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Food waste: environmental impact and possible solutions

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Food waste-induced environmental damage has been a primary concern for environmentalists for decades. Several studies have proven that greenhouse gases emitted by food waste worldwide are causing more damage than coal power plants in some cases. Over the years, many solutions have been proposed, but the problem is yet to be resolved. This mini-review aims to discuss some of the recent solutions proposed by researchers around the world. A discussion about the effective campaigns intended to target specific demographics to encourage sustainable consumer behavior, successful models designed to implement a systemic production process, and sustainable waste management programs is presented. This study emphasizes taking successful small-scale campaigns and models and utilizing them on a larger scale. It will help reduce food waste by consumers and producers in the long term. Biohydrogen and biogas production through anaerobic digestion (AD) of organic food waste sounds very sustainable and interesting. However, the supply chain optimization, economics involved and land for installing AD, and low-value of the end-products are the challenges that need to be addressed.

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Sustainability spotlight

The food waste issue is one of the most significant challenges faced by countries worldwide. The fact that sustainable amounts of food are produced but not consumed by humans has substantial negative impacts environmentally, socially, and economically. Therefore, innovations in solutions are believed to cater to the increasing global demand for food waste issues. The present review highlights the sustainable, scientifically proven, and cost-effective global intervention that addresses the food waste issue and work aligns with the UN's Sustainable Development Goals on Zero Hunger and Responsible Consumption and Production. For the benefit of people and the planet, reducing food waste at retail, food service, and household levels can be one of the possible solutions.

1. Introduction

According to a recent study, 108 billion pounds of food is wasted in the United States each year, costing around $408 billion, and is nearly 40% of the food produced in the country; meanwhile, 38 million people face hunger in the same regions.[1] Food waste makes up 24% of landfills and 22% of combusted municipal solid waste, which negatively impacts not only economic efficiency but also the environment. It produces 4.4 gigatons of carbon dioxide annually, approximately 8% of the anthropogenic greenhouse gas (GHG) emissions.[2] This excess amount of food waste is a major obstacle on the path to sustainability. To supply a large quantity of food every year, a lot of resources such as land, water, fertilizers, and utilities are needed; however, most of those could be utilized for a different purpose if the food waste could be minimized. According to FAO, 23–24% of the total cropland, water, and fertilizers are used to produce foods that are being wasted.[3] The statistics in the European Union (EU), Australia, and China are no different; in China, 2500 kg CO_2-eq. t^2 is produced by household food waste;[4] in Europe, the economic loss due to waste is about $160 billion;[5] and in Australia, 57 507 Gg CO_2-eq is being emitted annually because of excess food production.[6] Waste treatment processes are not an economically viable solution and leave a big carbon footprint. According to a study conducted by New York City, the city had to spend more than $1 billion for solid food waste treatment[7] with similar numbers in other large states. Most of these cities use landfills for food waste disposal; however, the decomposition of organic matter produces carbon dioxide, methane, and hydrogen. Although carbon dioxide and

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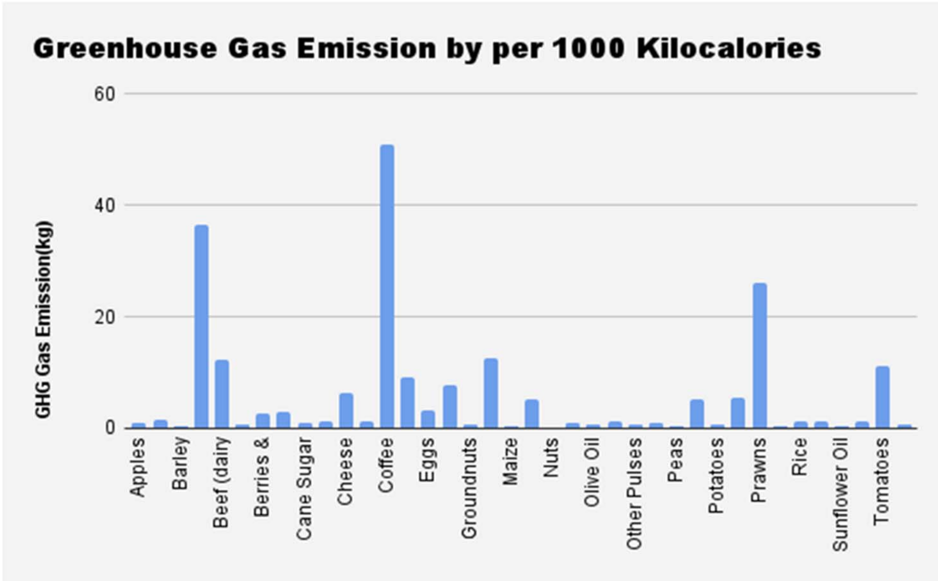

Fig. 1 Greenhouse gas (GHG) emission per kilogram of the food product.[9]

methane are the main gases produced, there are also smaller amounts of other gases that can be emitted. These gases may include trace amounts of volatile organic compounds, sulfur compounds, and nitrogen oxides. The migration of gas and leachate from landfill sites into the surrounding environment raises serious concerns such as air pollution, groundwater pollution, and climate change.[8]

As the world population grows and people's purchasing power increases gradually, the demand for quality food is also increasing. However, to battle food scarcity, keep up with the competition, and provide a variety of options, agricultural corporations and farmers are producing and processing more food than needed. Supplying food in sustainable ways is becoming harder every day due to the amount of uncontrolled GHG emissions (Fig. 1) during production and processing.[9]

50% of the world's habitable land pollution and 78% of the water pollution by nutrient-rich pollutants are caused by food production.[10] Therefore, to address issues such as water pollution, preserve wildlife, and minimize fossil fuel consumption, food production needs to be sustainable. However, the growing demand for fast production and heavily processed food is creating a major obstacle to preventing environmental damage.

One of the major problems with these emissions is the absence of advanced technology to reduce pollution. For example, to reduce the dependence on fossil fuels, renewable energy sources are being introduced, which can significantly lessen carbon dioxide production. However, we are yet to see such alternatives in the food production and supply sectors.

It has been long established that food waste is generating a significant amount of GHG, and it's important to address these issues and find a viable solution. This study aims to (i) identify the causes of the generation of food waste and (ii) explore practical and possible approaches for food waste mitigation. The idea is to provide an overview of the current state-of-the-art literature on food waste causes and possible solutions. It can help in designing the future research agenda. To fulfill these aims, the study collected the literature reported by researchers (mainly within the last decade) and analyzed the published data. Furthermore, the practice-oriented viewpoint offered by existing findings is discussed in this article. Many researchers suggest avoiding excess consumption and following necessary steps such as raising awareness, systemic production, and efficient recycling methods. These are discussed in detail in the following sections. We also address the challenges and future research. Many researchers suggest avoiding excess consumption and following necessary steps such as raising awareness, systemic production, and efficient recycling methods. These are discussed in detail in the following sections. We also address the challenges and future research.

2. Food waste sources

The food waste definition by the United States Department of Agriculture's (USDA) Economic Research Service (ERC) is "food discarded by retailers due to color or appearance and plate waste by consumers.[11] Food waste is grouped into three different types: (i) avoidable waste, food that was edible at some point in time but has become inedible by the time it reaches disposal; (ii) unavoidable waste, food items which are not edible, such as eggshells, come under this category; (iii) potentially avoidable food waste, which refers to a waste that is consumed at times but not always such as potato skins.

Food waste is generated (at the household and consumer levels) mainly due to irregularities in consumer demand, aesthetic preferences, and unsuitable storage or packaging. A major portion comes from the household level. In the household stage, food waste could be mainly due to over-preparation, over-purchasing, storage problems, date label confusion, large portion sizes, and unsuitable packaging.[11,12] In contrast, at the consumption level food waste is generated by the catering and hospitality (mainly at hotels, restaurants, hospitals, schools, and airplanes) sectors. In this case, food waste can occur either during the preparation phase or during the consumption phase. The preparation phase includes large portion size, bad storage, over-preparation, and expired products, while the consumption phase includes customer leftovers and over-ordering.[13,14]

The food service industry also generates a good quantity of food waste, and it is difficult to generate food waste estimates for the service industry.[15] It is due to the diversity of out-of-home environments in which food is consumed. The service industry includes restaurants, hotels, coffee shops, cruises, events, street food vendors, *etc.* Food waste in the service sector is mainly represented by plate waste. Traditionally, customers are held responsible for this waste; however, service industry administration and employees also contribute to this waste.[16] A study by Filimonau *et al.*,[17] revealed that plate waste was caused by customer over-ordering and by the large size of food portions offered by restaurant operators. The food service administration used large portions (for almost the same price) to gain a competitive advantage as they claimed large-sized meals were appreciated by customers.

A few reports[18,19] suggest that price promotions (buy one get one free) and low value of food items also trigger food wastage. It might be difficult to assess the relation between consumer behavior and price. The least price-conscious consumers might follow the "buying a lot and wasting a lot" concept. The great abundance of food might be a reason for food waste as the concept of "buying more for less" might prevail. However, Graham-Rowe *et al.*,[20] revealed that consumer motivation to avoid food waste is mainly driven by disliking the thought of "wasting money". In general, consumers are not comfortable when food is wasted, or food remains unused. However, it is unclear how this led to either their behavior towards prices or their tendency to show frugality in purchase consumption. Therefore, a clear understanding of the relationship between consumer behavior and food prices needs to be explored.

3. Detailed solutions

3.1. Raising awareness

Raising awareness to promote sustainable food consumption has been one of the key solutions proposed by social scientists. However, there has not been much progress because of a lack of research on target demographics. There should be specific campaigns designed for different demographics. Food is wasted by harvesters,[21] households,[22] and service industries (*e.g.* schools and hospitals).[23] Specific campaigns, designed to target one demographic at a time, would make it easier to raise awareness. Campaigns should be designed not only to encourage consumers' sustainable behavior but also for producers.

The service industry is the third-largest source of food waste, and the main cause is plate waste, followed by storage, preparation, and serving losses.[24,25] Another study concludes that increasing consumers' awareness is the key to controlling food waste; factors such as knowledge and skills heavily impact people to make sustainable choices.[26] Foodservice administrations can engage consumers in food waste mitigation by using nudging interventions and monetary (dis)incentives.[27] Another option is to provide plates of leftovers to consumers for takeaway. If plate waste remains, it can be given to farmers for material or energy recovery.[28] This will however require the commitment and willingness of farmers to collect and process food waste. In addition, food service employees should be prepared to separate it *in situ*.

To influence consumers' behavior on a microlevel, an airtight and engaging campaign should be designed. A recent study conducted by Pinto *et al.*,[29] proposed a campaign to reduce food waste and encourage sustainable choices in the service industry. The researchers claim that this initiative was able to reduce waste by 15%. More than 70% of the student body and faculty of the college actively participated in the campaign.[29] To ensure a large sample size the study was conducted when the school was in session. Two types of menus were designed: (i) mixed, where larger portions of carbs were served with smaller portions of proteins cooked together and (ii) non-mixed, where both carbs and proteins were served separately with raw or cooked vegetables. The study was conducted in two stages. Stage 1 was to analyze students' waste management skills and motivations; stage 2 was to implement the changes through events such as creating and advertising the downside of food waste and peer advocacy. During the first stage of research, it was found that only 44% of the students believed that the institution should concern itself with sustainable waste management programs. It helped the researchers to conclude that there was a lack of knowledge and enthusiasm. Also, the study found that initially, 11% of the main course was wasted and soup waste was almost 20%. At the beginning of stage 2, handmade posters were placed near the tray slide. The bread and meat waste dropped by 55% and 42%, respectively, after the campaign. This showed that creating specific posters and placing them in "right" spots can help change consumers' behavior leading to addressing more specific aspects researchers were trying to improve (*e.g.*, asking people to take what they can eat). Next time, they encouraged the staff to serve smaller portions; however, during rush hours it wasn't efficient. This finding led to concentrating more on consumers and asking them to buy what they can eat without wasting. The result showed a decline in plate waste, and the unacceptable proportion of plate waste decreased by approximately 25% overall within 16 days (Fig. 2).

Food labels can also play a promising role in promoting sustainable food consumption. The current food labels only represent a date the manufacturers think the food will be best to consume; most of the time, the food remains perfectly consumable after the printed expiration date. However, most consumers lack knowledge, and they believe that the food is safe only until the expiration date, which leads to a great amount of food waste in the US.[30] Moreover, to prevent consumers from throwing out food after the expiration date, many states require producers to include multiple dates ("shelf life", "best buy" *etc.*), and the lack of standardized language in food labeling further increases unsustainable consumer behavior.[31] It is important to raise awareness about "how to read a label" and establish a standardized language for the labels.

Web-based methods are very practical solutions because of the accessibility and reach of technology in this century. Most

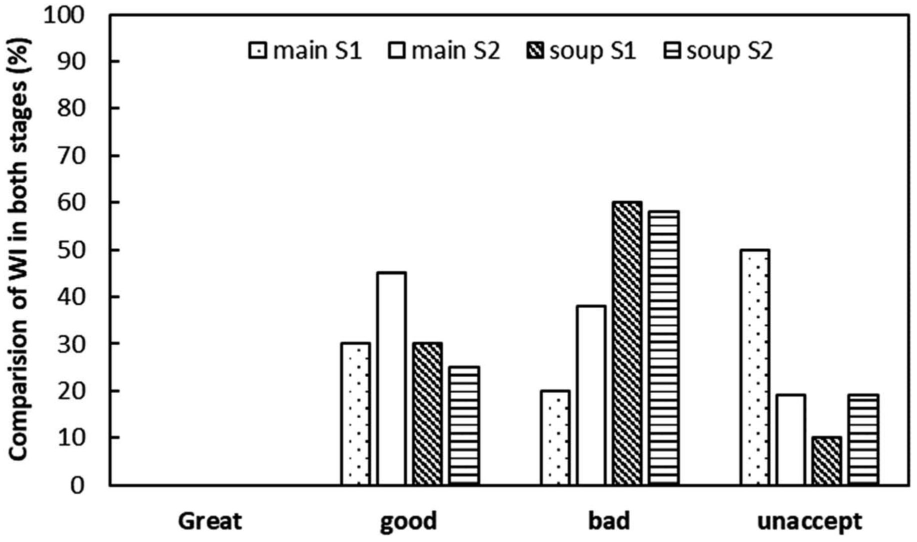

Fig. 2 Comparison of waste index (WI) before and after the campaign conducted by Pinto *et al.*,[29] (S1 and S2 represent stages 1 and 2, respectively). (Adapted with permission from ref. 29, 2022, Elsevier).

young and middle-aged people would be able to access this training without spending money on transportation or waiting for instructors.[32] However, many raise concerns about such training because of people's decreasing attention span and the gravity of the topic, and thus propose an in-person training system.[33] Another study argues that with time, web-based tools help increase efficiency and accuracy in reading labels, and it is an effortless and more convenient process than the controlled 1–1 learning system.

A recent study conducted by Miller *et al.*,[34] developed a web-based label learning tool, and they claim that the use of the tool improved the ability to comprehend food labels by approximately 79%. This study involved 140 college students who were divided into two groups: those with prior knowledge about label reading and those without any prior knowledge.[34] The training process was conducted in three steps. The first step was to inform the participants about how to read and navigate information on food labels, the second step required them to identify specific pieces of information on a food label, and the third step was to compare two different food labels and answer any follow-up questions. After completing the training, approximately 85% of the trainees reported the program to be easy to navigate, and 80% thought it was "very, very useful." Although the sample size was small, most of the participants were relatively young (<25 years). Thus, its effectiveness among the "older" demographic remains questionable.[34] However, such a method can be manipulated to accommodate and engage different age groups. This kind of program can be easily launched at any institution without spending a huge amount of capital on advertising.

3.2. Designing sustainable production models

A study conducted by the Department for Environment, Food, and Rural Affairs in the UK claimed that the solution to the food waste problem is sustainable production and consumption models throughout the food supply chain.[35] Another similar study claims that having "good intentions" isn't enough to reduce food waste because most of the waste is caused by systemic errors.[36] A study conducted by Warshawsky *et al.*,[37] found that approximately 25% of food waste is directly caused by "faulty" packaging, which makes it harder for consumers to empty the containers.

The amount of produced food waste depends on producers. Hence, it's up to them to design a model that can ensure food security without overproducing.[38] A study shows that one of the reasons behind food waste at the producer level is the desire to choose "aesthetically pleasing" contents to sell. A study shows that approximately 32% of food is wasted in the primary stage mainly because it does not meet the aesthetic scale while being perfectly consumable.[39]

A study conducted by Ribeiro *et al.*,[40] sheds light on the existence of high aesthetic standards and how a sustainable business model can be developed to address the issue and reduce food waste at the production level. During the study, the authors collaborated with a nonprofit organization that buys "ugly" fruits and vegetables and sells them in the market to save resources (*e.g.*, land, water, and power) from being wasted. They tried to understand the motivation behind these projects and used the gathered knowledge to design a sustainable business model. They developed a tri-layer business model (presented in Fig. 3), taking social, economic, and environmental benefits and concerns into account, and built a system to reduce waste. However, due to the subjectivity of the topic, it was hard to quantify the impact.

The business model is based on a replication scheme that involves taking advantage of fixed structures available in an area (*e.g.*, transportation, farmers' network, and stuff). Since this model emphasizes using local sources, the price remains relatively low since the produced food is not up to "aesthetic" standards. However, for this kind of model to be considered successful, there should be enough revenue; the study explores

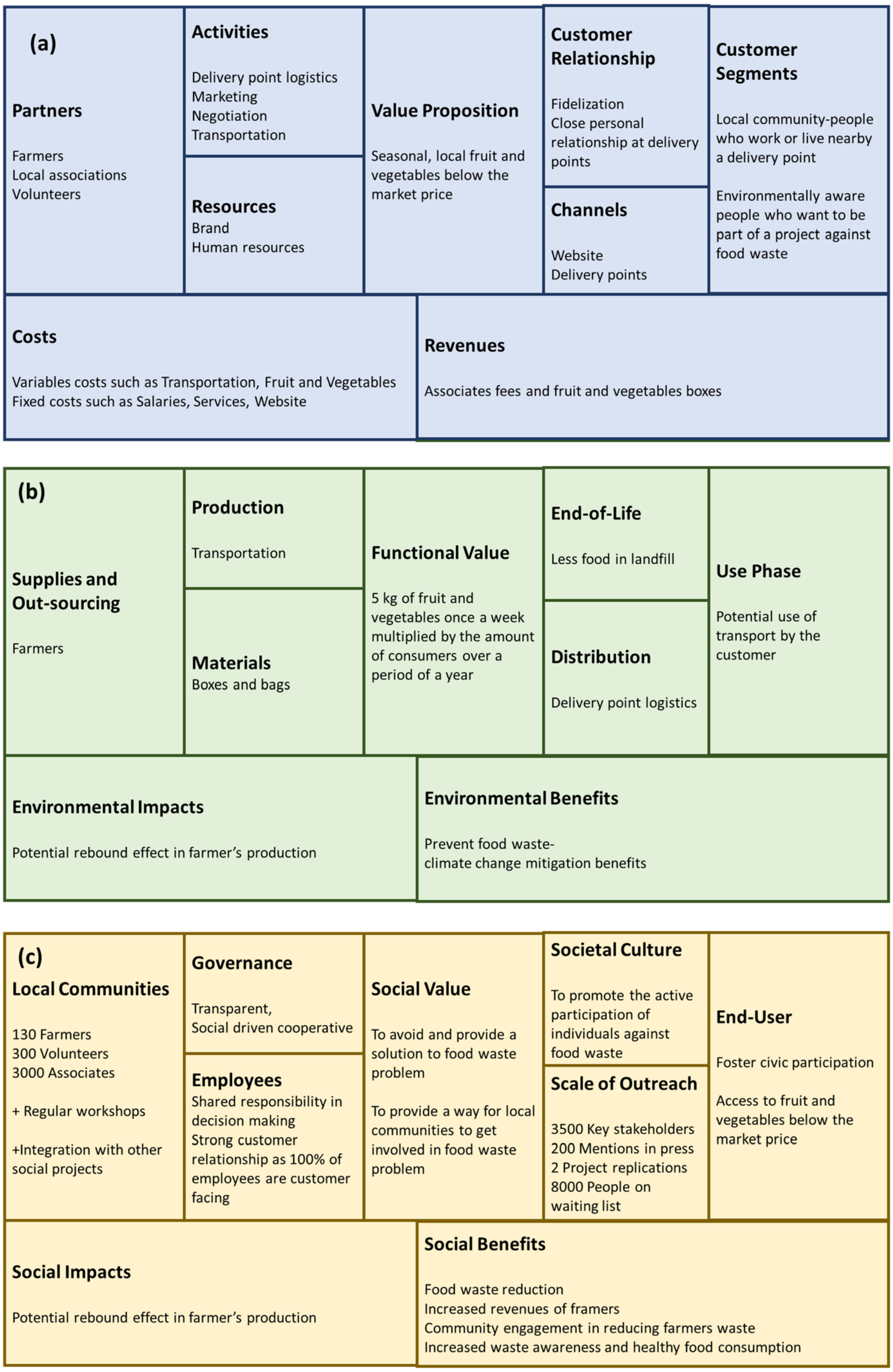

Fig. 3 Tri-layered business model: (a) economic layer, (b) environmental layer, and (c) social layer. (Adapted with permission from ref. 40, 2022, Elsevier).

the economic viability of the program and found that although the profit margin is low, this locally driven project can return the investment and generate profit as the delivery point increases. It also helps reduce GHG emissions locally, which would be caused by freshly produced fruits and vegetables otherwise.[40]

An impact assessment in CO_2-eq for the total amount of waste avoided for one year is shown in Table 1. The results show that the model had a positive impact of 0.14 kg CO_2-eq per kg considering the balance between transport and materials and avoided landfill scenario. This means for 1 kg of fruit and vegetables 0.14 kg CO_2-eq emissions can be avoided.

During the social assessment of the proposed model (Fig. 3), it was found that the farmer's salaries were slightly above the average in the region; however, it was rated poorly regarding the working time required of the staff. It was able to create jobs in

Table 1 Impact assessment of the project for one year and one region. (Adapted with permission from ref. 40, 2022, Elsevier)

Life cycle phase	Resource	CO_2-eq, kg
Production	Fruits and vegetables	132 343
	Materials (boxes and bags)	4796
Transport	Van	47 664
End-of-life	Landfill	76 867

areas where the fruits were delivered and where the foods were being produced. Community involvement is considered the key factor behind the success of the proposed business model.[40]

Another investigation, led by Lindh *et al.*,[41] found that several changes need to be made in the current packaging system to reduce food waste. Incorrect or inconvenient packaging by producers makes it harder for retailers to handle and more difficult for consumers to use sustainably. They propose using materials that are hard to damage during unloading and handling in retail, easy to open, easy to store, and realistic in size for consumers.

A study conducted by Pauer *et al.*,[42] claimed that a successful framework must address three important issues regarding food packaging: sustainable packing processes, environmental impact, and food loss due to packaging. A recent study in the UK showed that 20–31% of beef was wasted due to packaging and a notable amount of pork was thrown out in its original packaging.[43] A study led by Rivera *et al.*,[44] proposes a packaging prototype to preserve meat and fruits. Their proposed framework not only addresses an innovative packaging technique but also takes the environmental and economic sides of the spectrum into account. Their solution contains a double-layer design with an outer sealed quad (Fig. 4). This design allows consumers to preserve food, by sealing it with an air vacuum. The researchers chose raspberries and beef to test out the design due to raspberries' soft texture and beef's direct impact on climate change. They carried out several experiments to test safety, damage reduction, shell-life extension, and environmental and economic viability. Some researchers want to completely transform the food packaging industry and incorporate biodegradable smart food packaging, which can withstand greater stress and provide real-time information about the state of packaged foods. Many suggest using radio-frequency identification (RFID) tags in packaging, which use an electromagnetic field to send real-time information about the product.[45] Others propose using freshness indicators that navigate the state of the product using chemical changes.[46]

A study conducted by Medina-Jaramillo *et al.*,[47] designed a smart biodegradable thermoplastic film using starch and glycerol with 5 wt% of nature extracts (*e.g.*, green tea and basil). They claim that the design is highly responsive to pH change and has high thermal stability (<240 °C) while being flexible and biodegradable. The antioxidant coating of the film transfers its properties to fruits and vegetables, and starch-based films are known for their ability to preserve food for a long time. The film containing basil was most sensitive to pH changes. Such a property is crucial because it indicates the change in acidity in packaged food. The color-changing property is mainly useful when detecting the presence of unwanted microbial growth in food. The designed films were fully biodegraded in 12 days after being discarded in soil. The designed films were also hydrophobic mainly due to the presence of tea and basil extracts along with starch. Both films reduced water vapor permeability and improved thermal stability and antioxidant properties

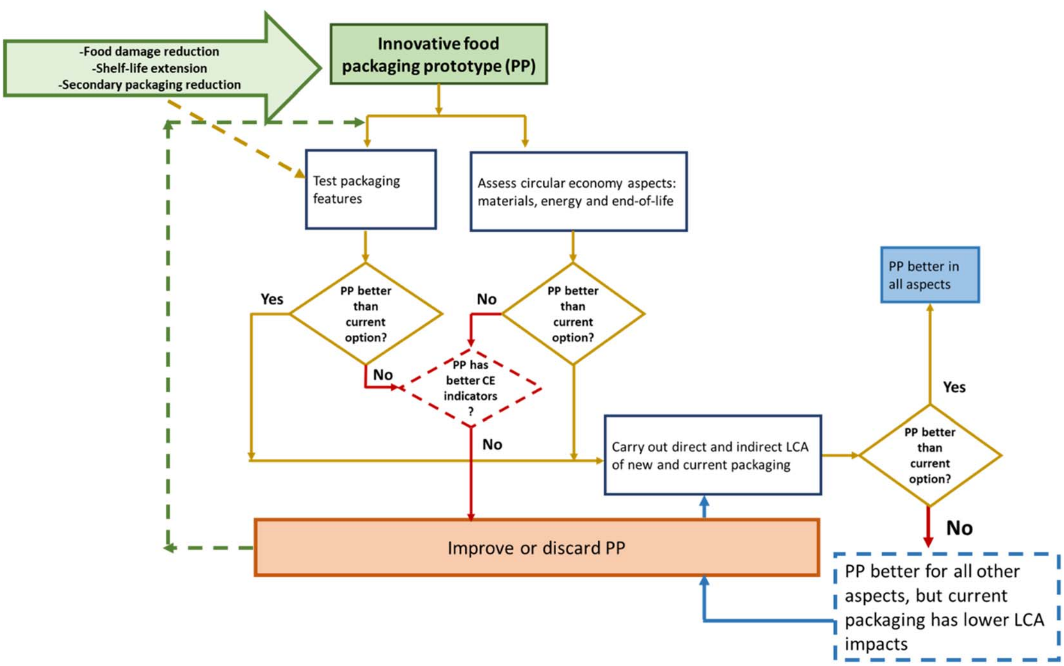

Fig. 4 Detailed methodological steps for the decision-support framework (CE: circular economy; LCA: life cycle assessment; and PP: proposed prototype).[44]

making them excellent food packaging materials to preserve food for a longer time leading to decreased loss of food because of "faulty" packaging.

To make commercially viable intelligent and biodegradable packaging, it needs to be low cost, reversible, reusable, and long-lasting. Probably, it might be more difficult to educate consumers about these packaging systems. However, intelligent packaging and the use of sensors have the potential to reduce food waste thereby improving food security. The aim of food safety and security must be aligned in a way to achieve sustainability. We need novel solutions for food security and sustainability without compromising food safety to achieve UN sustainable development goals such as sustainable land use, eradication of hunger and poverty, responsible production and consumption, sustainable life on land and water, and mitigating climate change. The changes in legislation and business behavior towards sustainable food production and consumption will be necessary to reduce food waste.

3.3. Efficient waste management technology

Despite all the attempts to reduce food waste in the earlier supply chains, there will always be food waste that will end up in landfills. However, current landfilling technologies are ancient and negatively impact the environment. Hence, many have been proposing upgrades to current waste management technologies to make them more environmentally viable without investing large capital.[48] Different studies over the years have proposed using organic food waste to produce hydrogen gas which is gaining popularity as a renewable source of energy.[49,50]

A study led by Jingjing *et al.*,[51] produced hydrogen gas through anaerobic digestion (AD) of organic food waste in a single-chambered microbial electrolysis cell (MEC) under negative pressure, yielding 96% of hydrogen gas. The food waste used in the study mostly consisted of rice (44%), vegetables (23%), noodles (16%), meat (6%), and tofu (11%) treated in a reactor that had one influent unit, pre-digestion unit, and combined AD-MEC unit. The entire experiment was performed under a negative pressure of 40.52 kPa at 30 °C.[51] A high salt environment was created to boost the rate of electron transfer in the system to increase density and eventually lead to greater hydrogen production. The hydrogen production in the reactor reached up to 511.02 ml H_2 g^{-1} VS (volatile solid) which is almost ten times the yield of "traditional" AD (49.38 H_2 g^{-1} VS) (Fig. 5).

The average recovery reached approximately 94% which is 4.7 times higher than the reported recovery rate of <20% in a study conducted by Beegle *et al.*[51,52] The significant increase in the yield rate is because of the presence of high organic matter (food waste) and salinity. The study also reports that energy recovery by AD-MEC was approximately 239%, which makes AD-MEC an excellent candidate for food waste treatment technology.[51]

Other studies suggest that using food waste to produce biogas is a more convenient and economically viable choice. A study conducted by Khoo *et al.*,[53] found AD to be the most environmentally viable food waste treatment technology available through the life cycle assessment method. An investigation led by Qianqian *et al.*,[54] studied the efficiency of single-phase anaerobic digestion (SPAD) and two-phase anaerobic digestion (TPAD) while using organic food waste as feedstock. The environmental performances of the two processes are shown in Fig. 6. In SPAD, food waste is treated in a single anaerobic tank, while in TPAD food waste is treated in two different stages *i.e.*, acidogenic and methanogenic stages. TPAD can achieve higher treatment efficiency and more stable operation than SPAD. The SPAD plant (S-plant) yielded 8.2% more biogas than TPAD; however, it used 43% more electricity in pre-treatment than the TPAD plant (T-plant), resulting in a production of −158.15 kg CO_2-eq/t by plant S, whereas plant T emitted −127 kg CO_2-eq/t. T-plant showed 66% higher elimination of acidic gases compared to S-plant and earned 10% higher revenue while spending less than S-plant.[54]

Both plants showed a decrease in carbon dioxide emission, which itself is an indicator of improvement in waste technology. Leaked methane from landfills has been identified as a major reason behind GHG emissions. However, this study claims that TPAD was able to achieve a 34% higher reduction of GHG than

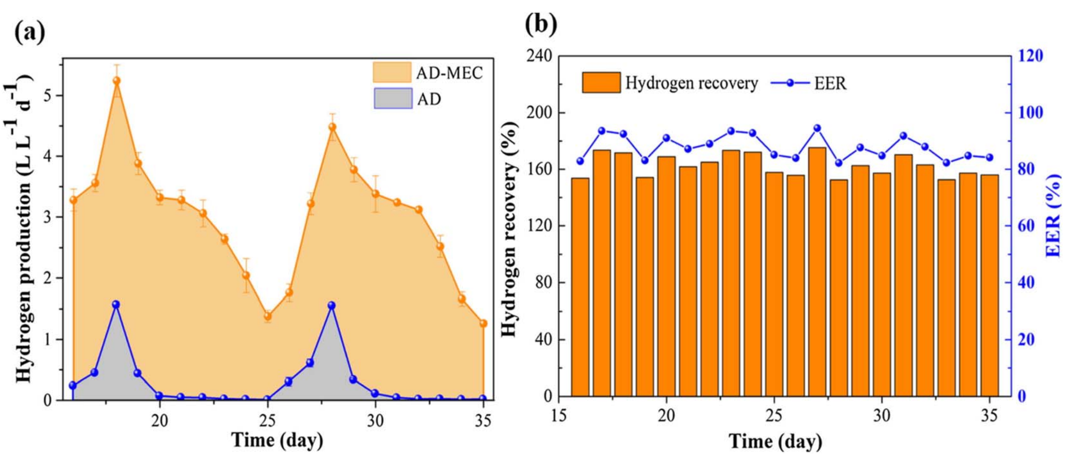

Fig. 5 (a) Comparison of the hydrogen production rate by AD-MEC and AD and (b) change of hydrogen recovery and electrical energy recovery (EER) for AD-MEC from days 16 to 35. (AD = anaerobic digestion and MEC = microbial electrolysis cell) (Adapted with permission from ref. 51, 2022, Elsevier).

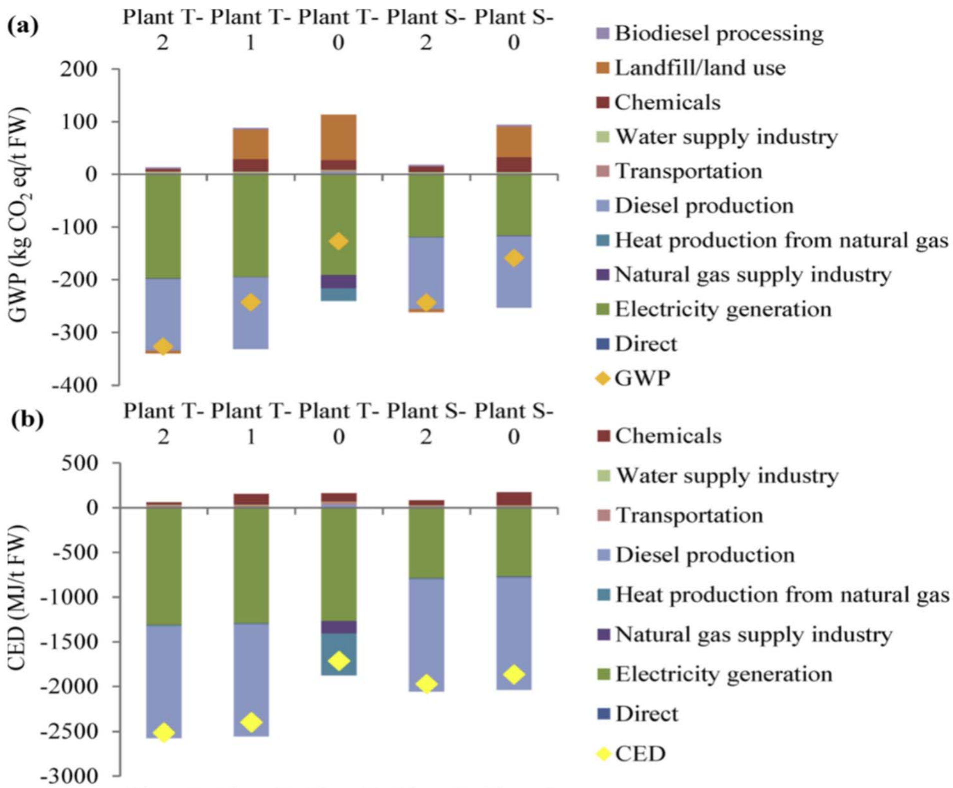

Fig. 6 Environmental performance of the two processes in different scenarios: (a) global warming potential (GWP) and the sources and (b) cumulative energy demand (CED) and the sources. The figures in the *x*-axis labels indicate the scenario number; scenario 0 indicates the real situation and the baseline; scenarios 1 and 2 mean improved processes. (Adapted with permission from ref. 54, 2022, Elsevier).

SPAD, which is a great achievement to achieve the goal of sustainability.[54]

Uen and Rodriguez[55] proposed an integrated model *i.e.*, a joint operation of AD and co-digestion (CoD) with a wastewater treatment plant (WWTP), to optimize the configuration and logistics for food waste valorization in Illinois, USA. The data presented show that installing anaerobic co-digesters at WWTP with a total capacity of 9.3 million metric tons could generate an 8.3% return on investment while reducing CO_2 equivalent by approx. 1 million metric tons annually. For long-term system planning and boosting food waste valorization, supply chain optimization along with land for installing AD are the factors that need attention.

4. Challenges and future research

Table 2 summarizes the challenges and future research for the discussed possible solutions to deal with the food waste problem. Although there have been many campaigns designed to address the food waste issue due to consumers' behavior, there haven't been many successful campaigns. Many studies over the year investigated such failures and found that most of the campaigns failed to create a sense of urgency among consumers,[56] most of them failing to recognize the target demographic. Most of the time, information-based technology fails to grab the attention of common people.[57] The two important factors that need serious consideration while designing a campaign are changing demographics, economics, and consumer convenience. Studies also suggest that web-based training programs are less effective in raising awareness because of a lack of feedback from instructors, short attention span, and technical issues.[58,59]

Although many studies suggest that smart packaging provides solutions to most of the existing complaints about food packaging, these studies fail to acknowledge the challenge from an industrial point of view. These smart packages aren't very cost-effective; their real capabilities on a large scale also haven't been studied; cyber security threats also arise from the "smart" technology. Also, most of the smart packages use artificial anti-bacterial elements, which could potentially lead to contamination, risking the quality of food. Also, the integration of thin film electronics in packaging is a big challenge for industrial production.[60,61]

Biohydrogen production sounds very sustainable and interesting; however, the problem lies in controlling the reaction environment while achieving higher efficiency and replicating small-scale production design on a larger scale without spending a significant amount of money.[62] Most studies failed to achieve higher energy conversion rates. A study conducted by Jayabalan found a conversion rate of 2.4–4% using biophotolysis to produce hydrogen.[63,64]

Biogas production is an efficient way to treat organic food waste; however, the implementation of biogas technology always suffers because of a lack of infrastructure, capital, and appropriate policy. Production of biogas on a larger scale and

Table 2 A summary of the challenges and future research related to practical solutions for dealing with the food waste problem

Proposed solutions for dealing with the food waste problem	Challenges	Future research
Raising awareness through campaigns and designing sustainable production models	• Lack of research on target demographics • Economics involved • Campaigns failed to create a sense of urgency among consumers • Technical issues related to web-based training and tools	• Evaluation of web-based training campaigns to read and navigate information on food labels • Design training programs to educate consumers about packaging • Development of low-cost, reusable, and long-lasting intelligent and biodegradable packaging
	• Faulty packaging • Lack of standardized language in food labeling	• An effective sustainable business model
Waste management through anaerobic digestion (AD)	• Food waste supply chain optimization • Land required and cost for installing AD	• Cross industry and public-private partnerships are needed along the food supply chain to implement the technology
	• High cost of food waste transportation • Digester construction and operation	• A deeper knowledge of biochemical pathways involved in the AD process along with process engineering is required
	• Low value of end-products • Precise control and effective troubleshooting of system instabilities	• Novel processes such as the possibility of integration of food waste facilities with a biorefinery to produce high value products need to be explored

transportation of biogas and converting it to energy have been challenges for decades now. There hasn't been a significant advancement in that sector.[65,66]

In the future, there should be research to address the challenges mentioned above. There should be a campaign designed to acknowledge the current shortcomings while making the campaign more interactive and relatable. Campaigns should involve people from target demographics to better understand the audience and design programs according to that.[29] Smart packaging is a very time-appropriate solution; a study conducted by Medina-Jaramillo *et al.*,[47] gives an insight into how biodegradable packaging, using only natural materials, can successfully incorporate smart technology. The use of eco-friendly materials for smart packaging can improve the quality of the products and will also contribute to the nutritional value of food. Also, in recent years, there have been many studies that are investigating the production of biohydrogen and biogas on an industrial scale without being cost-ineffective.[67]

5. Concluding remarks

Recent studies have proven that there are many solutions to food waste generation. Some studies address food loss at the production level, while others suggest incorporating environmentally friendly treatment of these wastes. To reduce supply chain waste, studies suggest designing "catchy" and informative campaigns, designing more sustainable packaging systems, and using the waste to generate more energy. Many other solutions remain unexplored; therefore, there should be more research on how to reduce the GHG emission from food waste every year. This paper suggests extensive research to identify the most desirable natural product for smart packaging along with national campaigns to raise awareness among citizens and review the existing packaging standards. The government should invest more capital in designing infrastructure to support environmentally friendly treatment of food waste.

Author contributions

Kirtika Kohli: writing – original draft preparation; writing – review and editing; Ravindra Prajapati: writing – original draft preparation, writing – review and editing; Raj Shah: writing – original draft preparation; Mrinaleni Das: writing – original draft preparation; Brajendra K. Sharma: conceptualization, writing – review, and editing.

Conflicts of interest

There are no conflicts to declare.

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