However, there are challenges associated with implementing ultrasound-assisted peeling on a larger scale, such as insufficient power intensity, reactor design complexities, and the potential for uneven peeling.

Overall, US-assisted peeling holds promise for enhancing tomato processing, but further research is required to address these limitations and optimize the technique (Gao et al., 2018; Kohli et al., 2021; Rock et al., 2012).

4.2.2.3. Ohmic heating (OH)-assisted lye peeling. The process of peeling tomatoes using OH involves immersing them in an electroconductive solution containing sodium hydroxide or sodium chloride. By passing an alternating electrical current through the solution, a combination of thermal, chemical, and physical mechanisms, along with electrical effects, effectively removes the tomato skin (Rock et al., 2012; Wongsa-Ngasri and Sastry, 2016a, 2016b).

The current flow causes the solution to heat up, leading to the degradation of the waxy cuticle and the disruption of hemicellulosic and pectic substances, making the skin less rigid. This, along with increased temperature and water vaporization (Gavahian and Sastry, 2020; Kohli et al., 2021), facilitates the splitting of the tomato skin and the separation of the outer layer from the inner part. As a result, a high peeling score of 4.5–5 out of 5 can be achieved using ohmic heating with a relatively low concentration (0.01–0.03% w/v) of NaCl. It's worth noting that preheating the solution above 40 °C can shorten the peeling time (Wongsa-Ngasri and Sastry, 2015). This use of OH for tomato peeling has the potential to reduce environmental challenges associated with lye peeling methods by utilizing a low-concentration NaCl peeling medium.

Combining OH with lye peeling at lower concentrations (0.5–1% w/v) than conventional methods can yield high-quality peeled products, minimize peeling losses, and accelerate the peeling process (Sawant et al., 2018; Wongsa-Ngasri and Sastry, 2016b). This is because in lye-ohmic peeling the diffusion of lye or NaOH is accelerated by electroporation, resulting in faster depolymerization of substances in the skin and separation of the peel (Gupta and Sastry, 2018; Rock et al., 2012; Wongsa-Ngasri and Sastry, 2015).

However, implementing OH on an industrial scale requires further research on engineering design, electrode corrosion, economic factors, and scaling up the process (Gavahian and Sastry, 2020; Pataro et al., 2014). Additionally, the safe disposal of used salt solutions is an important consideration for the application of this emerging technology (Kohli et al., 2021).

4.2.2.4. Pulse electric field (PEF)-assisted steam peeling. PEF-assisted steam peeling offers a promising and efficient technological solution for tomato peeling, enhancing the ease of peel removal, while saving energy (Arnal et al., 2018; Giancaterino and Jaeger, 2023). By applying a moderate electric field intensity ($E < 5$ kV/cm) and a relatively low energy input ($W_T < 5$ kJ/kg), structural modifications occur within the tomato's matrix, reducing the surface resistance of the skin and promoting detachment from the flesh (Andreou et al., 2020; Arnal et al., 2018; Giancaterino and Jaeger, 2023; Koch et al., 2022). Moreover, the application of an external electric field induces electroporation effects (Pataro et al., 2018), enhancing water mass transfer and increasing water availability under the tomato skin compared to untreated tomatoes (Arnal et al., 2018; Pataro et al., 2018). During subsequent steam heating, the greater pressure difference across the tomato skin, caused by vaporization, facilitates the formation of cracks, which aids in mechanical peel removal using pinch roller systems (Arnal et al., 2018). This results in reduced peeling loss, high-quality products, and reduced water and steam usage compared to traditional steam peeling methods (Andreou et al., 2020; Arnal et al., 2018; Giancaterino and Jaeger, 2023). The successful implementation of PEF-assisted steam peeling in existing industrial plants has demonstrated its feasibility and positive environmental impact (Arnal et al., 2018; Pataro et al., 2018). In the context of the EU project "FieldFood" (635632-FieldFOOD-H2020), specific industrial tests were conducted. These tests demonstrated that utilizing a relatively low-intensity pulsed electric field (PEF) pre-treatment at values of 0.45 kV/cm and 0.40 kJ/kg on tomato fruits before steam peeling led to a notable reduction of up to 20% in the total steam required during the thermo-physical peeling process. Additionally, a LCA study revealed that integrating PEF technology prior to steam peeling resulted in significant enhancements across all measured environmental indicators, with improvements ranging from 17% to 20%, thus suggesting that PEF is an environmentally friendly technology (Arnal et al., 2018).

However, further research is required at an industrial scale to validate energy savings and address technological challenges, including the long-term reliability of PEF generators and electrodes, as well as high initial investments (Pataro and Ferrari, 2020) before the widespread adoption and exploitation of PEF technology can be realized.

In conclusion, upscaling as well as optimization of process parameters and refining equipment design for novel technologies applied to microbial/enzyme inactivation and the peeling of fruits and vegetables is a pivotal stride. This aims to secure the intended process outcomes (microbial/enzyme control and high peelability) with the minimum expenditure of water and energy and avoiding excessive alteration of the food product, thus reducing reliance on traditional heating and chemical approaches. All of these achievements go into direction to improve sustainability and foster cleaner production.

5. Conclusion and remarks

The food and beverage industrial sector plays a significant role in energy consumption and global water footprints, leading to substantial environmental impact. Among these industries, tomato processing stands out as one of the most resource-intensive, consuming large amounts of water and energy (both thermal and electrical) while generating substantial solid and liquid wastes.

This review paper introduces a systematic approach based on Water-Energy Nexus (WEN) analysis, which serves to pinpoint the production process stages with the highest water and energy demands, thereby highlighting areas of inefficiency. This framework empowers decision-makers to implement customized strategies aimed at enhancing both efficiency and sustainability in tomato processing. By applying this approach, numerous key opportunities for efficiency enhancements have been identified.

The majority of water usage is concentrated in the initial pre-processing steps, primarily during tomato washing and conveying into the facility. Additionally, a significant portion of the total water is consumed as steam in thermal processes and cooling operations. It is imperative to focus on implementing water conservation measures, especially in a closed-loop system during the initial stages, as well as exploring the potential for reusing steam condensate.

Steam boilers within a tomato processing facility stand out as the most energy-intensive equipment by a considerable margin. Consequently, any comprehensive energy efficiency audit should prioritize the assessment of these boilers. The recovery of waste heat from various process effluents, through both direct and indirect heat exchange processes, should be a central strategy to achieve substantial energy savings. The evaporation step, in particular, offers a unique opportunity for waste heat and water recovery. While measures like installing mechanical vapor recompression (MVR) systems or additional evaporation stages are capital-intensive, they can lead to significant energy savings.

Electrical energy is more evenly distributed across the production line compared to water and thermal energy. The majority of this electrical energy is allocated to pump operations, with the remainder used for powering compressors, fans, separators, and aerators. Therefore, enhancing pumping efficiency is crucial for reducing electricity consumption in tomato processing.

In addition to conventional measures and technologies, integrating advanced thermal and non-thermal technologies like Pulsed Electric Field (PEF), High-Pressure Processing Homogenization (HPPH), Ultrasound (US), Infrared (IR), and Ohmic Heating (OH) shows promise solutions in saving water, improving energy efficiency, and reducing environmental impact, all while preserving or enhancing the quality of final products compared to traditional thermal methods.

Future research should focus not only on the technical feasibility but also on the economic viability of implementing conventional and unconventional practices and technologies. This is especially important for advanced technologies, as their integration into tomato processing lines requires a thorough assessment of their water and energy-saving potential at an industrial scale. Moreover, there are several technological challenges that must be addressed to enable their implementation on a larger scale. These challenges encompass upscaling as well as the need to improve equipment design, optimize process parameters, and manage the significant initial investment costs. Additionally, the seasonal nature of tomato production could be a further obstacle to their spread.

The approach discussed in this review, specifically tailored to the tomato processing industry, can serve as a model for addressing similar challenges in other water and energy-intensive sectors within the food industry. Nevertheless, regardless of the specific food sector, implementing alternative practices and technologies necessitates a rigorous comparison with initial baseline levels of water and energy consumption at the key processing stages to quantify improvements effectively. In this regard, the accurate collection of data regarding water and energy flow is of utmost importance. Achieving this may involve the installation of sensors and monitoring systems, as well as the utilization of process simulation tools to precisely solve water mass balances and estimate flow rates. These measures can significantly assist facilities in enhancing their resource consumption efficiency.

CRediT authorship contribution statement

Elham Eslami: Conceptualization, Investigation, Data curation, Figure design, Writing – original draft. **Emad Abdurrahman:** Investigation, Data curation, Figure design, Writing – original draft. **Gianpiero. Pataro:** Conceptualization, Supervision, Writing – review & editing. **Giovanna. Ferrari:** Supervision, Conceptualization, Writing – review and editing, Funding acquisition, Project administration, Resources.

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Declaration of competing interest

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

Data availability

Data will be made available on request.

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