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Sustainable food upcycling: perspectives on manufacturing challenges and certification requirements for large-scale commercialization

Arige Nikhil Swaraj, [a] Jeyan Arthur Moses[b] and Loganathan Manickam*[a]

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Upcycled foods, a novel and rapidly growing food category, have gained significant attention from environmentally conscious consumers seeking to reduce their carbon footprint. While repurposing food leftovers has long been a common practice in lower- and middle-income households, it is now emerging as a structured approach to addressing global food loss and waste. With increasing awareness of these issues, food upcycling offers a promising pathway to combat food insecurity and promote sustainable food systems on a larger scale. This review explores the production cycle of upcycled foods, shedding light on key challenges and potential solutions to facilitate large-scale commercialization. Challenges such as non-homogeneous and inconsistent input supply, variability in input quality, consumer scepticism, and a fragmented regulatory landscape are analysed in detail. Plausible solutions are proposed, including co-product upcycling, verified supply chains, technological interventions, consumer education, and innovative marketing strategies. Additionally, the review emphasizes the need for unified certification and labelling frameworks to ensure transparency, build trust, and create a robust supply chain for upcycled products. Although often viewed as a waste management strategy, food upcycling has the potential to evolve into a formalized food processing practice, contributing to circular and sustainable food systems. Addressing manufacturing and regulatory hurdles is essential to unlocking this potential and achieving successful commercialization at scale.

Sustainability spotlight

The growing concern over food loss and waste, which contributes significantly to environmental degradation, underscores the importance of food upcycling as a sustainable solution. This work addresses the critical need to transform food waste into valuable products, by exploring the manufacturing challenges and regulatory frameworks necessary for the successful commercialization of upcycled foods. This review supports sustainable food systems that align with the UN Sustainable Development Goals (SDG) like SDG 2.4 – ensure sustainable food production systems to achieve – Zero Hunger, SDG 12.3 – reducing food wastes along production and supply chain including retail – responsible consumption and production. The solutions offer a pathway to reducing food waste, ensuring food security, and minimizing the carbon footprint of the food industry.

1. Introduction

The world is currently grappling with urgent global issues, particularly the rise in food insecurity and hunger. As of 2021, 828 million people are suffering from hunger, and this number continues to climb.[1] FAO estimates that approximately 1.3 billion tonnes[2] of food—around one-third of all food produced globally—is wasted every year, leading to significant environmental and economic costs. This waste occurs at various stages of the food supply chain, with about 40% lost at the consumer and retail levels and the remaining 60% at production, post-harvest, and processing stages.[3] This highlights the existence of two polarizing extremes: surplus food alongside increasing global hunger. Factors like growing food demand, crop failures, high cultivation costs and insufficient policy support have compounded the challenge.[4] According to research by the United Nations Environment Programme, about 17% of global food production is wasted, amounting to 931 million tonnes.[5] Of this vast amount, a significant portion is suitable for upcycling into valuable food products. It is estimated that at least 25–30% of food waste, which includes by-products from food processing and surplus food that is still safe for consumption, can be feasibly repurposed into upcycled foods (UF).[6]

[a]Department of Academics and Human Resource Development, National Institute of Food Technology, Entrepreneurship and Management – Thanjavur, Ministry of Food Processing Industries, Government of India, Thanjavur, 613005, Tamil Nadu, India. E-mail: loganathan@niftem-t.ac.in; Tel: +9104362 228155

[b]Computational Modeling and Nanoscale Processing Unit, National Institute of Food Technology, Entrepreneurship and Management – Thanjavur, Ministry of Food Processing Industries, Government of India, Thanjavur, 613005, Tamil Nadu, India

1.1. Theoretical underpinnings

The development and commercialization of UF products are intrinsically linked to the principles of the Circular Economy (CE), a systems framework aimed at minimizing waste and maximizing resource efficiency.[7] CE emphasizes reducing material use, redesigning materials and products to be less resource-intensive, and recapturing waste as a resource for manufacturing new products.[8] Within this paradigm, UF production addresses inefficiencies in linear food systems by reintegrating food-processing by-products, agricultural residues, and surplus materials into the value chain. This strategy aligns with Sustainable Development Goals (SDGs) such as SDG 2 (Zero Hunger) and SDG 12 (Responsible Consumption and Production), as it simultaneously mitigates surplus food and promotes resource optimization. Upcycling is strategically positioned within the food waste management hierarchy, operating as an intermediate solution that adds economic and nutritional value while preventing waste from being relegated to recycling or disposal pathways.[5,9,10]

To elucidate the adoption trajectory of UF technologies, Diffusion of Innovations Theory[11] provides a robust analytical framework. Critical factors influencing the diffusion process include the relative advantage of UF over conventional food systems, its compatibility with existing supply chains and processing infrastructure, and the complexity associated with integrating UF practices into standard manufacturing protocols. Early adopters, including sustainability-oriented enterprises and environmentally conscious consumer groups, are pivotal in advancing UF toward mainstream acceptance. However, operational hurdles, such as the heterogeneity of raw materials and scaling inefficiencies, necessitate technological innovations like co-product valorisation and adaptive manufacturing systems.[12,13]

Consumer behavioural dynamics concerning UF products are effectively modelled by the Theory of Planned Behaviour.[14] This theory posits that consumer intentions are shaped by three constructs: (1) attitudes toward UF (*e.g.*, perceived environmental, nutritional, and economic benefits), (2) subjective norms (*e.g.*, social expectations regarding sustainable consumption), and (3) perceived behavioural control (*e.g.*, affordability, accessibility, and product availability). While UF products are positioned as sustainable and innovative, consumer apprehension stemming from their "waste-based" origins poses significant barriers. Addressing these concerns through precise labelling, credible certification, and targeted communication strategies is essential to bolster market confidence and adoption rates.[15–17]

Stakeholder theory[18] further delineates the critical roles and interdependencies among actors in the UF ecosystem. Producers must address intrinsic challenges such as variability in raw material quality and consistency through the deployment of advanced processing technologies. Regulatory agencies must establish standardized certification frameworks and labelling criteria to ensure transparency and foster trust along the supply chain. Additionally, collaborative initiatives led by organizations like the Upcycled Food Association (UFA) aim to harmonize definitions, certify products, and enhance public awareness, thereby facilitating the scaling of UF production.[19,20]

By embedding UF production within these theoretical constructs, the industry can adopt a structured approach to address its multifaceted challenges. The interplay between technological innovation, regulatory standardization, and consumer engagement is crucial for advancing UF as a commercially viable and environmentally sustainable solution. This theoretical integration underscores UF's potential to progress systemic transformation within global food systems while adhering to the principles of CE and sustainable development.

1.2. Literature review

Research has gained momentum in the field of UF in recent years with a quantifiable number in publications. The existing literature on UF has extensively covered areas like consumer acceptance, food labelling, environmental sustainability, nutrition and food waste management, innovation, and consumer behaviour.

1.2.1 Consumer attitudes, purchase intentions and communication through labels. The driving factors for consumer choices for UF in Sweden include ethical concerns, natural content, and sensory appeal as key motivators. It is found that consumers who prioritize ethical factors are less hesitant to purchase UF, while sensory-focused consumers are more cautious.[6] Bhatt *et al.* (2021) emphasized the role of price sensitivity in decision-making, as consumers exhibit lower Willingness to Pay (WTP) for UF. Also, a rational and benefit-focused messaging approach was suggested to boost consumer acceptance.[16] Similarly, Stelick *et al.* (2021) observed that Italian consumers, particularly younger ones, showed increased purchase intent for upcycled products when sustainability messaging was included.[21] Grasso and Asioli revealed that consumers initially preferred conventional ingredients over upcycled ones. However, the study found that sustainability-focused messaging effectively appeals to environmentally conscious consumers, suggesting that such communication strategies have the potential to increase the broader acceptance of upcycled foods.[12]

Studies have also explored the effects of labelling and psychological strategies on upcycled food acceptance. Clear, single labels (*e.g.*, pesticide-free) enhance WTP, while multiple labels can reduce perceived value, suggesting focused labelling for UF.[22] Mental simulation techniques, such as envisioning future benefits, positively influenced purchase intentions, particularly among future-oriented consumers.[15] Sustainability claims significantly increased WTP for virtue products, reinforcing the effectiveness of sustainability narratives in the upcycled food market.[23] Together, these findings suggest that clear, strategic communication around sustainability, ethical benefits, and product value can enhance consumer attitudes and encourage purchase intentions for UF.

1.2.2 Environmental benefits and contributions to CE. Upcycling transforms food by-products such as spent grain, fruit peels, and sunflower cake flour into high-value ingredients, reducing methane emissions from landfills and conserving resources like water and energy.[24,25] Residues from juice production and grain milling now serve as raw materials for upcycled food, reducing environmental impact.[10]

These practices align with the principles of the CE, which aims to create regenerative systems by prioritizing reuse, recycling, and resource efficiency.[10,26] These initiatives also support SDGs, particularly SDG 12 on responsible consumption and production, by addressing inefficiencies in the food supply chain.[25] Integration of UF into the CE also depends on the active participation of global stakeholders, who play diverse roles in implementing circular practices. Connective stakeholders, such as intergovernmental organizations, facilitate networks that promote knowledge sharing and regulatory cooperation, enabling the scaling of upcycling initiatives. Integrative stakeholders, including businesses and innovators, expand the scope of circular food practices by developing responsible products that incorporate upcycled ingredients. Operational stakeholders contribute directly by implementing upcycling techniques at various stages of the production and supply chain, ensuring that waste is efficiently repurposed into consumable products.[13] However, the existing literature has not adequately addressed the novel challenges specific to the upcycled food production cycle, which are crucial for creating a large and sustainable food system.

1.3. Research question

This review seeks to address two primary research questions:

(1) What are the key manufacturing challenges faced by the upcycled food industry and what solutions can optimize production processes for large-scale commercialization?

(2) How effective are current certification and labelling frameworks in ensuring transparency, trust, and regulatory compliance for upcycled foods?

By addressing these questions, the review aims to bridge gaps in the current understanding of upcycled food production and propose actionable strategies to enhance the industry's scalability, consumer acceptance, and integration into circular food systems.

1.4. Methodology

1.4.1 Research design. This study employs a qualitative research design focusing on systematic literature review and thematic analysis. The aim is to identify key barriers and enablers in the UF sector, synthesize the current knowledge, and propose actionable strategies to address identified gaps. The methodology is structured to ensure alignment with the three research questions.

1.4.2 Data sources and keywords. A systematic literature review was conducted using multiple scientific databases, including Scopus, Science Direct, PubMed, and Google Scholar, to capture peer-reviewed articles, reports, and relevant documents. The search was supplemented with grey literature, including industry reports and standards from organizations such as the FAO, UNEP, and UFA.

The main keywords used in the search included "upcycled food", "manufacturing" OR "manufacture", "upcycling", "recycling" "food waste", "food leftovers", "repurposed food" "valorisation", "production", "challenges", "certification", and "labelling". Combinations of these keywords with the help of boolean operators like AND, OR, AND/OR, parentheses (), and quotation marks ("") are used to narrow the search.

1.4.3 Inclusion criteria. The study included sources that met the following conditions:

(1) Topic relevance: focused on upcycled food production, manufacturing challenges, certification, or CE principles.

(2) Publication type: peer-reviewed articles, industry reports, and relevant regulatory documents.

(3) Time frame: published between 2010 and 2023 to ensure up-to-date and relevant insights.

(4) Language: written in English.

1.4.4 Data analysis. The analysis involved thematic categorization of findings to align with the study's research questions. The themes were:

(1) Manufacturing challenges: focused on variability of raw materials, technological limitations, and supply chain inefficiencies.

(2) Certification and labelling: explored the gaps in regulatory frameworks, trust-building measures, and the role of standards.

(3) Integration into CE: highlighted stakeholder roles, scalability, and alignment with sustainability goals.

1.4.5 Limitations. While the design provided required insights, certain limitations must be acknowledged:

• Reliance on secondary data excludes real-time empirical findings.

• The absence of globally harmonized UF standards poses challenges in interpreting regulatory frameworks.

It is structured to provide a comprehensive understanding of UF. This review elucidates their pivotal role in the CE and food waste management hierarchy. It delves into diverse manufacturing methodologies, encompassing serial and co-product upcycling, which find application in both retail and industrial settings. Furthermore, it sheds light on certified commercially available upcycled products. This article tackles with manufacturing challenges inherent to UF, proffering potential solutions, followed by comprehensive analysis of certification and labelling requirements.

2. Definition of UF

UF is a novel category of shelf products[27] that use ingredients that are typically discarded as a primary component. Utilization of by-products from the main process line for making a completely new product or addition to an existing product creates a very high-value upcycled product. Utilizing these ingredients and integrating them into the mainstream products present a viable opportunity for commercial companies aiming to reduce costs, create high-value products and comply with Environmental, Social and Governance norms.[28] Despite significant market growth, the definition of upcycled food remains vague due to limited involvement of food authorities

Table 1 Varied definitions of UF

Definition	Title or organization	References
"Food upcycling refers to creation of high value-added products by adding values and ideas to previously discarded agricultural products"	Review of food upcycling in South Korea: regulation, limitation, prospects	42
"Ingredients that otherwise would have not gone for human consumption are procured and produced using verifiable supply chains and have a positive impact on the environment"	UF Definition Task Force (UFDTF) convened by UFA	29
"Upcycled food products elevate ingredients that would otherwise to higher uses and have tangible benefits to the environment and society"	Defining upcycled food products (a Delphi approach of responses from the perspective of manufacturers)	27
"Foods made from surplus ingredients or ingredients obtained for the manufacturing of other foods that would have been otherwise wasted"	From food waste to value-added surplus products (VASP): consumer acceptance of a novel food product category (based on the consumer responses to upcycled food products)	48
"Upcycled foods are made from food ingredients that have nutritional value and are useable but generally discarded"	Addressing food waste: how to position UF to different generations	44

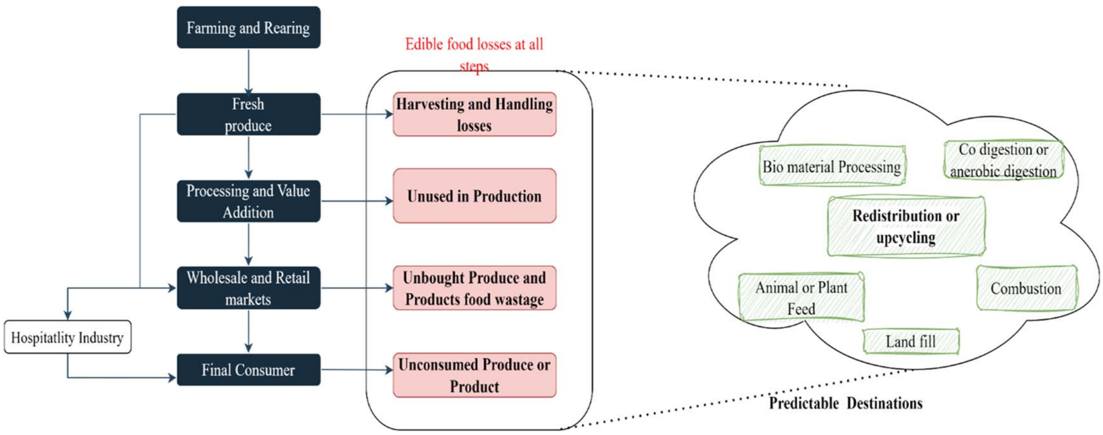

Fig. 1 Illustration of food losses at different stages from the farm to fork continuum (source: Nicastro & Carillo, 2021).[66]

and agencies. The Upcycled Food Definition Task Force (UFDTF), a task force established by Harvard Law School's Centre for Health Law and Policy Innovation, defines UF as edible products from "ingredients that otherwise would have not gone for human consumption are procured and produced using verifiable supply chains and have a positive impact on the environment". It also refers to transforming food leftovers, food surplus and other potentially unused ingredients and industrial by-products (peel, bran, seeds, *etc.*). UFDTF emphasized that UF should be value-added products, sourced from certified supply chains and accurately labelled with all ingredients.[29] A comprehensive compilation of alternative definitions given by various researchers is given in Table 1.

Food waste is quantifiable at all stages of the supply chain, including pre-consumer and post-consumer stages. Fig. 1 illustrates the different types of food wastage that occur along the farm to fork continuum. The current utilization of this food or feed is primarily limited to animal or plant feed and redistribution within the edible food losses vertical (refer to Fig. 1). The lack of coordination among the stakeholders throughout the production-to-consumer vertical poses a major challenge in curtailing food losses. UF offers the opportunity to create value-added products from various stages of the vertical, ensuring that they are safe and viable for human consumption without allergic and harmful substances.[29]

2.1. Working definition

Upcycled foods are products made from surplus or discarded ingredients that retain nutritional value, created through verified supply chains to ensure safety and quality. These foods reduce waste, promote sustainability, and deliver tangible environmental and social benefits while supporting circular food systems.

3. Role of UF in the CE and food waste hierarchy

The linear economy, based on the principle of 'take, make, and dispose,'[30] has dominated industries for decades. However, growing resource scarcity and increasing global consumption patterns have raised concerns about its long-term sustainability.

Like other sectors, the food industry follows a linear resource flow, leading to significant surplus food and limited recycling efforts.[1,7] Transitioning to a CE model offers an alternative that prioritizes resource efficiency and waste minimization but poses substantial challenges for the food sector.[7]

Currently, the food industry's integration into the CE remains at an early stage, though it holds considerable potential for improvement. Moshtaghian *et al.* (2021)[9] proposed a five-step hierarchy of food waste management, beginning with prevention and ending with disposal. Within this framework, upcycling is positioned between the reuse and recycle stages, emphasizing its role in creating sustainable food systems (Fig. 2A).

According to the hierarchical structure of the food waste management system, food upcycling is to be placed right above the animal feed, because the stages below the animal feed usage are inedible for human consumption. Upcycling comes after the stages of redistribution and prevention, where processed and redistributed foods are just given as charity. It is better depicted in Fig. 2B by the structure of the food hierarchy.[9]

The recent traction in the upcycled food industry is driven by the desire to meet the ESG norms and achieve the objectives of SDGs 2 and 12. However, the industry faces inherent constraints of a poorly governed supply chain, the presence of perishable produce and inconsistent yields.[31] With these hurdles in place, the commercialization of production and distribution becomes cumbersome. To overcome these challenges, food technologists and scientists have made significant contributions to finding new ways for the reutilization of waste products and by-products from food processing industries. This is evident from the scientometric evaluation under the umbrella term "UF" which has seen a great uptick from the year 2019 to the year 2022. This indicates the amount of recognition and

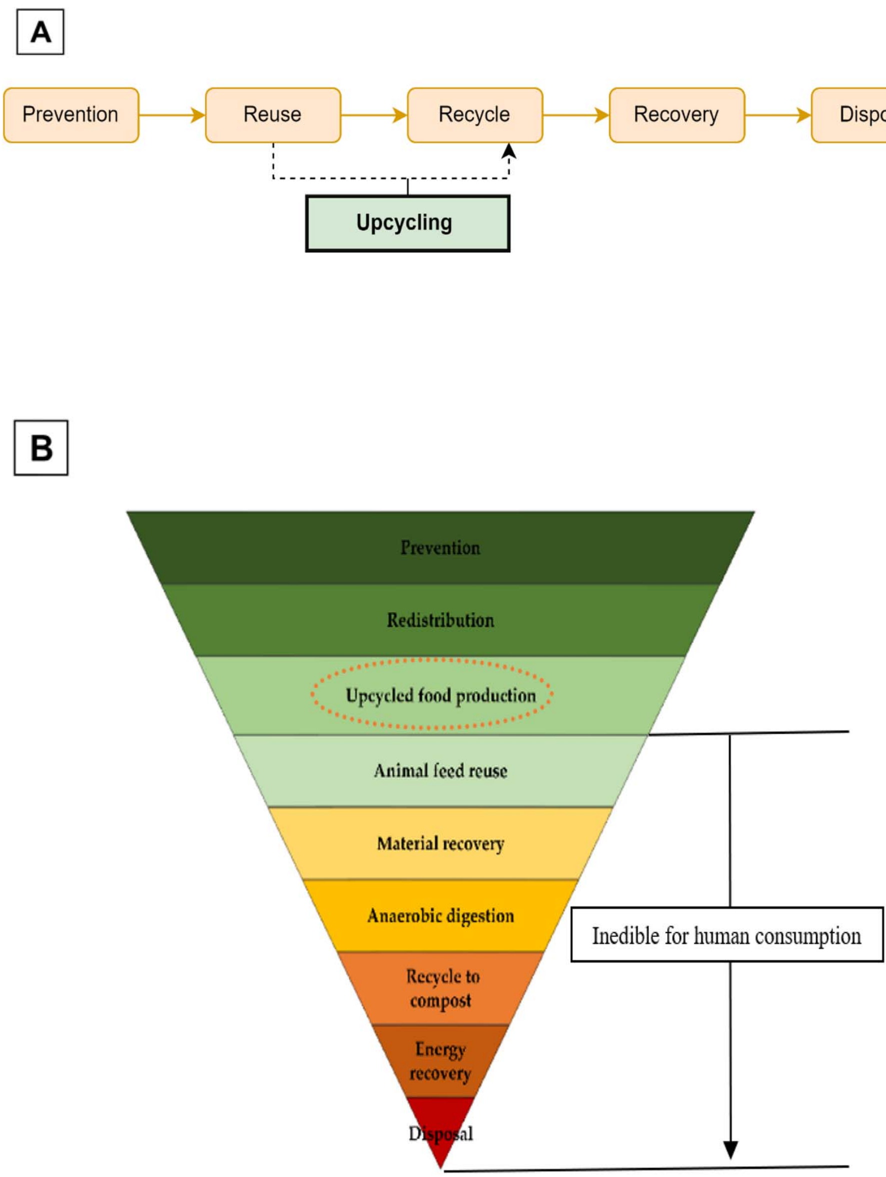

Fig. 2 Role of upcycling in the food waste management hierarchy. (A) Upcycling of waste in the waste management flowchart.[67] (B) Placement of upcycled food production in the food waste management hierarchy (source: Moshtaghian *et al.*, 2021 [9]).

conscience among the community in finding alternatives to recycle waste.

4. Manufacturing methods for producing UF

The food recovery hierarchy of the Environment Protection Agency (EPA) (Fig. 2B) emphasizes source control to mitigate food waste. Different methodologies are used to tackle both sides of the problem, employing tailored approaches. Two primary types of upcycling methods can be distinguished: co-product upcycling method[32] that is most commonly used in the upcycling manufacturing or production line and serial-product upcycling method[33] that is primarily employed in the retail operations side.

4.1. Co-product upcycling

Co-product upcycling (CU) is a production methodology used in industries to derive additional value from by-products generated during the processing of a primary product. It involves utilizing these by-products as input raw materials for secondary production lines. The secondary production line facilitates the transformation of waste materials into new products through optimized and streamlined processing steps.[32]

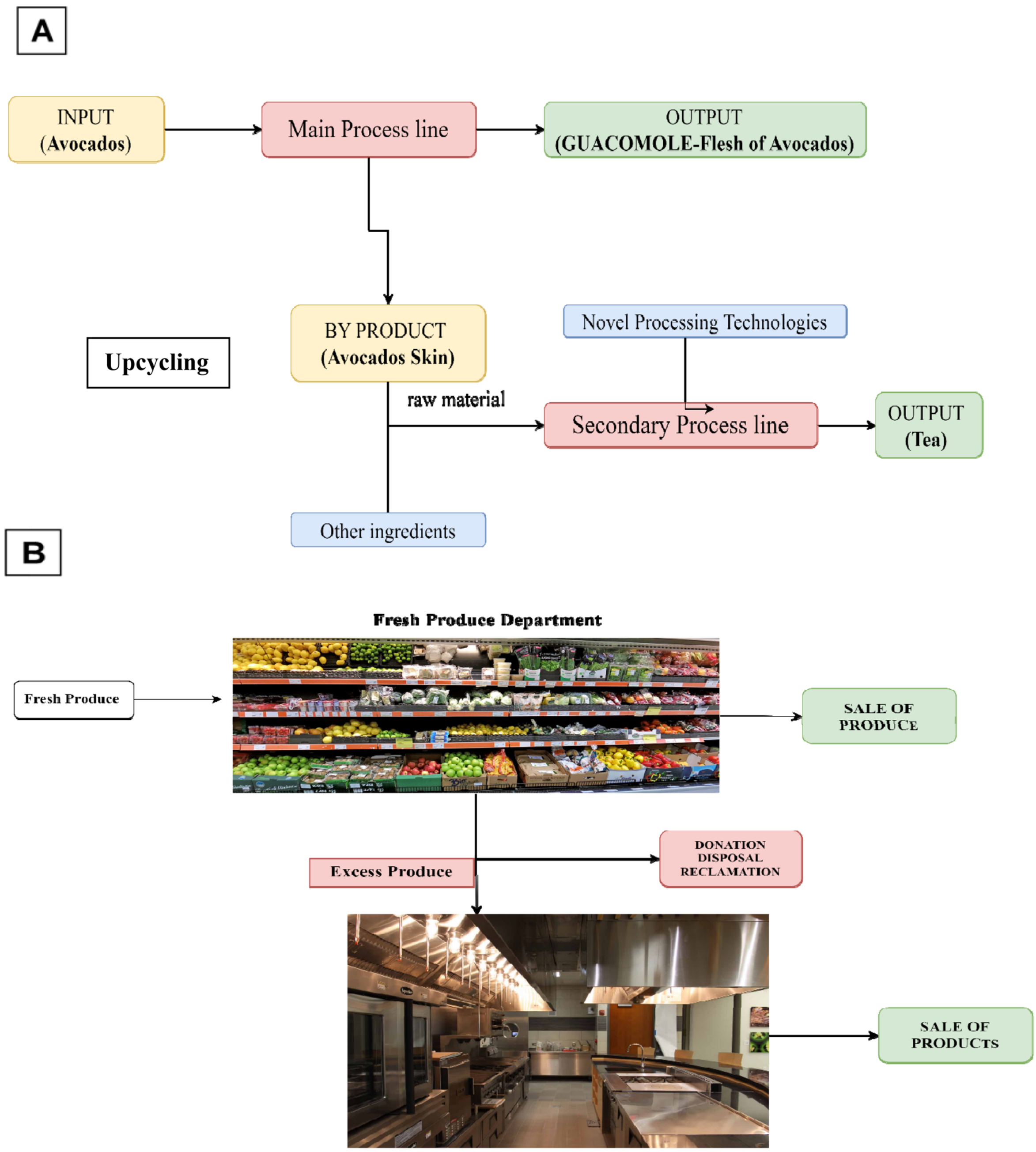

Fig. 3 Types of food upcycling methods. (A) Co-product upcycling of avocado skin (redrawn from ref. 33 and 34). (B) Serial product upcycling in retail operations (redrawn from ref. 33).

CU is an effective production strategy that facilitates the commercialization of UF by transforming waste generated during the primary processing line into raw materials for the secondary production line, resulting in the creation of a secondary product, also known as the "co-product". An exemplary instance of CU is the production of guacamole, where the skin of avocados, typically discarded as a waste by-product, is repurposed into avocado skin tea in the secondary line (Fig. 3A).[34]

Talens *et al.*[35] examined the potential utilization of by-products generated during orange processing from the production of orange juice and other related products. This study focused on extracting various valuable components such as polyphenols, carotenoids, and other bioactive compounds. Additionally, the researchers explored the extraction of fibre from the by-products using a combination of hot air and microwave drying techniques, resulting in a fibre product comparable to commercially available products.

In the CU production line, the waste generated by the primary processing line is consistently utilized as the input raw material for the secondary processing line. Additional ingredients and innovative technologies are employed to ensure the continuous production of both the primary and secondary products. This approach enables synchronization between the two production processes, mitigating the concern of inconsistent raw material supply, which is a significant challenge in the commercialization of upcycled products.[6] Detailed discussion on the latter challenge is provided in the subsequent sections.

4.2. Serial product upcycling (SU)

SU is a food upcycling method implemented during retail operations to address surplus and perishable inventory that remains unsold by the end of the day. This method stands as the sole known approach capable of generating value-added products from such excess inventory.[36] It is essential to effectively manage this surplus inventory, transform it into high-value products, and ensure profitability for the company while minimizing retail losses and addressing disposal challenges. Lee *et al.*[33] conducted a comprehensive study on upcycling within a retail store setting, highlighting how serial product upcycling serves as an alternative to mitigate issues arising from demand fluctuations and perishable produce.

In the retail sector of food operations, ensuring customer convenience has always been a priority. This convenience is often achieved by maintaining a stock of fresh produce that exceeds the current demand. Consequently, there is often a surplus of fresh produce that is either past its sell date or has lost its freshness. Fresh produce has a limited shelf life and requires suitable environmental conditions to prolong its freshness. Approximately 17 percent of food loss and waste can be attributed to the retail and consumer sectors.[1] Addressing this unsold and unconsumed fresh produce is essential, as it allows for mitigating food losses and financial losses recorded on the balance sheet.

In their work on SU or by-product synergy,[37] the reduction of surplus leftovers in retail by focusing on two departments: the fresh produce department and the food preparation department. The Fresh Produce Department deals with surplus inventory of fresh produce that has passed its sell-by date. To minimize waste, this surplus is transferred to the Food Preparation Department, where it is transformed into new food products, such as apple pie or banana cake. This process serves as an additional source of revenues and increased profit (Fig. 3B).

However, challenge arises as the Food Preparation Department cannot solely rely on the excess leftovers from the Fresh

Table 2 List of notable commercially available upcycled food products[a]

Company	Activity	Products
Barnana	It upcycles the food waste of bananas and their plantains into banana snacks and chips	(1) Organic plantain scoops with rowdy ranch flavour (2) Organic plantain scoops with Himalayan salt
Act Bar	It upcycles food waste cereal grains into a wonderful protein bar	(1) Cashew coconut bar (2) Peanut butter cocoa nib bar
Octonuts	It turns almond by-product waste from almond oil processing into a range of almond and walnut packaged products	Almond protein and walnut protein powder with different flavours
Pluck Tea	It produces tea products with several upcycled ingredients in tailored batches	(1) After dinner mint tea (2) Chocolate chai tea (3) Citrus ginger and Southbrook Berry tea
Harmless Harvest	It upcycles coconut meat into dairy-free products reducing coconut waste to zero	Alternative dairy-free yogurts with several flavours
Uglies Kettle Chips	It turns blemished and irregular-looking potatoes into chips in batches (kettle)	Potato kettle chips with different flavours
RIND snacks	It converts fruits waste into thinly sliced crispies	Products made out of kiwi, apple, orange, and coconut into thinly sliced crispy snacks
Spudsy	It makes upcycled fries from sweet potatoes discarded during farm operations	Sweet potato fries with different flavours
Chix Soup Co	This company makes chicken soups and broths out of unused chicken parts like feet and bones along with upcycled vegetables	Several types of broth with different seasonings

[a] Source: ref. 51.

Produce Department. Similarly, the Fresh Produce Department cannot over-order to sustain its operations. To address this issue, Lee *et al.*[33] designed a hybrid BPS approach. It reduces interdependence between both departments and allows each to optimize orders for both sides. However, despite the potential decrease in profits when viewed solely from the BPS perspective, there is no occurrence of overordering. On the other hand, when the sections are combined, the profit is higher compared to the fresh produce section alone.

Both types of upcycling, SU and CU, have been demonstrated as highly efficient and effective methods for utilizing by-product waste generated from both retail operations and production lines. The operational efficiency of these upcycling methodologies not only enables companies and industries to expand their market reach and profitability but also ensures compliance with ESG standards. Additionally, these upcycling practices address the issue of waste disposal in the food retail and production operations, contributing to sustainable waste management.

The UFA, an independent organization and stakeholder of the upcycling community, had certified a variety of food products that are exclusively made using ingredients derived from upcycled sources in both farm-side and retail-side operations. The list of commercially available brands in this field can be found on the brand list (Table 2). This compilation includes unique brands that offer upcycled food products commercially.

5. Challenges in the manufacturing of UF on a large scale

The upcycled food became the new dawn for several issues like climate change, food insecurity, and global hunger. However, upcycled food remains a "chaotic solution" unless the several setbacks in its production cycle are addressed accurately. In this paper, we aim to identify and outline the hurdles encountered during the production of UF. The review specifically focuses on the less commonly recognized challenges within the well-established and regulated field of the food sector. By doing so, we aim to shed light on the key obstacles that need to be overcome to improve the production of UF.

5.1. Non-homogenous raw materials and inconsistent supply

5.1.1 Challenge. A crucial step in the production of UF is the careful sourcing of ingredients from verified supply chains with traceable sources. According to the defined criteria for UF,[9,27] these should be exclusively made of only by-products that are not included in the main product for consumption. However, there are two significant challenges in sourcing input materials: finding verified suppliers and ensuring consistency in the quality and quantity of raw materials. When sourcing from sectors like hotel, restaurant and catering (HoReCa) and retail markets, the amount and quality of by-products may vary. The increase in supply chain vulnerability, driven by heightened supply uncertainty,[38] adds to the complexity. Manufacturers of UF heavily rely on excess or by-products from other food industries.[9] Consequently, the oscillation in the supply of the raw input material and the lack of consistency in the ingredient quality have emerged as major concerns in the push towards UF commercialization.

5.1.2 Prospective solution. Fluctuations in the supply of raw materials and the presence of non-homogeneous raw materials pose significant challenges to production lines in the industry. To overcome these issues, adoption of co-product upcycling, as illustrated in the types of upcycling, can be beneficial. Co-product upcycling involves integrating the primary processing line with a secondary upcycling processing line, where the processing by-product from the primary line is directly connected to the secondary line.[34] By doing so, we can mitigate the variations in input supply for the secondary line and effectively address the problem of non-homogeneous raw material supply. This approach minimizes the impact of these challenges by leveraging the regulatory procedures already in place for acquiring raw materials in the main processing line, reducing the occurrence of such issues to a near-zero level.

Additionally, by forming partnerships and collaborations with waste producing or collection companies, upcycling companies can ensure a consistent and year-round supply of byproducts, thus overcoming the limitations imposed by seasonal variations or unpredictable availability of raw materials. By leveraging the waste generated by partnering companies, upcycling companies can effectively mitigate supply chain disruptions, reduce waste generation, and enhance the sustainability of their operations.

5.2. Control of quality in the input

5.2.1 Challenges. Supply Chain Management in the food industry is so crucial for the aversion of risk or failure in the production line and ensuring safe food products for the consumer. The control of raw material quality is a key factor in determining product yield, as well as the quality and safety of the product in the production line.[39] Emphasizing the importance of raw material quality is paramount in both conventional and upcycled food industries. Most of the food borne illnesses are associated with multiple products produced (various items from diverse sources), accounting for 55 percent of cases, while single product produce (single source raw material) contributes to 45 percent of cases, highlighting the significance of high-quality input materials.[40]

In the case of UF, the input raw materials are typically sourced from multiple vendors or a single raw material aggregator who collects from various verticals like the HoReCa sector, food industries (without co-product upcycling) and retail markets (without serial upcycling).

5.2.2 Prospective solution. The problem is addressed by the already existing legislation in various countries, which aims to establish verified supply chains for the mainstream food industry. These laws are applicable to both conventional and upcycled food production, ensuring the quality of input materials. A concise overview of the laws and organizations addressing the issue of proper supplier verification has been tabulated in Table 3.

Table 3 Countries and laws towards raw ingredient safety and quality

Name of the law/ organization	Country	Interpretation of the law applicable to raw ingredients in foods	Reference
Food Safety Modernization Act (FSMA), 2011	United States of America	Establishment of hazard analysis and risk-based preventive controls (HARPC) Produce safety rules Foreign supplier verification program (FSVP) Produce transportation rules	(Public law 111–353—Jan. 4, 2011)
General Food Law Regulation (EC 178/2000)	European Union	Established safety limits for contaminants, microbes, and pesticides EU food hygiene law applicable to all novel foods with emphasis on traceability	70 and 71
Canadian Food Inspection Agency (CFIA)	Canada	CIFA ensures the compliance of suppliers with laws like the Foods and Drugs Act and Safe Foods for Canadians	Canada Food Inspection Agency, 2014
China Food Safety Law, 2015	China	Record keeping: it requires food ingredient suppliers to keep a record of the source of ingredients, date, and time of sourcing, and storage record	The Food Safety Law of the People's Republic of China, 2009
Food Standards Australia New Zealand (FSANZ)	Australia and New Zealand	It requires food suppliers to comply with laws pertaining to the Food Standards Code and Imported Food Control Act	Food Standards Australia New Zealand., 2005

In the context of UF, there is a need for specific and precise regulations that address the presence of contaminants, as the utilization of food waste by-products from industries requires scrutiny of ingredients for certification purposes. While individual laws may exist for conventional settings, UF necessitates more focused and stringent regulations from regulatory bodies. These regulations should establish defined limits for contaminants and provide guidelines for industries to identify suitable ingredients for the large-scale commercialization of UF.

The Upcycled Food Association (UFA), a non-profit organization based in Denver, Colorado, USA, is a consortium of companies dedicated to advancing the upcycling industry. The UFA aims to support industry growth and enhance public trust in upcycled products through standardization and advocacy. To this end, UFA has established a standardized definition for the term "upcycled ingredient" to ensure clarity and consistency within the industry. According to this definition, an ingredient can only be classified as upcycled if it is derived from at least 95 percent upcycled input and can consist of multiple inputs until the minimum requirement of 95 percent diverted material is met. Furthermore, the UFA has established a comprehensive database of certified upcycled ingredients, which enables the emergence of new industries and the use of the upcycled ingredient label. In addition, the UFA has implemented a vendor certification program, whereby vendors can register as certified upcycled vendors following an assessment conducted by the association, which ensures compliance with verifiable supply chain requirements.

5.3. Consumer perception and awareness

5.3.1 Challenge. Consumer perception plays a crucial role in driving the sales of upcycled food products, surpassing other factors. Despite fulfilling the necessary criteria, the perception of consumers regarding upcycled food is a decisive factor that significantly impacts sales. Notably, Pasqualone *et al.*[41] found that the consumer perception of upcycled food quality is often negative due to alterations in sensory attributes. For instance, when almond skin powder was incorporated into biscuits, resulting in a darker colour, consumers perceived the product as unappealing and unattractive. Moreover, Moshtaghian *et al.*[9] further discussed how consumer perception and awareness of this emerging category affect the overall acceptability of UF.

The limited recognition and lower public acceptance of UF can be attributed to the absence of regulatory authorities validating the assertions made by upcycled food manufacturers.[42] Additionally, there is a dearth of supervision concerning the dissemination of misleading information pertaining to the nutritional and environmental consequences of these foods within the novel food category, aimed at reducing food waste.[43]

5.3.2 Prospective solution. The wider acceptability of upcycled products as convenient shelf products in the market can be achieved through public awareness and proper labelling. Moshtaghian *et al.* 2020 and Zhang *et al.* 2021 (ref. 9 and 44) highlighted that consumer age and awareness play crucial roles in determining the consumer acceptability of upcycled products. Zhang *et al.*[44] found that Generation Z (refers to individuals born between 1995 and 2015) shows greater acceptance of upcycled products compared to Generation X (refers to individuals born between 1965 and 1979) and millennials, as the latter perceive such to be of lower quality when informed about their production as repurposed food products. However, various studies on consumer preferences have indicated that consumers are willing to embrace novel food categories when they are presented as reducing food loss or waste initiative. Grasso *et al.* in 2020 (ref. 12) reported that 85 percent of the consumer test subjects are willing to accept UF despite the forehand knowledge about it. This appears to be a positive step towards the acceptance of urban consumers in terms of overall acceptability. The environmental benefits of the upcycled products and their safety aspects are key factors to be used in product development and marketing to increase the acceptability over all age groups.[45] Grasso *et al.* (2019),[46] Grasso and Asioli (2020)[12] and Pasqualone *et al.* (2020)[41] have reiterated that the consumer perception can be changed by highlighting the environmental and nutritional impacts of UF on human health. They further noted that the consumer preferences and WTP have changed with slight changes in labelling instructions.[46]

5.4. Regulatory environment

5.4.1 Challenges. UF is a burgeoning category in the field, but the regulatory implications and norms surrounding it is still in the early stages of development. This innovative type of food is created using by-products that serve as inputs to produce UF.[27] In many countries, upcycling is viewed as a component of the food waste management hierarchy and is considered merely as a method for managing surplus waste.[9] For instance, in South Korea, upcycling is regulated under the laws governing food waste management.[42]

As discussed above, the lack of a suitable regulatory environment has created a lack of trust and awareness among the consumers in the UF market. It affects supply chain management risk in the production lines of upcycled products. It requires a proper regulatory compliance network and certifications are essential for the recovery and growth of the upcycled food industry. The growing number of commercially available upcycled food products also throws light on the requirement of stringent laws on this subject to deal with their re-utilization as edible products.

5.4.2 Prospective solution. The UFA, a stakeholder and first mover in the food upcycling industry, has already taken leap in establishing frameworks and guidelines with the help of certification and awareness programmes. The UFA detailed the steps to be followed to attain the certification of UF, which is discussed in detail in the upcoming section and devised several guidelines for companies to verify their supply chains for the registration of inputs as upcycled ingredients and products. The UFA has onboarded more than 30 companies as member companies that produce commercially available UF with the upcycled certified mark on the packaging. Government organizations around the world should distinguish UF as a separate novel food category and should work with organizations like the UFA to establish contours for upcycling products with permissible limits and guidelines as applicable for conventional foods abiding by the present laws and regulations.

5.5. Financial viability

5.5.1 Challenges. Financial viability poses a significant challenge to the extensive production of upcycled food, despite its appeal in terms of closing the loop of the linear model flow of resources and addressing global hunger and food crises. The conversion of byproducts into edible food products requires substantial capital investment at every stage of the process like collection, sourcing, sorting, processing, and packaging.[34,47] Each stage requires an investment of new infrastructure, new technology infusion and skilled human resource, which increases the overall cost of production higher. This capital-intensive nature of upcycled food production deters small and medium enterprises from entering the market. Moreover, additional costs and complexities arise from research and development efforts for upcycled product development, pilot testing, safety and quality testing, and regulatory compliance.

Consumer acceptance and price sensitivity are other factors that further impede the financial viability of upcycled food products.[4,16,48] While there is a demand for environmentally sustainable products, consumers are reluctant to pay a premium price.[16,49,50] This poses a challenge of market sustenance with a competitive pricing on par with traditional products.

5.5.2 Prospective solution. To overcome these financial challenges in upcycled food production, a multidimensional approach would be necessary. Here are some potential solutions listed below.

5.5.2.1. Partnerships and collaborations. By fostering strategic partnerships among stakeholders in the upcycled food industry, such as collaborating with organizations like the UFA, companies can streamline various aspects of the innovation process. This includes facilitating technology transfer, accelerating adoption, conducting prototype testing, and ensuring compliance with certification standards.[27,51] These partnerships also offer the opportunity to optimize supply chains and lower production costs by establishing strong connections with suppliers and retailers. Overall, such collaborations strengthen the upcycled food industry, promoting efficiency, sustainability, and market viability.

5.5.2.2 Government intervention. Governments have a critical role in promoting and achieving the SDGs 2 and 12 (ref. 5) by alleviating the financial burdens and offsetting the investment costs for industries. They can do so by implementing production linked incentive schemes, tax breaks and subsidies. Additionally, governments can encourage voluntary pursuance of upcycling practices in the food industry and gradually mandate as a regulatory compliance. As already discussed, this policy framework would distinguish the organized and the unorganized sectors, ensuring high standards for products. By implementing this measure, governments can effectively reduce the substantial capital investment required for research, production and marketing, thereby making sustainable products economically viable.

5.5.2.3 Consumer education and market demand. Consumer perceptions play a pivotal role in establishing upcycling as a financially viable choice for industry. However, a strong negative effect of neophobia, combined with limited knowledge about innovative technologies in food processing, is prevalent among consumers.[4,52] To overcome these challenges, consumer awareness campaigns are crucial for educating the public about the environmental and nutritional benefits of upcycled products. This, in turn, will positively impact the consumer perception and increase their WTP a premium price for these products.[16,50] Moreover, the subsequent surge in demand not only facilitates scalability but also leads to economies of scale, resulting in reduced production costs and lower cost per unit product due to increased efficiency and throughput.

In conclusion, overcoming the financial challenges associated with upcycled food production requires a comprehensive approach that emphasizes collaboration, innovation, and consumer education. By strategically addressing the cost factors, economies of scale, leveraging collaborations and capitalizing on market opportunities, we can pave the way for a sustainable future for the upcycled industry. As the market continues to evolve and innovate, adopting new innovative business models, fostering industry partnerships, and implementing supportive regulatory policies are crucial to unlocking the full potential of upcycling.

6. Novel technological solutions for the upcycled food value chain

Global perspectives of upcycled food highlight its significance in addressing the global challenges of food waste, environmental sustainability, and food security. It helps in reduction of surplus food and its associated environmental impacts like greenhouse gas emissions and resource depletion. With these global perspectives shifting towards environmental sustainability and resource optimization, innovative technologies have emerged to tackle the challenges associated with the entire upcycled food value chain. These challenges serve as critical junctures that can hinder the advancement of the upcycled food industry. This emerging category presents inherent technological hurdles, which can be overcome through the implementation of modern and novel technological solutions. By leveraging the general understanding of the upcycled food value chain and industry, we have compiled a comprehensive table that outlines these challenges alongside potential targeted technological solutions (Table 4). Furthermore, a broad estimation of the Technology Readiness Levels (TRLs) for each solution has been provided to gauge the maturity, readiness, and viability of the respective technologies within the industry. The TRL range of the respective technologies showcases their level of advancements in terms of developmental and implementational standpoints.

7. Scientific overview on upcycling

This section gives an overall idea of recent scientific studies converting an upcycling input ingredient to a secondary/intermediary input or final upcycled food product. It explores the innovative techniques and process methodology used to convert one or more upcycled ingredients to an intermediary input or food product.

7.1. Consumable final product

Pecan nut press cake (PNC) can be utilized as a co-product to enhance gluten-free cookies made from rice flour and corn starch. By incorporating PNC flour at concentrations of 15% and 30%, the cookies exhibited increased lipid, insoluble fiber, and protein contents, while reducing carbohydrates. Texture analysis revealed improved dough processing characteristics, with increased hardness and decreased cohesiveness. Baked cookies with PNC flour maintained desirable expansion factors but required higher cutting force due to elevated insoluble fiber levels. Overall, incorporating up to 30% PNC flour proved successful in developing gluten-free cookies with favorable nutritional and textural properties, offering a sustainable approach to upcycling pecan press cake.[53]

Ahmadzadeh *et al.* in 2023 (ref. 54) have shown the effective upcycling of imperfect carrots and broccoli from farms into attractive 3D printed food products. Freeze-dried powders were added to the wheat flour formulation at 50 and 70 percent. It is observed that the printed snacks show high homogeneity with progressive addition of fruit powders. Further, they show shear thinning behaviour suitable for extrusion printing.

Acid whey is the major cause of environmental concerns from yogurt processing companies. This study addresses the environmental issues associated with the inefficient utilization of acid whey in Greek yogurt production. By incorporating underutilized and healthy alkaline grains, specifically kodo and proso millets, into the acid whey, the spray-drying process is optimized, resulting in a high-yield, free-flowing powder with excellent water solubility and dispersibility. The developed matrix demonstrates potential as a shelf-stable complementary food, offering a sustainable solution for the upcycling of acid whey.[55]

7.2. Production of additives and replacers

Okara, a byproduct of soy processing, can be used as an innovative oil-structuring ingredient. Structured emulsions with high oil content and superior oil holding capacity were successfully prepared through high-shear mixing. Microstructural analysis revealed even distribution of the oil phase in the okara matrix. In practical applications, okara emulsions proved effective in reducing saturated fatty acids, increasing protein and fiber content, and lowering oil release in sweet bread preparation. The use of okara as an ingredient aligns with the demand for sustainable and healthy diets, offering clean-label foods with reduced saturated fat and increased nutritional value. This approach contributes to the comprehensive upcycling of okara, addressing both economic and environmental concerns.[56]

Acid whey, a challenging byproduct in the dairy industry, can be transformed into an acid whey white powder (AWP) by encapsulating it in millet flour. The AWP exhibited higher L^* values than titanium dioxide (TiO_2) and other millet formulations. While the AWP had lower crude protein content compared to millet flour, it contained higher lactose levels and retained essential amino acids. The AWP also showed increased macrominerals and microminerals, with reduced tannin content. Overall, AWP emerges as a promising natural alternative food whitening agent to TiO_2, offering nutritional value for diverse applications in the food industry.[57]

7.3. Bioflavor production

The global issue of soy whey waste was addressed by fermenting it with the basidiomycete *Ischnoderma benzoinum* to produce a bioflavor and mycoprotein. Controlled fermentation within 20

Table 4 Innovative technological solutions for challenges in the upcycled food value chain along with their Technology Readiness Levels (TRLs)

Upcycled value chain stage	Challenge	Potential-novel technological solution	Application	[a]Surmised TRL range
Resource identification	Identify reliable surplus food streams	Value stream mapping (VSM) and quantum geographic information system (QGIS)	VSM helps in identification of the flow of materials in the supply chains and QGIS for predictive analysis of food waste information[75,76]	4–6
Sorting systems	Non-homogenous raw materials and foreign materials	Optical sensors, NIR spectroscopy and neural network-based sorting systems	Optical or machine vision and spectroscopic technique-based sorting systems are used to sort food waste based on the characteristic attributes of the waste such as colour variations, surface characteristics, quality and its chemical profile[77]	5–7
Processing and transformation	(a) Process optimization	Cyber-physical systems (CPSs) and big data analytics for process optimization	CPS provides real-time monitoring, automation and control, and predictive maintenance, which generates an enormous amount of data. These data are used to optimize processes and enhance supply chain efficiency[78]	4–6
	(b) Product formation technologies (selected based on the "5-stage universal recovery" process, alongside accessibility and availability of references)	High pressure homogenization (HPH)	HPH can be employed in food sterilization by inactivation of spores and presents emulsification of raw ingredients in upcycled food production[79]	6–8
		Fermentation	Example: a melon-based wine produced by alcoholic fermentation of discarded melons from supermarkets and HoReCa using *Saccharomyces cerevisiae*[80]	
		3D printing	Example: conversion of potato peel powder, a by-product of potato processing industry waste into nutritional noodles[81]	
		Pulsed fluid bed agglomeration (PFBA)	Example: PFBA is an effective method for instant agglomeration of discarded or damaged green banana flour, preserving its resistant content and dietary fibre intact. Higher retention of functional components[82]	
Quality assurance	Traceability	Integration of product life cycle management (PLM) tool and blockchain technology	PLM tools capture data on ingredient origin, production, quality and distribution, while blockchain provides transparency and immutability. The integration enables traceability and verification of product quality, enhancing trust and transparency among the supply chain. But it requires collaboration of stakeholders of the supply chain due to considerations of data interoperability and standardization.[78,83]	7–9
Packaging and distribution	Food safety monitoring	Intelligent packaging systems (nanosensors and Internet of Things (IoT))	Nanosensors can be used for identification and detection of any chemical residues or contaminants released during storage and transportation of upcycled products. These data can be correlated to the data from other sensors like humidity, temperature and time with the help of the Internet of Things (IoT)[84]	6–8

Table 4 (Contd.)

Upcycled value chain stage	Challenge	Potential-novel technological solution	Application	[a]Surmised TRL range
Marketing and consumer education	Consumer awareness and campaigns	Interactive mobile applications	Mobile applications for consumer engagement and education are useful to provide benefits, nutritional value, recipes and diets and the environmental impact of upcycled food products and ingredients to make more informed choices. But this technology is still in the stage of development and adoption; it further requires user acceptance testing for larger implementation	6–8
		Augmented (AR) and virtual reality (VR)	AR and VR help the depiction of the overall upcycled food value chain of the targeted product to the consumer making him more aware and educated about the product. But the technology is still in the early stage	3–5

[a] Technology readiness levels – to assess the maturity, readiness and viability of a technology in an industry. TRLs range from 1 to 9.[85] (1) Basic principles observed; (2) technology concept formulated; (3) experimental proof of concept; (4) technology validated in a laboratory; (5) technology validated in a relevant environment; (6) technology demonstrated in a relevant environment; (7) system prototype demonstrated in an operational environment; (8) actual system completed and qualified; (9) actual system proven in the operational environment. The provided TRLs are broadly estimated based on the comprehensive understanding of the technology and its application in the upcycled food value chain.

hours resulted in an intense almond-like and sweetish aroma perceived by a sensory panel. Analysis revealed the presence of benzaldehyde and 4-methoxybenzaldehyde, contributing to the pleasant almond-like odor note. The fermented soy whey also accumulated dry mass of *I. benzoinum* with 73.2 mg g^{-1} crude protein and seven essential amino acids. This innovative approach offers a sustainable solution for repurposing soy whey into valuable products.[58]

7.4. Bioactive compound extraction

Li *et al.* in 2023 (ref. 59) discussed the potential of upcycling flavanol rich Chardonnay and Pinot Noir's thin cluster seeds and seedless fractions, which are rich in flavanols like epicatechin and catechin compared to the widely used market cocoa powders. The study illustrated that these cluster seeds rich in flavanols can be upcycled as a functional ingredient for cocoa products to enrich overall flavanol content.

Vilas-Franquesa *et al.* in 2024 (ref. 60) examined the impact of sequential enzymatic and fermentation treatments on mango peels. Contrary to the hypothesis, enzymatic pretreatment did not enhance bacterial growth, and the production of antioxidant dietary fibre was not efficient as both processes depleted bound phenolic compounds. However, bacterial strains (B501 and LP01) showed consistent growth, leading to substantial changes in phenolic compound recovery. Combining enzymatic pretreatment with bacterial strains significantly increased the recovery of gallic acid and mangiferin aglycones, as well as the antioxidant activity of the final product. Despite the brief enzymatic treatment and the use of common probiotic strains, this approach holds potential for industrial applications in producing functional food ingredients. Further exploration of enzymatically assisted fermentation with other byproducts is recommended, and optimization processes may enhance fibre production from mango peels.

A "zero-waste" biorefinery approach was used to simultaneously extract bioactive compounds (BEs) and dietary fiber fractions (FCs) from quince peel. Optimal conditions yielded high BE content (69% w/w), phenolic compounds (10.6 mg per g BE), and malic acid (7.9 g/100 g BE). FCs with higher yields had lower fiber percentages, and those richer in dietary fiber were darker. Validated extraction conditions demonstrated the BEs' potential for inhibiting lipid peroxidation and exhibiting antimicrobial properties. These natural extracts, particularly the malic acid-enriched BE, show promise as functional food ingredients for preservation and fortification. Future studies could explore additional extraction parameters and assess stability in various food matrices, including beverages.[60]

8. Certification and labelling of UF

Food quality and safety certifications have become critically important considering recent global health crises, including the COVID-19 pandemic, and recurring foodborne illness outbreaks, such as those caused by *Salmonella* and *Listeria monocytogenes*.[5] Governments and regulatory agencies worldwide have responded with stricter enforcement of food safety standards and enhanced surveillance measures, aiming to safeguard public health and prevent the devastating consequences of such outbreaks. It has also pushed the boundaries of the law inwards, making them more stringent for the food industry with mandatory regulatory compliance through proper auditing procedures.[61] The consumer perception of food has evolved over time with different generations having different perspectives on foods with their growing awareness of laws and regulations.[44] Truong *et al.* and others[52,62,63] have reiterated the importance of certification and proper and clear labelling effects on how the consumer perceive food. This is also applicable to UF, where the foods have been perceived as produced from lower-quality food material or food that is unconsumable.[9,12] Apart from these, there is also literature showing the effect of consumer preference on the selection of the specific product based on the supply chain of the specific food product from the farm to retailers, which has also been detrimental to the choice[62] and can also be observed in the choice of UF. All the effects of consumer perceptions, certification and labelling requirements, and growth objectives in the field of UF push toward the creation of the stringent certification requirements and labelling of UF.

The certification of novel food provides a significant boost to the growth of sales of the specific product in the market. As discussed above, it also has the power to shape consumer perception, leading to either positive or negative implications for the product's success.[43] But in the sphere of UF, governments around the world have not given clear regulatory norms and guidelines in the perspective of their own food safety laws. UF is considered under the food waste management rules of several laws, but still there are no proper contours to what is to be called an upcycled food, what it is to be sold as, or which category of novel foods it falls under.[9,19,42]

The UFA was instrumental in the creation of certification programs for upcycled products in several sectors like food and beverage, personal care, household, and pet food products. It has devised proper certification requirements and a certification logo of UF with detailed requirements in its charter. It has certified more than more than 30 individual companies with more than 50 upcycled products listed on its website.[51]

8.1. Certification of UF

The UFA has clearly defined upcycled products and classified them under three different types of certifications such as upcycled ingredient (UI), Products containing Upcycled Ingredients (PUI), and Products with Minimal Upcycled Ingredient content (Minimal content PUI). An ingredient is certified as UI if the input of the ingredient is greater than or equal to 95 percent of the upcycled source and may be sourced from the various inputs of diverted materials. It is further used in the PUI or in the minimal content PUI. For a product to be certified as the PUI, it should be made of greater than or equal to 10% upcycled ingredients by weight, and it can be a composite of several inputs or a single one that is certified to be UIs, PUIs, or minimal content PUI (Fig. 4). Minimal content PUI is a PUI that contains less than or equal to 10% of the upcycled material input.[64]

For a product or ingredient to be certified as per the above-mentioned certifications, it requires providing all the compliance certificates of FDA compliance, HACCP, GMP, and GAP certifications and a production flow chart of the product, determined under Section 4.2 of the technical requirements under requirements for the certification (Section 4) in the guidelines document of the UF Association.[20] The document detailed all the requirements of certification from the source of the product to the certification and labelling instructions of the upcycled product.

8.2. Labelling of UF

To change the consumer perception, the information flow to the consumer needs to be right, which gives the required

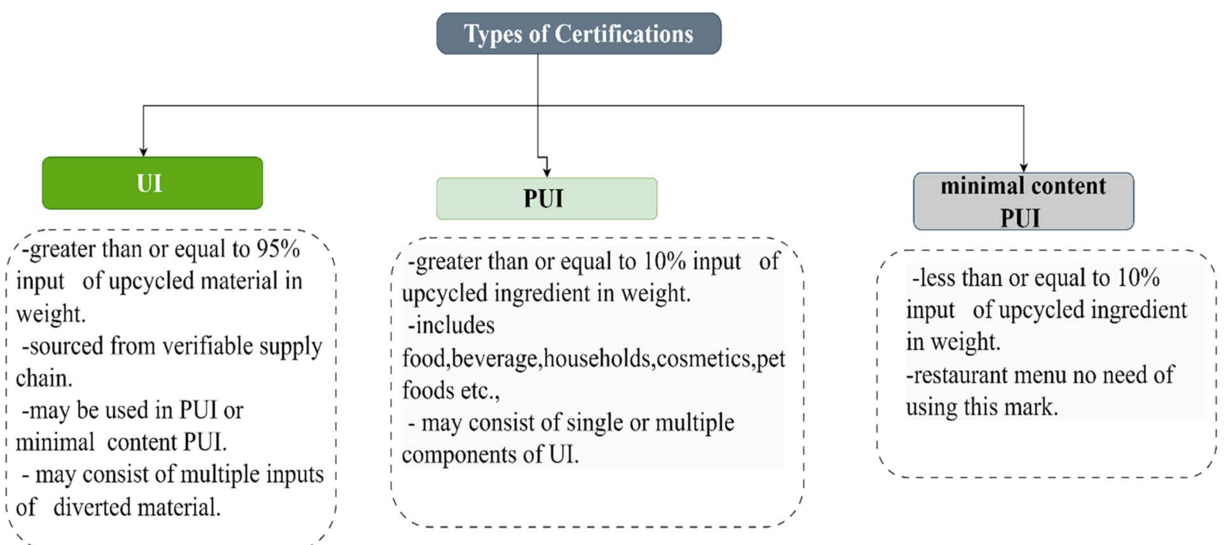

Fig. 4 Types of upcycled certifications (source: Upcycled Food Association, 2022).

Fig. 5 Different certification logos for labelling upcycled ingredients and foods (source: ref. 64).

information about the product and makes the consumer aware of the product. In the case of UF, enough literature has suggested that the WTP for upcycled products has increased with the providence of effective nutritional and environmental impact information provided to the consumer. In the case of biscuits where the WTP has seen rise as reported by ref. 24. Further, James Kopcke[49] reported that when the consumer is informed that UF reduces food wastage and loss, WTP has seen a rise compared to before. Labelling furnishes the essential information that the consumer must know regarding the product and makes the consumer aware of the choices in selection of foods. Aschemann-Witzel *et al.*[65] have tabulated the different types of framing of UF like climate framing, frugal framing, and taste framing, which indicates the effect of the framing of actionable words on labelling positively influences consumer perception of UF. Grasso *et al.* and Zhang *et al.*[12,44] have reiterated the importance of proper labelling and giving essential information to the consumer, which has led to an inclination toward choosing UF over conventional foods. The UFA has taken steps towards establishing a labelling procedure and devised certain logos for all three certifications of UIs, PUIs, and minimal content PUI products.

8.3. Labelling guidelines for UF

In the case of UF, ample literature suggests that WTP for upcycled products rises when consumers receive clear nutritional and environmental impact information. This has been notably observed in biscuits, where an increase in WTP has been reported.[24] Jannes Kopcke[49] have reported that when the consumer is explained that the UF reduce food wastage and loss, WTP has seen a rise compared to before. Labelling furnishes the essential information that the consumer must know regarding the product and makes the consumer aware of the choices in selection of foods.[65] have tabulated the different types of framing of the UF like climate framing, frugal framing, and taste framing which indicates the effect of the framing of the actionable words on labelling causing the positive communication of the UF to the consumer.[12,44] Have reiterated on the importance of proper labelling and giving essential information to the consumer, which has shown an inclination toward choosing UF over conventional foods. UFA has taken steps towards establishing a labelling procedure and devised certain logos for all three certifications of UI's, PUI's, and minimal content PUI products.

Here are a few important labelling requirements interpreted from the guidelines document to be followed by commercially UF-producing companies in accordance with the UFA standards of labelling of Section 10 of the UFA Upcycled food labelling Handbook.[20]

(1) Upcycled Certified™ can be used only in accord with the Annex A of ref. 20 and 64.

(2) Companies are required to take prior approval before utilizing the mark on packaging materials.

(3) The colours and specifications of the logo should be in harmony with those mentioned in ref. 64.

8.3.1 For labelled UIs or PUIs for utilization in a UI or a PUI. (4) Labelled UIs or PUIs or minimal content PUIs used as an input for other UIs, PUIs, and minimal content PUIs should have the Upcycled Certified mark specifications and other documents and labels of products used.

(5) There should not be any alteration of words in the "Upcycled Certified™", and it should be used on the input label.

8.3.2 PUIs. (6) Out of all the input ingredients used in the PUI, the upcycled ingredients should be clearly indicated in the ingredient list.

8.3.3 Minimal content PUIs. (7) It should use the Upcycled Certified™ along with the minimal content together logo on the back side of the package as mentioned in the UFA handbook[64] Annex A.

(8) There should not be any kind of romance language or graphical representation of the input on the packaging.

The UFA under its labelling guide[64] for certification and labelling of upcycled ingredients and upcycled food products has given logos for 3 different types of certifications in Fig. 5.

9. Conclusion

In conclusion, this review provides a comprehensive analysis of key challenges and opportunities in upcycled food production, emphasizing its potential to create sustainable food systems while addressing food waste and food insecurity. The primary manufacturing challenges identified include inconsistent raw material quality, non-homogeneous inputs, consumer perception barriers, and the need for robust regulatory frameworks. To overcome these obstacles, the review highlights viable solutions such as implementing co-product and serial-product upcycling methodologies, fostering partnerships among stakeholders, investing in technological innovations, and establishing clear certification and labelling standards.[68,69]

Furthermore, the review underscores the role of certification programs, like those developed by the Upcycled Food Association, in enhancing consumer trust and promoting market adoption. However, it also calls for more globally harmonized regulations and collaborative efforts among governments, industry stakeholders, and researchers. Future research should focus on optimizing supply chains, improving consumer education, and advancing the technological readiness of innovative solutions. By addressing these critical aspects, upcycled foods can play a pivotal role in building a circular, resilient, and environmentally sustainable food system.[72–74]

Data availability

No primary research results, software or code have been included and no new data were generated or analysed as part of this review.

Author contributions

Arige Nikhil Swaraj – idea conceptualization, design of methodology, acquisition of data, analysis, and interpretation, and writing the original draft; Jeyan Arthur Moses – conceptualization, design of methodology, review and editing of the draft and supervision; Loganathan Manickam – conceptualization, review and editing of the draft, supervision, and project administration.

Conflicts of interest

The authors have no conflicts to declare.

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