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Upcycled proteins: reconceptualising waste as a sustainable resource

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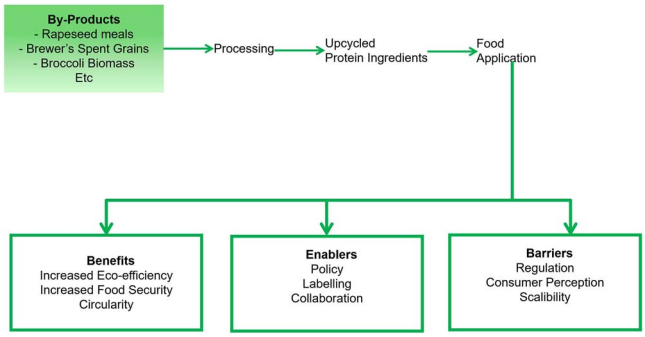
Abstract

The global demand for protein continues to rise amid intensifying environmental pressures and limited natural resources. Conventional animal-based proteins contribute substantially to greenhouse gas emissions and biodiversity loss, creating an urgent need for sustainable alternatives. This viewpoint article examines the potential of upcycled proteins as a strategic component of the circular bioeconomy. By converting by-products like rapeseed meal, broccoli biomass, and brewer's spent grain into valuable food ingredients, upcycling helps retain nutrients, enhance food security, and lower environmental impacts. Yet, regulatory ambiguity, consumer perceptions, and challenges in scaling production remain significant constraints. Achieving broader adoption will require supportive policies, transparent labelling, and public–private collaboration. Reframing upcycling from "waste reduction" to "resource renewal" could also strengthen consumer confidence and stimulate market growth. Incorporating behavioural insight into innovation and policy frameworks will further enable inclusive and long-term engagement across the food sector. Overall, upcycled proteins represent a shift from linear to circular food production, integrating technological progress, policy support, and societal participation. As the global population approaches 10.4 billion, reconceptualising by-products as renewable resources offers both an ecological necessity and a viable pathway to sustainable nutrition.

Keywords upcycled proteins, circular bioeconomy, sustainable nutrition, food by-products valorisation, alternative protein systems

Graphical abstract



Introduction

Consumer appetite for protein has steadily increased worldwide. Still, with the global population projected to rise from approximately 8.5 billion in the next 5 years to 10.4 billion by 2100 (United Nations, 2024), the environmental strain of current consumption patterns is unsustainable. Animal-based protein production contributes heavily to greenhouse gas emissions (Munialo, 2024), and also foster deforestation, water scarcity, and other environmental impacts. Without effective intervention, the very systems that sustain food production may face irreversible damage.

In the United Kingdom, support for alternative proteins is growing, exemplified by the launch of the National Alternative Protein Innovation Centre in August 2024. Similar initiatives exist across Europe and Asia, yet the transition remains uneven. Technological innovations often receive greater attention, while consumer acceptance and

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Figure 1 The circular flow of upcycled proteins in sustainable food system.

scalability lag. At the 2025 Institute of Food Science and Technology (IFST) Autumn Conference, Gareth Payne of Adamo Foods Limited highlighted the challenges of scaling their mycelium-based product, which possesses high protein and fibre content, cooks quickly, and has a reduced environmental footprint.

Large quantities of protein-rich by-products from crops such as rapeseed are often discarded annually, leading to nutrient loss and greenhouse gas emissions (Manikandan et al., 2024; Peydayesh et al., 2023). These by-products, however, have the potential to enhance food security and reduce environmental impact if upcycled effectively. Policy, research, and industry collaboration are required to harness this potential. This article highlights how upcycling protein waste can foster innovation, strengthen food systems, and support sustainable nutrition within a circular framework (Figure 1), emphasising that technology alone is insufficient, policy and societal adoption are essential.

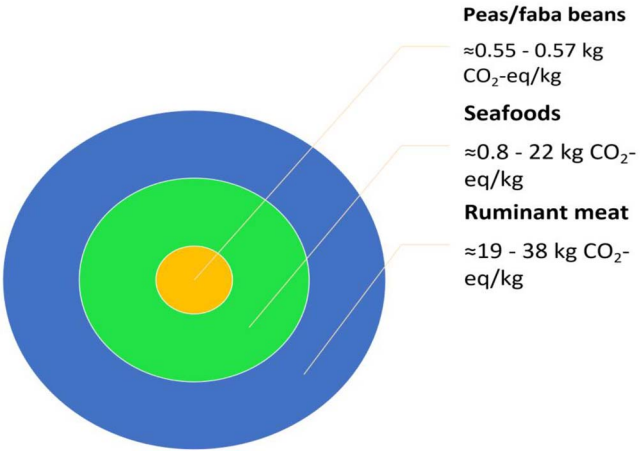

Figure 2 Greenhouse gas emissions of some protein sources. Source: Svanes et al. (2022).

Global protein demand and sustainability challenges

Feeding the growing population requires not just more protein, but more responsible production. Animal-based proteins, particularly ruminant meat, are resource-intensive, producing 1 kg of beef emits up to 38 kg of CO_2-equivalent, while peas and faba beans generate less than 0.6 kg per kilogram of protein (Figure 2) (Svanes et al., 2022). These differences highlight the urgent need for environmental-conscious protein choices.

Plant-based proteins form part of the strategy, nonetheless an even greater opportunity lies in upcycling what is currently treated as waste. Large quantities of protein-rich by-products, including broccoli biomass, rapeseed meal, and brewer's spent grain (BSG), are inadequately harnessed annually. Turning these by-products into food ingredients faces challenges: taste, texture, and anti-nutritional factors can limit consumer acceptance. Still, plant-based burgers incorporated upcycled whole potatoes demonstrate that some challenges can be overcome (Uluocha & Grinter, 2025). This shows that innovation and science can transform waste into beneficial resources for sustainable nutrition.

Integrating upcycling into industrial and national protein strategies offers multiple benefits: it can reduce biodiversity loss, improve

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Figure 3 Extrusion-based valorisation of underutilised crops. Source: https://www.spginnovation.co.uk.

resource efficiency, and create new markets and products from materials that would otherwise go to waste. Such strategies also strengthen food security by providing more affordable protein sources for communities worldwide. The future of sustainable protein lies not only in plant alternatives but also in rethinking what we discard. By embracing plant-based proteins and upcycling strategies, policymakers, industry, and consumers can work together to meet global protein demand while protecting the planet. Minor modifications in consumption and production could significantly impact global food sustainability.

Upcycling protein waste towards circularity

Upcycling transforms by-products and food waste into higher-value materials or products with enhanced functionality (Aschemann-Witzel et al., 2023a). In the protein transition, it closes nutrient loops while addressing food loss and climate impact. Globally, considerable quantities of protein-rich by-products, from broccoli biomass to rapeseed meal and brewer's spent grain, are generated yearly, yet remain underutilised. The UK alone generates over 900,000 tonnes of BSG yearly (Waste Managed, 2024). Still, many of these resources are used for lower-value applications, such as animal feed or landfill, which contribute to greenhouse gas emissions.

Technological advances in protein extraction, enzymatic hydrolysis, and fermentation create opportunities to convert these by-products into edible protein ingredients or functional food components. In the UK, firms like SPG Innovation Limited explore extrusion-based valorisation of hemp and other underutilised crops (Figure 3), demonstrating industrial-scale innovation aligned with circular bioeconomy goals. Rebel Meat in Austria combines organic meat with plant-based ingredients like mushrooms to lower environmental footprints and appeal to flexitarian consumers. More so, EverGrain, a subsidiary of AB InBev in the United States, produces high-quality protein and fibre ingredients from brewer's spent grain, showing how large-scale brewing residual biomass can become nutrient-dense food components. These examples highlight diverse valorisation strategies advancing a circular protein economy. However, they represent only a small fraction of global protein production, revealing the vast untapped potential of upcycling.

Large-scale adoption continues to be constrained by regulatory ambiguity, inconsistent by-product quality, and limited consumer awareness. Moshtaghian et al. (2023) found that consumers value nutrition, safety, and environmental benefits in upcycled foods, particularly older adults, highlighting the need for targeted product development and education. Legal definitions of "waste" and "by-product" restrict use for human food in many regions. While life cycle assessments show that valorisation reduces carbon intensity (Peydayesh et al., 2023), few studies examine socioeconomic feasibility or policy integration. Environmental benefits depend on local infrastructure and energy sources, which vary widely across regions.

Policy alignment is essential. Governments could integrate upcycling incentives into national circular economy and food waste reduction strategies, promoting research, industry collaboration, and market access. Tax incentives, pilot-scale processing funding, and transparent labelling could normalise upcycled proteins as safe, and sustainable ingredients. Upcycling should move beyond niche sustainability experiments to become an established component of resilient food systems.

Policy framework for a circular protein economy

Transitioning to a circular protein economy requires more than technological innovation; it demands coherent policy frameworks that align regulatory measures, market incentives, and societal engagement. Many countries, including the UK, have policies targeting food waste reduction, such as Scotland's Food Waste Reduction Action Plan, which set a legal target to reduce food waste by 33% by 2025 (Scottish Government, 2019). Nonetheless, progress remains variable as of November 2025. Few policies explicitly recognise upcycling as a core component of national food strategy. Without clear legal definitions distinguishing "waste" from "by-product," firms face regulatory uncertainty, limiting the scale and scope of valorisation efforts.

Policy measures could bridge this gap. Integrating upcycled proteins into national food security and sustainability strategies would provide legitimacy, encourage investment, and stimulate industry participation. Economic levers, such as tax incentives for pilot-scale processing, research and development grants, or preferential procurement for public institutions using upcycled ingredients, could accelerate adoption. Standards for labelling, safety, and environmental claims, like the emerging "Upcycled Certified" certifications, would bolster consumer trust while reducing the risk of misrepresentation.

Policy-making cannot rely solely on top-down measures. Multi-stakeholder engagement is essential: food technologists, industry representatives, local authorities, and research institutions must collaborate to identify practical barriers, align innovation priorities, and ensure equitable access to benefits. Demonstration projects and regional bioeconomy clusters could provide test-beds, linking scientific evidence with market feasibility and enabling knowledge transfer across the sector. Challenges remain, however. Disparities in local infrastructure, energy access, and supply chain logistics can undermine environmental gains, while fragmented policies across jurisdictions risk creating loopholes or disincentives. Policy-making should therefore be adaptive, incorporating iterative feedback from pilot projects, life cycle assessments, and consumer studies to refine regulatory frameworks.

In essence, a policy framework for circular proteins should couple regulatory clarity with market facilitation and societal engagement.

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This approach can move upcycling beyond niche sustainability experiments to a recognised, scalable, and resilient component of national and global food systems.

Consumer perception and behaviour in the protein transition

Technological innovation and strong policy can catalyse the protein transition. Nevertheless, success fundamentally depends on public trust and behavioural change. Consumers are the ultimate arbiters of food system transformation. Without their acceptance, even the most efficient upcycling technologies risk stagnation. Although sustainability increasingly influences purchasing intentions, consumers often interpret "upcycled" or "waste-derived" foods through emotional and cultural lenses. The notion of "eating waste" may evoke hesitation, reflecting deep-seated beliefs about purity, freshness, and food safety. Overcoming this perception requires more than marketing; it calls for reframing the narrative from "waste reduction" to "resource renewal."

Trust and transparency are indispensable. When sustainability claims are credible, traceable, and easy to understand, consumer confidence grows. Labelling schemes, such as the emerging "Upcycled Certified" standard in the United States, are gaining attention. Similar approaches in the UK and Europe could complement existing food waste reduction strategies, assuring consumers that upcycled proteins meet established safety and quality standards.

Behavioural science can elucidate mechanisms for acceptance. Social marketing campaigns and educational initiatives like "Love Food, Hate Waste" illustrate how positive framing and collective responsibility can normalise new consumption habits. Studies show that consumers are more receptive to upcycled food products presented in familiar formats, such as burgers or snacks, and when they are involved in co-creation processes influencing taste and design (Aschemann-Witzel et al., 2023b). This participatory approach transforms consumers from passive end-users into active contributors to sustainability innovation.

Consumer behaviour exerts a feedback effect on policy and industry. Widespread demand for transparent, sustainable protein sources can accelerate regulatory adaptation and private investment in circular technologies. Thus, consumer perception is not merely a barrier to overcome but a lever for systemic change. Integrating behavioural insight into food product development, education, and communication strategies goes beyond traditional sensory evaluation. While sensory testing assesses how products are perceived, behavioural insights explore why people adopt, reject, or continue consuming them. This deeper understanding aligns technological innovation with cultural values and real-world decision-making, making the protein transition more inclusive and sustainable.

Policy opportunities and future outlook

Transforming food waste into valuable protein ingredients is not merely a technological or regulatory challenge; it is a societal and policy opportunity to foster a more sustainable and resilient food system. While technological innovation and policy frameworks establish the foundation, adoption pace primarily depends on consumer confidence and engagement. Without public trust, even well-designed policies may fail to translate into meaningful change.

The United Nations Sustainable Development Goal (SDG) 12.3 calls for halving global food waste by 2030 (United Nations, n.d.). Nonetheless, progress is uneven, with some regions making significant strides while others lag behind. Current policies often prioritise redistribution or composting over nutrient recovery. While these approaches reduce visible waste, they seldom address the inherent environmental costs of lost proteins, including resources used in production and associated greenhouse gas emissions. Initiatives, such as Food Works in Upperthorpe, Sheffield, UK, demonstrate how local programmes can harness alternative proteins by upcycling protein-rich by-products like brewer's spent grains or pulse hulls into nutritious food products, recovering valuable nutrients otherwise lost. Integrating such community-based initiatives into national food innovation and sustainability strategies could amplify their impact, bridging local action with systemic change.

To accelerate adoption, policy measures should move beyond end-of-pipe interventions, shifting focus from managing waste to valorising by-products and preventing nutrient loss at the source. The EU's Farm to Fork Strategy provides a framework for sustainable food transitions (European Commission, 2020), nevertheless, it lacks specific mechanisms to encourage upcycling protein-rich by-products. Establishing measurable targets for resource recovery, akin to renewable energy quotas, could stimulate private sector participation. Including upcycled protein ingredients within national food security frameworks would signal institutional legitimacy and encourage investment.

Public trust and communication remain essential. The success of sustainability-focused food innovation depends not only on performance or price but also on consumer confidence. Transparent sustainability claims, backed by verified life cycle assessments and communicated through regulated labelling (e.g., "Upcycled Certified" standards emerging in the United States), could enhance acceptance. Policies must ensure sustainability does not become a marketing tool detached from scientific evidence.

A multilevel policy approach is imperative. Collaboration between food technologists, policymakers, supply chain stakeholders, and consumers ensures research priorities align with practical needs. Universities and innovation hubs, such as the Advanced Food Innovation Centre in the United Kingdom, can bridge scientific progress with real-world application through demonstration projects and public–private partnerships.

Future directions for research and industry

Despite growing momentum, the full potential of upcycled proteins is relatively underexplored. Standardised assessment metrics covering nutritional, sensory, and environmental parameters are urgently needed to benchmark products, guide investment, and enable comparisons across extraction methods and substrates. Integrating environmental accounting into research and development (R&D) frameworks could make life cycle assessments predictive as well as evaluative, steering innovation towards maximum sustainability gains while supporting evidence-based policy and consumer communication.

Industry scalability depends on integrated logistics and digital traceability systems. Waste collection networks must shift from linear disposal to circular utilisation, leveraging sensors and blockchain systems to monitor flow, ensure safety, and maintain quality. Integrating upcycling within regional bioeconomy clusters could facilitate economies of scale, shared infrastructure, and co-location with

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existing food processors, while aligning with policies incentivising circular practices.

Academic and industrial collaboration should explore novel multifunctional applications of upcycled proteins beyond food fortification, including bioplastics, edible films, and fermentation substrates. Diversifying applications mitigates dependency on food use alone and strengthens resilience across multiple sectors. Caution is needed to avoid "greenwashing": valorisation strategies relying on high energy inputs or long transport chains may compromise sustainability objectives.

Strategically, research should prioritise systemic integration of upcycled proteins, connecting by-product valorisation with food policy, agricultural practices, energy systems, and consumer behaviour. Bridging technological innovation with governance frameworks and societal adoption can deliver measurable resilience and environmental benefits while contributing to a more sustainable global food system.

Conclusion

Feeding a growing population sustainably demands more than substituting animal proteins with plant-based alternatives. It requires rethinking waste as a renewable resource and reconceptualising the consumer's role within that transformation. Upcycling protein-rich by-products presents a pivotal scientific, economic, and ethical opportunity to close loops within the food system. Notwithstanding, technological promise and policy ambition alone will not suffice.

Realising this potential requires coordinated policy support, industrial commitment, and social acceptance. Consumers must be seen not merely as end-users but as key stakeholders whose perceptions and choices can foster or derail the protein transition. Building trust through transparency, education, and participatory innovation can bridge the gap between concept and consumption. Incentives for circular innovation, investment in scalable technologies, and evidence-based communication together define the pace and permanence of change.

Although upcycling may not immediately rival conventional protein sources, it can complement them, mitigating environmental burdens, diversifying supply chains, and strengthening food system resilience. In rethinking food waste as a foundation for sustainability, the future of protein depends not only on new ingredients but also on new approaches: a shift from extraction to regeneration, and from disposal to renewal. Upcycling is not waste management; it is resource renewal.

Data availability

No datasets were generated or analysed for this study; therefore, data sharing is not applicable.

Author contributions

Maduabuchi Daniel Uluocha (Conceptualisation, Visualisation, Writing—original draft, Writing—review & editing) and Seun Seidu (Writing—original draft, Writing—review & editing, Project administration)

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Conflicts of interest

The authors declare no conflict of interest related to this article.

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