Sustainable postharvest processing technologies for dried food commodities and firm-level adoption: A critical review

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Abstract

Numerous studies have considered various food production technologies and their adoption factors for enhanced agricultural productivity. However, there needs to be more research on the technology adoption factors for post-harvest management, especially in the dried food industry, as the processing stage of this value chain is characterized by significant post-harvest losses (PHL) and, thus, has unique challenges and opportunities. Several emerging technologies have been developed recently to ensure food safety and nutrition security as alternatives to using chemicals in post-harvest management. Although these technologies and their applications have been explored extensively, there still needs to be a clear understanding of the factors that influence their firm-level adoption and diffusion, which are still low. Using the implementation of the global development goals as a focal point, this paper reviews over 20 years of research on novel post-harvest processing technologies, examines their sustainability features, and identifies relevant firm-level adoption factors. The study finds that technology-related factors, firm characteristics, and the external environment determine adoption. Based on the results, promising research areas that are important for firms, consumers, and the planet are presented.

Keywords: *Postharvest pest management, food processing, firm adoption factors, non-thermal technology, thermal technology, sustainability.*

1. Introduction

Dried food commodities such as grains, nuts, pulses, dried fruits, and dried vegetables form part of the daily diet of everybody in the world. These commodities are ingredients for a wide range of food products and serve as rich sources of carbohydrates, proteins, lipids, minerals, and vitamins (Carcea, 2020). Whole grains, which are vital for developing new and high-valued food products with improved health benefits, provide essential bioactive compounds and dietary fiber (Hall, et al., 2017). Dried fruits and vegetables are also known to add significant amounts of magnesium, calcium, iron (Onwude et al., 2021), vitamins A, C, and E (García-Martínez et al., 2013), phenolic antioxidants, and fibers to the diet (Chang et al., 2016). Additionally, pulses provide about 21–25% of proteins (Rebello et al., 2014), and can be a successful source to switch out animal-derived proteins (Marinangeli, 2022). According to Marinangeli (2020), all essential amino acids are present in a combination of pulses with cereals. Pulses and whole grains have been shown to lower risk factors for cardio-metabolic illnesses (Ferreira et al., 2021; Viguiliouk et al., 2017) with significant direct and indirect healthcare cost-saving implications (Abdullah et al., 2017; Murphy et al., 2020) and positive environmental impacts (Marinangeli, 2020). Abdullah et al. (2021) asserted that increasing whole grain consumption to 48g/day among the adult Australian population is associated with an estimated 1.4 billion AUD[1] in healthcare cost savings over the next 20 years. Thus, for the global population in general and particularly for pregnant and nursing mothers, elderly

[1] AUD stands for Australian dollar.

individuals, and children, the nutritional elements of dried food commodities are crucial (Carcea, 2020).

However, dried food commodities, when in storage, serve as a hiding, feeding, and breeding place for insect pests (Rajendran, 2020). This causes damage to farm produce leading to post-harvest losses (PHL), which threatens farm income security, food price stability, nutrition security (Debebe, 2022), and the achievement of the sustainable development goals (SDG). Gordon (2023) reports that on average, pests account for 20-40% of yield losses worldwide, costing the global economy about $290 billion. Figure 1.0 provides statistics on PHL in America and Europe.

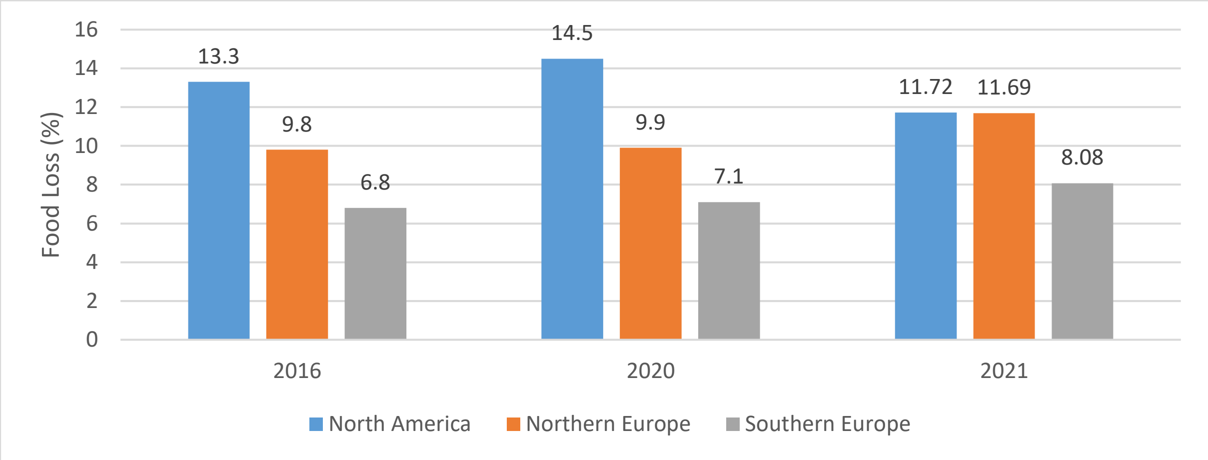

Figure 1.0: PHL in America and Europe (FAO, 2023)

According to recent studies, the current pest problem has a high likelihood of exacerbating due to climate change (Skendžić et al., 2021). Skendžić et al., (2021) contend that rising temperature and atmospheric CO_2 levels significantly drive pest population growth. In addition to damage caused by insect pests is damage caused by microbial infestation emanating from the symbiotic and pathogenic relationship between insects and microorganisms (Gupta & Nair, 2020). Ic et al. (2007) found a fungal bioburden of 102 to 103 CFU/g on some dried fruits and nuts sold in retail stores. Globally, grains, dried fruits, and nuts comprise a significant portion of traded food. For instance, from 2018 to 2022, the average proportion of trade exports of grains to total agricultural product exports in the European Union was 22.6%. Hence, the presence of microbes on these commodities has dire consequences for food safety (Ic et al., 2007). From a public health perspective, reducing the microbial bioburden on these commodities using appropriate postharvest technologies could drastically improve food safety to meet consumer demands.

Over the years, using synthetic chemicals (i.e., fumigants, insecticides, or pesticides) in conventional agriculture to control pests has increased yields (Ma & Abdulai, 2019). Nonetheless, it has also caused damaging effects on human health and the environment (Shrestha & Baik, 2013). Moreover, research has shown that due to prolonged exposures, pests have developed resistance to the use of synthetic chemicals (Zakladnoy, 2020), making their use costly, less effective, and unsustainable. Also, the use of chemicals leaves poisonous residues in the end-product for consumers and may affect workers' health if misapplied due to a dearth of technical expertise on their application, especially in developing countries (Adarkwah et al., 2022). Consequently, strict regulations on the use of chemicals have led to prohibiting some chemicals (e.g., methyl bromide) (Sirohi et al., 2021; Wisniewski et al., 2016). For instance, Europe's farm-to-fork action plan intends to reduce the overall use and risk of chemical pesticides from 20% to 50% and the use of hazardous pesticides by 50% by 2030. Besides government regulations, some value chain actors impose in-house standards to prevent chemical residues in foods (Narrod et al., 2009; Wisniewski et al., 2016). These regulatory protocols have driven research in developing advanced technologies such as modified and controlled atmosphere (MCA) methods for product storage. MCA decreases metabolic activity and prolongs product shelf-life (Falagán & Terry, 2018). Nevertheless, they involve high investment costs (Navarro, 2012). Furthermore, limitations such as "imprecise monitoring of fruit and vegetable response, high energy requirements, high cost of materials and reduced retention of initial quality" (Falagán, & Terry, 2018, p.114) render MCA technologies unsustainable and less likely to be adopted by small-scale dried food processing firms.

Recent studies have assessed and proposed using emerging technologies broadly categorized as thermal (i.e., radiofrequency, etc.) and non-thermal (pulse electric field, etc.). It is argued that these technologies could serve as alternatives for postharvest pest management and food processing due to their potential benefits over conventional methods (Mangang et al., 2022; Wang & Tang, 2004). These technologies promise shorter processing times, accelerated heat and mass transfer, control Maillard reactions, improved product quality, enhanced functionality, reduced environmental stress, and extended shelf-life (Galanakis, 2013). For instance, Orsat & Raghavan (2014) noted that applying radiofrequency (RF) to food products reduced processing time, optimized energy use, and yielded quality products while mitigating environmental risk. Rosi et al. (2019) found emigration effects of dried fruit beetles from infested dates using RF treatment. These discoveries with emerging technologies are remarkable for achieving the SDGs 1 (no poverty), 2 (zero hunger), 8 (decent work and economic growth), and 12 (responsible consumption and production). Nevertheless, studies reveal a low firm-level uptake because of several factors mainly associated with cost, a lack of understanding of these new technologies' effects on food quality, and consumer acceptance. (Priyadarshini et al., 2019). Moreover, the literature on emerging technologies lacks a consensus on some aspects of the sustainability features of these technologies. This lack of consensus may be due to the type of product researched, geographical location, and/or other heterogeneous factors. To mention but a few, while Kalla et al. (2017) hailed microwaves for having a higher consumer acceptance, Singh et al. (2021) argued that microwave-treated food may degenerate the immune system thereby becoming unpopular among consumers. In another case, Pereira & Vicente (2010) and Singh et al. (2021) posited that ultraviolet (100–280 nm wavelength) disinfection neither leaves chemical residues nor produces toxic by-products. However, Uthairatanakij et al (2023) rebutted this assertion and claimed that UV wavelengths below 260 nm produce ozone, which is hazardous to the environment. Furthermore, although Barba et al. (2015) and Chua & Chou (2014) asserted that microwave heating has low energy efficiency; Singh et al. (2021) and Aaliyah et al. (2021) claimed microwaves consume less energy and, therefore sustainable. Sustainability in the context of this review is defined along the three pillars: social, environmental, and economic, which are often referred to as the triple bottom line or people, planet, and profit, according to Purvis et al. (2019).

Research and development inform firm-level technology adoption decisions, and the need for currency and conclusiveness in some aspects of the emerging technology literature may reduce bias in the adoption decision-making process and even render firms more willing to adopt. Therefore, using the implementation of the global development goals as a focal point, the current systematic review of the state-of-the-art seeks to achieve three objectives. Firstly, the paper identifies emerging technologies suitable for dried food postharvest management.

Secondly, the review points out features associated with these technologies under the three pillars of sustainability: economic (e.g., input-saving (time, water, energy, PHL reduction)), social (e.g., quality and consumer health), and environmental (e.g., energy-saving, waste management). Lastly, using the Technology-Organization-External Environment (TOE) framework, the paper identifies relevant adoption factors for firms within the dried food commodities' value chain. A similar review by Priyadarshini et al. (2018) attempted to understand the factors that drive the adoption of these technologies in the food (plant and meat-based) industry. Nonetheless, the factors outlined were rather theoretical as opposed to insights from empirical findings. This study distinguishes itself from that review by providing empirical findings on adoption factors, and as a contribution to the literature, generating new, relevant insights into the sustainability features of these technologies. Thus, as an improvement in the general literature, the current paper serves as a *one-stop-shop* providing information on novel technologies, their sustainability features, and adoption factors to improve decision-making for firms seeking to pursue or maintain a competitive edge within the dried food commodity industry.

The rest of the paper proceeds as follows: Section 2 provides materials and methods used in this review. Sections 3 and 4 present and discuss emerging technologies and their sustainability features. Section 5 discusses the adoption factors. Section 6 provides a general discussion of the study and Section 7 concludes the review.

2. Materials and Methods

This study relies on a systematic literature review to achieve the research objectives. It follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method.

2.1. Search strategy and inclusion/exclusion criteria.

Keyword searches in electronic databases (Google Scholar, Science Direct, Web of Science, and Scopus) served as the primary method for finding pertinent literature. For objective one, "emerging food processing technologies", "emerging post-harvest technologies", and "novel food processing technologies" were keywords used. For objective two, the keywords used include "green technology," "clean," "resource-saving" "economic sustainability", "environmental sustainability", and "social sustainability". "Adoption factors", "adoption determinants", "firm-level adoption" and "industry-level adoption" were used as keywords for objective three. A combination of these keywords produced the relevant articles for this review. The selection of articles was based on the criteria provided in Table 1.0, and Figure 2.0 shows search results.

Criteria	*Inclusion*	*Exclusion*
Type of Literature	Peer-reviewed articles, and reviews	Book chapters, editorials, conference proceedings, commentaries, magazines, etc.
Language	English	Non-English languages
Focus Years	From 2001 to October 2023	Articles published before 2001
Title and Abstract	Focuses on emerging food processing and postharvest pest management technologies	Articles on technologies other than those in focus (e.g., PICS, hermetic bags, metal silos, etc.,) are excluded.
Full-article Screening	Includes information on at least one of these themes: emerging technologies, sustainability, and adoption factors within the dried food industry.	The study excludes literature on meat, juice, fresh fruit, and vegetable processing.

Table 1.0: Inclusion/exclusion criteria

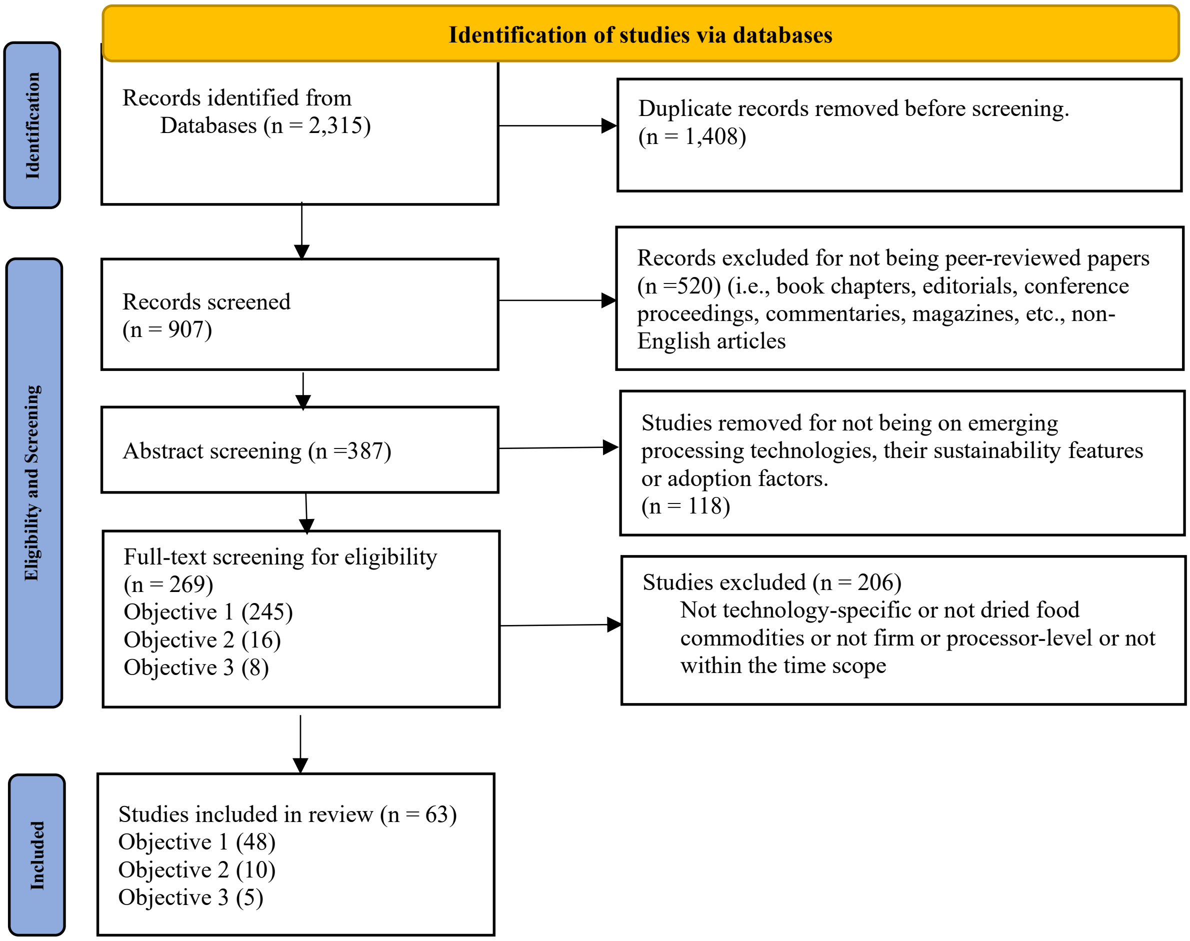

Figure 2.0: Data collection using PRISMA[2]

[2] Nine (9) articles in the "Included" stage of the PRISMA are common to Objectives 1 and 2 but counted in the number of articles used in Objective 1, (i.e., 48) to avoid double counting.

3. Emerging food processing and pest management technologies[3]

Emerging technologies are non-chemical alternatives used to dry and disinfest grains and their products. Extant literature classifies them into two (2) broad categories: thermal (e.g., microwave, radiofrequency, infrared, ohmic heating) and non-thermal (i.e., ultraviolet radiation, pulse electric field, ozonation, cold plasma, high-pressure processing, and ultrasound) technologies.

3.1 Emerging thermal technologies

Radiofrequency (RF) and microwave (MW) treatments, both considered dielectric heating, use electromagnetic energy between 10 MHz to 30000 MHz (Wang & Tang, 2004). Commonly used industrial frequencies are 27.12 MHz for RF which provides a good compromise to neutralize the problems associated with the low and high frequencies and 2450 MHz for MW (Macana & Baik, 2018). Studies have reported using microwaves to disinfest dried commodities such as walnuts (Das et al., 2014), wheat (El-Naggar & Mikhaiel, 2011), mung beans (Purohit et al., 2013), and date fruit (Manickavasagan et al., 2013).

Manickavasagan et al. (2013) experimented with the effect of microwave treatment on selected date fruit pests (adult *Tribolium castaneum* and *Oryzaephilus surinamensis*, and larvae of *T. castaneum*), and achieved a 100% mortality for all species with 45-50 °C and 800 W within 40 s. Applying microwave (480 W) for 4 min to disinfest walnuts in an experiment in India, Das et al. (2014) found that at 50–55 °C, the peroxide value (PV) decreased from 2.08 mEq O_2/Kg of oil to 1.10 and 1.66 mEq O_2/Kg of oil while the free fatty acid (FFA) value reduced from 0.68% to 0.11 and 0.51%. The reduction in PV and FFA facilitated shelf-life extension for 6 months, while untreated nuts were heavily infested after a month of storage (Das et al., 2014).

RF has been applied in the disinfestation of dates (Pegna et al., 2017), chickpeas, green peas, lentils (Wang et al., 2010), walnuts (Wang et al., 2001), rice (Liu et al. 2021), wheat (Shrestha & Baik, 2013), macadamia nuts (Wang et al., 2014), pistachio (Ling et al., 2016), chestnuts (Hou et al., 2018;), and coffee beans (Pan et al., (2012). Pegna et al, (2017) achieved a 100% mortality of the larvae, pupae, and adult *Carpophilus hemipterus* in 6min after disinfesting dates with 3.5 kW, 27.12 MHz radiofrequency. In China, Liu et al. (2021) provided experimental evidence for disinfesting rice. Using a 6 kW, 27.12 MHz RF protocol, a 100% mortality of the adult lesser grain borer was recorded at 54 °C within 12 min.

Some researchers have asserted that MW and RF heating are associated with heating non-uniformity (Vadivambal & Jayas, 2010). However, current studies have validated the use of forced hot air (Cui et al., 2023; Hou et al., 2018), conveyor belt movement (Ling et al., 2016), polyurethane foams (Wang et al., 2014), computer simulation (Cui et al., 2023; Alfaifi et al., 2016) and modifying the electrode configuration of the treatment system (Alfaifi et al., 2016)

to improve heating uniformity. Zuo et al. (2022) improved heating uniformity in RF-treated walnut kernels by increasing the electrode gaps and mixing different sizes of walnut kernels.

Infrared heating (IR) uses electromagnetic radiation between the visible light and microwave regions. It has shorter wavelengths, (0.75-1000 μm), or higher frequencies (0.3-400 THz) than

[3] The current study considers only the application of these technologies to dried food commodities rather than their principles as these have been covered extensively in the literature. See Priyadarshini et al. (2019) and Zhao et al. (2019) for principles underlying these technologies work.

microwave and radiofrequency (Sakai & Hanzawa, 1994). Infrared radiation is divided into three types: near-IR (NIR) (0.75 to 1.4 μm), mid-IR (MIR) (1.4 and 3 μm), and far-IR radiation (FIR) (3 and 1000 μm) (Rosenthal, 1992). IR is used to dry, pasteurize, and remove antinutrients from legumes (Sakare et al., 2020). In the USA, Bingol et al. (2011) provided evidence of microbial disinfestation of almonds using infrared and concluded that the recommended protocols are either (a) heating almonds to 120 °C with subsequent holding at 90 °C for 5 min; (b) 110 °C with subsequent holding at 90 °C for 10 min; or (c) 100 °C with subsequent holding at 90 °C for 10 min.

Ohmic heating (OH) facilitates rapid uniform heating in food products (D'cruz et al., 2023). Heating occurs as alternating electric current passed through food matter converts to heat energy (Gavahian et al., 2019). Applications of OH include disinfestation (Pino-Hernandez et al. 2021), extraction (Pereira et al., 2021), parboiling (D'cruz et al., 2023), and cooking (Dias-Martins et al., 2019; Gavahian et al., 2019). In Portugal, Pino-Hernández et al. (2021) applied OH at 55°C and found it effective for controlling molds and larvae growth in chestnuts. In Brazil, Dias-Martins et al. (2019) cooked millet grains for 30 and 20min using the conventional open-pan and OH respectively. Although there were no differences between the texture and color for both cooking methods, ohmic-heated samples were harder and had a lower cooking yield than conventionally cooked samples. Gavahian et al. (2019) studied the effect of OH and traditional cooking on the textural and physical attributes of rice and concluded that although ohmic heating changed the color, OH-cooked rice was softer compared to hotplate cooking.

3.2 Emerging non-thermal technologies

Pulsed electric field (PEF) processing involves subjecting food placed between electrodes to multiple pulses of electric field (0.1-100 kV/cm) (Wang et al., 2020). Applications include microorganism inactivation (Qian et al., 2014), bioactive compound extraction (Buchmann et al., 2019), and modifying biomacromolecules such as corn starch (Zhao et al., 2011). In China, Qian et al. (2014) noted that PEF inactivated about 60% of lipase in brown rice thereby slowing down lipolysis under these conditions: 715 Hz, 9 kV, and 13 μs pulse width. Zhao et al. (2011) extracted polysaccharides from corn silk using PEF. Optimal conditions produced a 7.31% yield, reported as 1.95% and 1.13% higher than the hot water method and microwave-assisted extraction respectively (Zhao et al. 2011). Eisa et al. (2003) showed evidence of PEF for reducing aflatoxin in maize. Exposing *A. flavus* to 600-800 Hz for 2h reduced aflatoxin by at least 60.4%, while a combination of electric waves (800, 700, 600, 500 Hz) for at least 4 h yielded more than 95% reductions in *A. flavus* (Eisa et al., 2003). Bulut et al. (2020) provided evidence for PEF-treated (10 kV, 100 and 180 Hz) sesame seeds with a 14.1% to 56.1% reduction from the initial *A. parasiticus* count of 4.06 log CFU/g.

High-pressure processing (HPP) uses a pressure of 100–800 MPa below 20 °C (Chacha et al., 2021). Applications of HPP include microbial inactivation, shelf-life extension (Pino-Hernandez et al., 2022), and hydration (Belmiro et al. 2018). For instance, Belmiro et al. (2018) demonstrated that applying up to 600 MPa improved the hydration of treated common beans (*Phaseolus vulgaris L.)* by 4.7 times faster, increased drying by 27% higher, increased rehydration by 2.1 times faster and reduced cooking time by 15min than control samples. At 600 MPa and 20 °C for 5 min, compared with the conventional hydrothermal method at 50 °C for 45 min, Pino-Hernandez et al. (2022) discovered that HPP was better at destroying molds and insect larvae and extended chestnut shelf-life by 40 days.

Ultraviolet (UV) radiation is another non-thermal technology used to decontaminate and extend the shelf-life of food commodities (Bahrami et al., 2020). UV has wavelengths 100–400 nm on the electromagnetic spectrum and is classified as UV-A (315-400 nm), UV-B (280-315 nm), UV-C (200-280 nm), and UV-Vacuum (100–200 nm) (Vasuja & Kumar, 2018) with the different categories suitable for inactivating different pathogen types (Chacha et al., 2021). Applying UV (100–280 nm), Izmirlioglu et al. (2020) observed a reduction of *Salmonella* Enteritidis on inoculated walnuts from 5.56 Log CFU/g to 3.18 log CFU/g within 45 s without affecting the physicochemical properties of walnut samples.

Cold plasma (CP) is an ionized gas composed of excited electrons, photons, and ions (Misnal et al., 2021). Applications of cold plasma include microbial decontamination of rice (Park et al. 2020), wheat and barley (Los et al. 2018), almonds (Hertwig et al., 2017), maize (Wielogorska, et al., 2019); and the germination rate of rice (Amnuaysin et al., 2018). Los et al., (2018) reported 48% and 54% reductions in bacteria and fungi respectively in barley, and 63% and 34% reductions in bacteria and fungi respectively in wheat after treatment with CP (80 kV, 50 Hz) at 15 °C for 20 min. Los et al., (2018) also found a significant reduction in *E. coli* and *P. verrucosum* by 75% and 94% respectively on inoculated barley grains.

Ultrasound (US), a cavitation process technology, uses low (below 100 kHz) or high-frequency (above 100 kHz) sound waves and power intensity of 1 to 1000 W/cm^2 (Fu et al., 2020). Ultrasound is applied to extract bioactive compounds (Susanti et al., 2021), modify starch (Xu et al., 2021), inactivate enzymes, and protein enzymolysis (Zhang et al., 2015). Using ultrasound (20 kHz) at 30 °C for 20 min, Zhang et al. (2015) concluded that treatment of wheat gluten increased the angiotensin-I converting enzyme inhibitory activity by 29.8% while the inhibitory concentration value at 50% decreased by 36.92% compared to control samples. In India, Muzaffar et al. (2016) reduced the microbial load on cherries by 35% (bacteria), and 33% (yeast and mold) after ultrasound treatment (33 kHz, 60 W) for 40 min at 4°C.

Ozonation (O_3) is a chemical produced by exposing a gas mixture containing oxygen to a high-energy electric field, ultraviolet radiation, or by converting oxygen molecules (Tiwari et al., 2010). Ozone treatment is effective in modifying starch (Pandiselvam et al., 2019), disinfesting insects (Kells et al. 2001; Mishra et al., 2019), and inactivating microbes (Akbas & Ozdemir, 2008; Brodowska et al., 2018). In the USA, Kells et al. (2001) reported complete mortality of adult maize weevil, adult red flour beetle (92.2%), larval Indian meal moth (94.5%), and a 63% reduction of *Aspergillus parasiticus* in maize while control samples produced 3.2% to 9.2% insect disinfestation. In Turkey, Akbas & Ozdemir (2008) observed that applying ozone (1.0 ppm) at 20 °C for 360 min to inoculated dried figs reduced *Escherichia coli* and *Bacillus cereus* counts by 3.5 $\log_{10}$CFU/g. Recently in India, Mishra et al. (2019) provided evidence of 97-100% mortality of *Rhyzopertha dominica* in all life stages after treatment of infested wheat with 2.5 g/m^3 ozone concentration for 8 h.

4. Sustainability features of emerging food-processing technologies

4.1 Economic sustainability

Compared to conventional methods, the technologies discussed above could facilitate economic sustainability. Economic sustainability refers to efficient energy use, shorter processing time, greater throughput, shelf-life extension, and processing cost minimization or profit maximization. Energy use is intensive in the food industry due to the use of conventional processing methods (Ladha-Sabur et al., 2019). In Europe, for example, industrial processing accounts for 28% of total energy with fossil fuels making up almost 79% of the energy consumed (Motola et al., 2015).

Notable technologies for economic sustainability include ohmic heating, radiofrequency, PEF, and microwaves. In India, D'cruz et al. (2023) found that conventional steaming for paddy rice parboiling consumed 0.367 kWh while OH (50Hz) with a voltage gradient of 18 V/cm consumed only 0.15 kWh of energy for 10 min. Moreover, the steaming method requires a steam-generating boiler which increases the processing cost, therefore, using OH saves resource costs (i.e., water, energy, and labor costs) (D'cruz et al. 2023). In Thailand, ohmic cooking consumes about 73–90% of the energy required by the rice cooker method (Jittanit et al., 2017). Gavahian et al. (2019) concluded that ohmic cooking of rice reduced the process duration and energy used by the hotplate method by 48% and 30% respectively.

In the USA, Lagunas-Solar et al. (2007) demonstrated that exposing rice to continuous RF at 60 °C with a throughput of 1.0 ton/h, assuming a 37 °C-temperature change requires about 12 kW of power and an estimated electricity cost of $1.35 per metric ton using $0.10 per kWh, assuming electricity cost accounts for 80% of operational costs. Lagunas-Solar et al. (2007) also showed that using lower frequencies proved effective in disinfestation, hence, energy costs for commercial systems operating with solid-state electronics and using <1.0 MHz frequencies can be as low as $300 to $400 per kW. Moreover, Lagunas-Solar et al. (2006) stated that continuous RF is 10% to 15% more energy-efficient than conventional heating and pulsed RF systems require only about 10% of the energy consumed by the latter.

Bulut et al. (2020) reported that PEF-treating sesame seeds reduced the initial peroxide value and acidity value by 67.4% and 85.7% respectively. These reductions facilitate shelf-life extension, thereby maintaining the commodity's economic value.

Compared to conventional methods, all emerging technologies require shorter processing times though commodity quantity varied in studies reviewed. For instance, within 30 to 40 s, Manickavasagan et al. (2013) achieved complete disinfestation of adult *Tribolium castaneum* and *Oryzaephilus surinamensis*, and larvae of *T. castaneum* in stored dates using microwave treatment while Dhouibi et al. (2015) fumigated *Ectomyelois ceratoniae* and *Ephestia kuehniella* from dates by combining CO_2 and phosphine for 8h at 35 °C and 24h at 20 °C.

4.2 Social sustainability

Concerns about food safety and security have become topical issues due to the food industry's globalized nature (Ladha-Sabur et al., 2019) and the use of synthetic chemicals which have dire consequences for human health. However, extant literature provides evidence of emerging technologies' ability to ensure social sustainability (Arshad et al., 2021). Social sustainability in this context relates to the quality, safety, and nutritional security of treated food products and their implication for consumer and public health. Quality standards of dried food commodities include appropriate color, flavor, texture, moisture content, independence from microbes and insects, and insect eggs (Kader & Hussein, 2009).

Many studies (e.g., Bingol et al., 2011; Izmirlioglu et al., 2020; Pino-Hernandez, et al., 2022) have shown the efficacy of emerging technologies in disinfesting pests, inactivating microorganisms, and maintaining quality. Using infrared, Bingol et al. (2011) achieved more than a 5.5-log reduction of *Pediococcus* on almond kernels. Assessing quality and sensory attributes, the authors illustrated that 70% to 90% of 80 panelists who tasted both IR-treated and untreated products found no detectable difference in the appearance of the samples. Regarding the texture and flavor, 50-60% and 50% of panelists respectively claimed that there was no significant difference in these attributes (Bingol et al., 2011). Assessing microwave-treated dates quality, Manickavasagan et al. (2013) reported that only 13 respondents out of 40 panelists correctly identified treated dates as there were no noticeable color or sensory changes based on Meilgaard et al. (2007) criteria for a triangular test (i.e., the number of correct responses should be at least 20 for a sample size of 40 to be statistically different at the 95% confidence level).

Hou et al. (2014) found no significant differences between chestnut quality parameters (moisture content, fat, soluble sugar, firmness, and color) of RF-treated and control samples. The protein content of treated nuts was slightly higher than the control and sweetness was within acceptable limits even after 8 days of storage at 35 °C or simulating for 1 year of storage at 4 °C (Hou et al. (2014).

Izmirlioglu et al. (2020) assessed the quality of *Salmonella*-inoculated walnuts using UV treatment and found no statistically significant differences between control and treated samples. Pino-Hernandez, et al. (2022) provided evidence that HPP treatment retained more than 98% of ascorbic acid and extended chestnut shelf-life. Using various frequencies (i.e., 50 Hz, 500 Hz, 2 kHz), Pereira et al. (2021) studied the impact of OH on the immunoreactivity of soybeans and concluded that low frequencies (≤500 Hz) tend to reduce the immunoreactivity of Glycine max trypsin inhibitor. The finding by Zhang et al. (2015) concerning a 29.8% increase in the inhibitory activity of angiotensin-I converting enzyme in wheat gluten using ultrasound is important for cardiovascular health.

4.3 Environmental sustainability

Environmental sustainability entails using ecological resources (i.e., energy, water, land, air, etc.) efficiently to meet the demands of current and future generations while limiting processing waste to acceptable levels. Given the high hygiene standards demanded by the food industry and the use of conventional methods, there has been increased consumption of energy and water for heating and cleaning during processing resulting in high environmental footprints (Pereira & Vicente, 2010). The increased use of fossil fuels, despite their economic consequences, has environmental implications. Moreover, the cereal industry poses a serious risk to the environment because of the various nutrient-rich and organically loaded effluents and solid wastes (Kumar et al., 2016), which are mostly disposed of in water bodies (Hassan et al. 2021). Industrial waste from cereal processing is associated with high biological oxygen demand (BOD) (1050–7950 mg/L), chemical oxygen demand (COD) (1400–29000 mg/L), pH (3.5 to 8.5) (Hassan et al. 2021), and pesticide residues, which cause hypertrophication and pollute groundwater (Karunaratne, 2011). Corn starch processing, for instance, yields acidic waste with large amounts of BOD (4327 mg/L) and COD (8527 mg/ L) (Neogi et al., 2016). Waste from dried fruit processing has similar harmful effects on the environment (Oladzad et al., 2021). Plazzotta et al. (2017) reported that date fruit waste has large amounts of biodegradable organic compounds that pollute the environment by producing leachate and releasing odors. Meanwhile, the International Finance Corporation's environmental guidelines for effluent levels for food and brewery processing are given as pH (6–9), (BOD) (50 mg/L), and (COD) (250 mg/L).

According to the extant literature, plasma, ultrasound, microwave, PEF, and ozone facilitate environmental sustainability. For example, using plasma treatment, Rajeev et al. (2019) extracted reducing sugars from brewer's spent grain with a yield of 123.95-162.90 mg/ml, compared to a control yield of 75.94 mg/ml. Also, a maximum ethanol titer of 25.062g/l was obtained, while the bioethanol produced from the control sample was only 11.231g/l (Rajeev et al., 2019). In China, Wang et al. (2013) investigated the effects of ultrasound for preparing dietary fiber from corn pericarp, an industrial waste of corn starch production. Under optimal conditions, 86.84 % of dietary fiber was extracted within 80 min with 90% of ultrasonic power (Wang et al. 2013). In Japan, Yoshida et al. (2010) provided evidence of microwave-assisted extraction of carbohydrates from corn pericarp. Heating at 176.5 °C for 16 min, the authors reported a 70.8% yield. In the USA, Ki et al. (2015) found that PEF treatment of primary sludge (PS) achieved microbial inactivation and enhanced conversion of PS COD to methane by 8%. Using ozone treatment to remove pesticide residues from wheat grains in Brazil, Savi et al. (2015) found 66.7% and 89.8% reductions in fenitrothion and deltamethrin respectively after a 180-minute treatment.

5. Factors influencing the adoption of emerging food-processing technologies.

This section uses the TOE framework to categorize adoption factors. The characteristics of a novel technology, and a firm's internal and external environments influence firm adoption behavior. Firm characteristics denote the internal environment of the firm. The external environment comprises suppliers and competitors within the industry, government, regulatory and financial institutions, and consumers.

5.1 Technological factors

Regarding technological factors, the extant literature provides evidence of 4 groups of factors: (i) available infrastructure/equipment to support technology; (ii) relative advantage or benefit of technology; (iii) investment cost; and (iv) information and development.

Concerning factor group (i), Joubert & Jokonya (2021) reviewed 67 papers of which 51% of the articles were studies conducted in Europe, Asia (24%), and North America (15%). Infrastructural availability to support the technology played the most critical role in adoption, with 76% of included studies in favor of this finding (Joubert & Jokonya, 2021). In Indonesia, Fauziana et al. (2023) provided empirical evidence of factors influencing PHL-reduction technologies' adoption in the mangosteen value chain. Using structural equation modeling with a sample of 35 processors (33 middlemen and 2 exporters), Fauziana et al. (2023) concluded that available infrastructure drives adoption at the 1% level of statistical significance. In a survey of 207 food processing firms in the USA of which 18.5% and 13.6% process cereals and fruits and vegetables respectively, 31.7% of responses cited that lack of quality equipment slows down adoption (Khouryieh, 2021)[4]. In another survey of 87 professionals from the food industry in North America (44%), Europe (21%), South America (14%), Australia and New Zealand (9%), and Asia and Africa (12%), Jermann et al. (2015)[5] observed that 53% of the responses claim high-quality equipment drive adoption.

Evidence regarding factor group (ii) is provided by Khouryieh (2021), Jermann et al. (2015), and Sharma et al. (2022). Khouryieh (2021) concluded that better nutrient/sensory quality properties of emerging non-thermal technologies are the most critical adoption determinant. This factor represented 71.1% of the responses from industry professionals and 30% of respondents cited better nutrient/sensory quality as the major factor influencing HPP technology adoption. Khouryieh (2021) also found factors such as shelf-life extension (39.3%) and technologies' ability to solve food safety problems (25.4%) are important. Jermann et al. (2015) claimed the main adoption drivers were better product quality (94%), solutions for product safety (92%), and shelf-life extension (91%). Sharma et al. (2022) opined that infrared technology is easy to adopt due to its highly secured priority score compared with microwaves, radiofrequency, and ohmic technologies. Khouryieh (2021) found that 11.9% of responses attributed their adoption reason to the technology's convenience. Of the 11.9%, 4.0% and 3.5% favored HHP and PEF respectively as the most convenient technologies. Jermann et al. (2015) also reported that 81% of responses cited convenience as a driver of adoption.

Relating to group (iii), Jermann et al. (2015) found that the cost of technology (96% of responses) was the most important limiting factor. Similarly, Khouryieh (2021) found that high investment cost (41.6%) was the biggest barrier to firm-level adoption. Khouryieh (2021) also reported that only 10.5% (lowest factor response) supported adoption due to cheaper prices of equipment.

Concerning the last group: information and development, Jermann et al. (2015) claimed that 58% of responses considered lack of information and training (53%) on novel technologies as adoption barriers. Likewise, Khouryieh (2021) reported that lack of scientific information about novel technologies (21.3%) and technology still under development, (35.6%) are other limiting factors of adoption. Table 2.0 summarizes the relevance of technology-related factors for adoption.

Factor	Specific factor	Adoption factor relevance (% of sample)	Reference
Available infrastructure	Infrastructural availability	76.0	Joubert & Jokonya (2021)
	Lack of quality equipment	31.7	Khouryieh (2021)
	High-quality equipment	53.0	Jermann et al. (2015)
	Better nutrient/sensory quality	71.1	Khouryieh (2021)

[4] In Khouryieh (2021), survey respondents made multiple selections of adoption factors.
[5] Multiple response choices were also used by Jermann et al. (2015).

Relative advantage	Better quality/added value	94.0	Jermann et al. (2015)
	Food safety solutions	25.4	Khouryieh (2021)
	Food safety solutions	92.0	Jermann et al. (2015)
	Shelf-life extension	39.3	Khouryieh (2021)
	Shelf-life extension	91.0	Jermann et al. (2015)
	Cost saving (water and energy)	79.0	Jermann et al. (2015)
	Cost saving (water and energy)	13.4	Khouryieh (2021)
	Convenience	11.9	Khouryieh (2021)
	Convenience	81.0	Jermann et al. (2015)
Investment cost	Cost of technology	96.0	Jermann et al. (2015)
	High investment cost	41.6	Khouryieh (2021)
	Cheap equipment price	10.5	Khouryieh (2021)
Information and development	Lack of information	58.0	Jermann et al. (2015)
	Lack of training	53.0	Jermann et al. (2015)
	Lack of scientific information	21.3	Khouryieh (2021)
	Technology still under development	35.6	Khouryieh (2021)

Table 2.0: Relevance of technology-related factors for adoption

5.2 Firm characteristics

Notable firm characteristics in the adoption literature can be classified into 3 main groups, namely: firm size, management, and resources.

Jermann et al. (2015) found that 81% of responses supported large corporations as drivers of innovation as opposed to medium-sized (47%) and small-sized (34%) firms. Similarly, Khouryieh (2021) asserted that large-scale food manufacturers (33.3% of responses) are better drivers of innovation than medium-scale firms (9%) in the USA. According to Joubert & Jokonya (2021), 64% of 67 articles reviewed claimed firm size influenced adoption, while 94% were in favor of management and 87% cited the firm's assets as influential. Only 15% of articles claimed human resources are crucial for adoption (Joubert & Jokonya, 2021).

Factor	Specific factor	Adoption factor relevance (% of sample)	Reference
Firm size	Large	81.0	Jermann et al. (2015)
	Medium	47.0	Jermann et al. (2015)
	Small	34.0	Jermann et al. (2015)
	Large	33.3	Khouryieh (2021)
	Medium	9.0	Khouryieh (2021)
Management	Top management support	94.0	Joubert & Jokonya (2021)
Resources	Firm asset	87.0	Joubert & Jokonya (2021)
	Human resource	15.0	Joubert & Jokonya (2021)

Table 3.0: Relevance of firm-related factors for adoption

5.3 External factors

Firms operate in a very dynamic external environment, shaping their operation and adoption behavior (Arifin, 2015). From the literature, external factors influencing adoption fall under 3 major categories: (i) government support/regulatory requirements, (ii) value chain actors (i.e., competitors and suppliers), and (iii) consumers.

Government/regulatory requirements crucial to firm innovation and adoption decisions are political, economic, and environmental. Wang & Tang (2004) asserted that the mandated cessation of methyl bromide fumigation by 2005 in the USA due to environmental concerns led to RF's development. Khouryieh (2021) observed that 13.4% of adoption responses were because of government/regulatory requirements in the USA. Specifically, 5% and 3% of respondents chose HPP and PEF because of regulatory requirements. In a global survey, Jermann et al. (2015) found that 76% of responses for adoption were due to government/regulatory requirements and 61% because of environmental concerns. According to Joubert & Jokonya (2021), 63% of articles claimed that government policy influenced firm adoption. Lack of regulation is a limiting factor according to 53% of responses, while 80% asserted that the absence of government/regulatory approvals negatively impacts adoption globally (Jermann et al, 2015). Considering non-thermal technologies only, Khouryieh (2021) found that only 3% of responses, representing the lowest category, in the USA mentioned the absence of government/regulatory approvals as a limiting factor. Furthermore, Jermann et al. (2015) found that 61% of responses stated funding support as an adoption enabler. Khouryieh (2021) claimed that 13.9% of responses cited the lack of funding as a barrier.

Regarding the second group of factors: value chain actors (i.e., competitors and suppliers), Joubert & Jokonya (2021) observed that 81% and 88% of articles claimed that competitors and suppliers respectively drive firm-level adoption within the food industry. Finally, 96% of articles claimed that consumer behavior is critical for technology adoption (Joubert & Jokonya, 2021). These results are summarized in Table 4.0.

Factor	Specific factor	Adoption factor relevance (% of sample)	Reference
Government	Regulatory requirements	13.4	Khouryieh (2021)
	Regulatory requirements	76.0	Jermann et al. (2015)
	Lack of regulation	53.0	Jermann et al. (2015)
	Absence of regulatory approvals	80.0	Jermann et al. (2015)
	Environmental issues and waste	69.0	Jermann et al. (2015)
	Funding support	61.0	Jermann et al. (2015)
	Lack of funding	13.9	
Value chain actors	Competitors	81.0	Joubert & Jokonya (2021)
	Suppliers	88.0	Joubert & Jokonya (2021)
Consumers	Consumer behavior	96.0	Joubert & Jokonya (2021)

Table 4.0: Relevance of external factors for adoption.

6. Discussions

Regarding sustainability features, this study has identified three thermal treatments (i.e., Ohmic, radiofrequency, and microwaves) and one non-thermal treatment (i.e., PEF) from the literature as economically sustainable technologies. Nonetheless, the economic sustainability attribute can be said of other technologies covered in the study because their successful application for disinfestation and microbial inactivation maintains the economic value of products, and the shorter processing time associated with them could minimize input costs as depicted by the adoption relevance of the cost saving attribute in Table 2.0.

Again, as noted in Table 2.0, firms have adopted emerging technologies even though investment and equipment costs are reported to be high (Khouryieh, 2021; Jermann et al., 2015). Juxtaposing this finding with the derived benefits (e.g., better nutrient/sensory quality, cost-saving, etc.) could imply that firms are more likely to adopt a technology if their benefits outweigh the cost. This suggests that the main drivers of adoption lie in the benefits. For example, the quality retention or food safety solutions offered by these technologies ensure better consumer-focused products, which may boost the firm's return on investment upon adoption. This implies that despite the high initial investment cost, the adoption of these novel technologies could serve as a profit maximization strategy in the long run.

Among firm-related factors, top management support is the most relevant factor of adoption (94% relevance). This is because management sets the tone for innovation, provides resources and strategic direction for profit maximization, and steers the change management that comes about during technology adoption. Relating to form size, the finding that large firms are more likely to adopt emerging food technologies compared to medium or small firms could be due to their larger firm assets which makes them benefit from economies of scale, thus reducing the per unit cost of technology adoption. Another reason could be the urge to maintain their market position vis-a-vis competitive pressure within the industry. The results also show that a firm's human resource pool is less crucial for adoption. This could be due to the specialized knowledge and standardized training required for operating and maintaining these technologies. Hence, there is a reduced need for extensive human resources allocated specifically to technology adoption and training.

Regarding external factors, it can be deduced that through regulations and policy instruments, governments play a leading role in creating an enabling environment for innovation and technology adoption. Therefore, the presence of regulations facilitates adoption while the absence of them slows it down as shown in Table 4.0. This is because potential adopters may be uncertain about the legal and financial risks associated with adoption in a regime without regulations. Both Khouryieh (2021) and Jermann et al. (2015) agree that regulatory requirements drive adoption decisions although there is a wide gap between the adoption factor relevance for regulatory requirements from both papers. This gap could be attributed to the sample representativeness or overlap or better still differences in government regulations available to processing firms surveyed in the different countries. Given that Khouryieh (2021) sampled firms in the USA while Jermann et al. (2015) conducted a global survey, the results could also imply that there are international regulatory discrepancies that may require standardization.

Observing the results on adoption factors through the lenses of the two most used technology adoption theories, e.g., the diffusion of innovation (DOI) theory (Rogers, 1983) and the collective approach model (CAM) (Dissanayake et al., 2022), the findings align with the innovation diffusion and adoption perception paradigms (Melesse, 2018) and thus highlight the technology's relative advantage in the DOI theory or perceived usefulness and ease of use in the CAM. The findings on available infrastructure support the economic constraint paradigm, the DOI, and the CAM, i.e., available capital resources and their compatibility with the new technology facilitate adoption. In line with the DOI theory, firm characteristics such as firm size or management shape the information-seeking behavior about the technology's perceived attributes (e.g., relative advantage), and large firms are better placed to obtain state-of-the-art information than small firms, which consequently influences attitude formation. Thus, firm-related findings also support the economic constraint paradigm and both theories, in that firm assets facilitate adoption and large firms have more of these resources than small firms. Findings related to external factors such as government support/regulations, value chain actors, and consumers shape subjective norms or facilitate behavioral controls towards firm adoption behavior, and this aligns with the CAM or the economic constraints paradigm.

It is also worth noting that the adoption or non-adoption of emerging technologies in agribusiness has implications for the SDGs. Therefore, this review proposes an extension of adoption theories by linking them to the pillars of sustainability with the view that technology adoption is a path to sustainable development. Thus, when firms adopt technology, it could bring about economic, social, or environmental change and sustainability. For instance, firms may adopt novel technology to reduce food waste, extend product shelf-life, reduce energy costs, or optimize water usage, thereby achieving the SDGs at the firm level. These achievements could motivate non-adopter firms in the social system to adopt later, implying that the adoption-sustainability nexus could be bi-directional. For instance, the mandatory phasing out of methyl bromide in some countries led to the development and use of radiofrequency. This implies that government regulations in favor of sustainability facilitate technological innovation and adoption.

7. Conclusion

This review has identified four thermal (i.e., microwave, radiofrequency, infrared, ohmic) and six non-thermal (i.e., ultraviolet radiation, pulse electric field, ozonation, cold plasma, high-pressure processing, and ultrasound) technologies for dried food postharvest management.

All the technologies are suitable for pest and microbial disinfestation within a shorter processing time with shelf-life enhancement compared to conventional methods. Thermal technologies are more suitable for insect disinfestation, while non-thermal technologies are more applicable to microbial inactivation. According to the extant literature, ohmic, radiofrequency, PEF, and microwaves are shown to be economically sustainable, while infrared, ultraviolet, ohmic, radiofrequency, microwaves and HPP facilitate social sustainability. Evidence exists for cold plasma, ultrasound, microwave, PEF, and ozone as environmentally sustainable technologies. Therefore, firm-level usage of these technologies could facilitate sustainable development (i.e., generate more profit for the firm, enhance public health, and reduce environmental stress).

Concerning the factors influencing their firm-level adoption, three main groups have emerged: (i) technology-related factors: infrastructure/equipment availability, benefit/relative advantage, investment cost, and available information; (ii) firm-related factors: size, management, and resources; and (iii) external factors: government support/regulatory requirements, competitors and suppliers, and consumers acceptance.

Industrial adoption of emerging technologies is still low due to a lack of information on their benefits, as provided in this review. Adoption factors itemized in the previous section were gathered from surveys, hence further research is needed to ascertain their relative importance econometrically in an adoption model. Given that firm characteristics influence adoption, characteristics such as firm ownership, age, absorptive capacity, and cooperative membership which could also influence adoption are missing in the current empirical literature and could be investigated in future research. Another task for future research is industrial case studies to clarify cost-benefit analysis between emerging and conventional methods and within emerging technologies, in terms of investment, installation, and energy costs. These analyses should be conducted under current economic conditions to elicit the return on investment associated with adopting these technologies. Again, although all emerging technologies require shorter processing times, there is a need for comparative case studies with conventional methods using similar/equal commodity quantities for further validation.

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