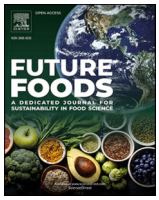
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Nature's minor plants: a multi-dimensional analysis of their integration into European value chains

Amine Zouaghi [a,b,#], Marija Knez [c,e,#], Konstadinos Mattas [d,*], George Baourakis [a,#], Eleni Stamataki [a,#], Mirjana Gurinovic [e,#], Cyril Tisseyre [f,#], Burkhard Schaer [f,#]

[a] Business Economics and Management Department, Mediterranean Agronomic Institute of Chania, CIHEAM MAICh, 01 Makedonias Street, Alsyllion Agrokipiou, PO BOX 85, Chania, Crete, 73100, Greece
[b] Department of Food and Drug, University of Parma, Kennedy Street 6, Parma, 43125, Italy
[c] Centre of Research Excellence in Nutrition and Metabolism, Institute for Medical Research, National Institute of Republic of Serbia, University of Belgrade, Belgrade, 11060, Serbia
[d] Department of Agricultural Economics, Aristotle University of Thessaloniki, Thessaloniki, 53124, Greece
[e] CAPNUTRA, Capacity Development In Nutrition, Belgrade, 11126, Serbia
[f] ECOZEPT, 145 Rue Guillaume Janvier, Montpellier, 34070, France

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ABSTRACT

Addressing the challenges of climate change, economic instability and sustainability in food production requires a shift toward more diversified and resilient agricultural systems. The integration of minor crops, underutilized, neglected, and climate-resilient species, presents a viable strategy for enhancing food security, biodiversity, and sustainability while reducing the environmental footprint of food production. This conceptual study integrates a literature review, policy analysis, and evidence from EU-funded projects to evaluate pathways for integrating minor crops into sustainable food systems. This study applies the 6Ms framework (Methods, Machines, Materials, Manpower, Measurements, and Milieu) to support the adoption of minor crops into European food value chains. The framework addresses barriers related to processing, product innovation, scalability, regulation, and market uptake. It also emphasizes the role of minor crops in enhancing food security, biodiversity, and resilience to climate change. The findings highlight the need to improve crop productivity and advance food processing technologies, while promoting stakeholder collaboration to address supply chain gaps, regulatory constraints, and financial barriers. By aligning with evolving dietary trends and consumer preferences, minor crops can contribute to more resilient food systems. Our study identifies key trade-offs and synergies across the 6Ms and provides evidence-based recommendations, from crop selection and processing to awareness and policy measures, to improve adoption, nutrition, and sustainability of minor crops. Overall, this work provides a roadmap for advancing minor crops as sustainable food sources through innovation in processing, policy support, and consumer-oriented strategies, contributing to climate-resilient food systems and the achievement of Sustainable Development Goals (SDGs).

1. Introduction

Today's global food systems are under increasing pressure from climate change, water scarcity, economic instability, and shifting consumer demands, all of which pose significant threats to food security. According to the Food and Agriculture Organization (FAO), agro-food production needs to increase by almost 70% to satisfy growing demand (Bélanger and Pilling, 2019; Coulter, 2004), as the global population is projected to approach approximately 9.7 billion by 2050 (United Nations, 2022). Traditionally, agricultural production has relied on resource-intensive monoculture (Roe et al., 2019) and a limited number of crop species (Bélanger and Pilling, 2019; van der Sluis et al., 2022), which places increasing pressure on the environment (Roe et al., 2019) and contributes to biodiversity loss (Bélanger and Pilling, 2019;

* Corresponding author.
E-mail addresses: amine.zouaghi@unipr.it (A. Zouaghi), marijaknez186@gmail.com (M. Knez), mattas@auth.gr (K. Mattas), baouraki@maich.gr (G. Baourakis), eleni@maich.gr (E. Stamataki), mirjana.gurinovic@gmail.com (M. Gurinovic), tisseyre@ecozept.com (C. Tisseyre), schaer@ecozept.com (B. Schaer).
# These authors contributed equally to this work.

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van der Sluis et al., 2022).

Biodiversity loss negatively impacts not only planetary health but also human well-being (Shroff and Cortés, 2020). More specifically, it affects food quality and availability, access to clean water, and other natural resources essential to the entire ecosystem (Pongsiri and Roman, 2007). Biodiversity loss is aggravated by several factors linked to the global food system, including land use, dietary models, and food waste (Read et al., 2022). The FAO emphasizes that biodiversity in food and agriculture is essential for ensuring food security, promoting sustainable development, and maintaining other vital ecosystem services (Kalmpourtzidou et al., 2025).

The narrowing of diversity in crop species contributing to the world's food supplies is a potential threat to food security, with significant ecological and socio-economic implications. This dependence also causes inequalities in global agricultural trade by neglecting smallholder farmers and minor crops, despite their considerable potential to enhance food system sustainability and biodiversity (Chivenge et al., 2015). These minor crops include a broad range of plant species that have historically received limited attention from mainstream agricultural practices, scientific research, and global food markets (Kaur et al., 2025).

For the purposes of this study, we use the term 'minor crops' to refer broadly to underutilized, neglected, or so-called future smart foods, while acknowledging that each term has specific nuances in the literature. Minor crops, understood here as an overarching category that includes neglected and underutilized species (NUS), present a conceptual challenge due to inconsistent terminology within agri-food scholarship. In this study, we employ 'minor crops' to denote species characterized by restricted cultivation areas, limited market penetration, and disproportionately low research and policy investment relative to dominant global staples. These species, ranging from pseudocereals and legumes such as buckwheat, lentils, and grass pea to horticultural landraces including Armenian cucumber and traditional tomato varieties, as well as wild edibles like Sonchus oleraceus, frequently exhibit production, knowledge, and policy gaps that hinder their integration into European value chains (Timaeus et al., 2022; Lara et al., 2023). Minor crops are also known by other terms—orphan, neglected, underutilised, underexploited, underdeveloped, lost, new, novel, promising, alternative, local, traditional, and niche crops—used interchangeably throughout the literature, reflecting the complex history and evolving perception of these species (Lara et al., 2023).

Regardless of the huge number of existing plant species (300,000–500,000), <10% are considered edible (Garn and Leonard, 1989). Historically, only 7000 species have been either cultivated or collected for food. What is particularly concerning is that only 20 species account for 90% of the world's food supply, despite the huge number of potentially edible plant species (Lachat et al., 2018). This dependence on a limited number of crops leads to lower diversity in human diets, while the majority of potentially edible plant species remain neglected despite their potential to contribute to the growing global food demand (Collins and Qualset, 1998; FAO, 2022).

Shifting toward agricultural diversity is necessary to create a sustainable food system that can reduce environmental stress, enhance global food systems, and improve biodiversity (Bélanger and Pilling, 2019; IPBES et al., 2019; Knez et al., 2024b). Discovering and using more underutilized crop species (UCS) is a promising approach, as they are well-adapted to local growing conditions (Padulosi et al., 1999) and harsh environments, ensuring sustainable food production (Idowu, 2008). Additionally, these neglected and minor crops, as defined by FAO, are 'nutritionally dense, climate-resilient, economically viable, locally available or adaptable as Future Smart Food (FSF)' (Li and Siddique, 2018).

The incorporation of minor crop-based novel foods into European diets may effectively mitigate environmental impact, enhance dietary biodiversity, promote sustainability, address global food security challenges, and stimulate innovation in food production, thereby establishing resilient food systems that meet both environmental and nutritional requirements (Devos et al., 2022; Mazac et al., 2023; Scaffardi and Formici, 2022). However, it is important to note that minor crops do not automatically deliver environmental benefits if grown under high-input or poorly adapted systems; we highlight the importance of appropriate, locally adapted, and sustainable agricultural practices (Timaeus et al., 2022).

These alternative food sources have the potential to enhance dietary biodiversity and facilitate a transition to more sustainable eating patterns, as many of them—particularly neglected and minor crops—are predominantly plant-based, produced locally, and highly resilient, making valuable contributions to sustainable food systems (Kalmpourtzidou et al., 2025; Knez et al., 2024a;Padulosi et al., 2013). Although minor crops have been widely studied for their nutritional and agronomic benefits, limited research has systematically examined how these crops can be integrated into food value chains while simultaneously addressing technological, market, behavioral, and regulatory constraints. Existing studies typically focus on individual crops, isolated nutritional assessments, or generic recommendations for novel foods, without linking stakeholder actions to measurable outcomes or accounting for the interplay between agronomic, processing, market, and socio-cultural factors (Chimonyo et al., 2022; Ali and Bhattacharjee, 2023). This gap limits the translation of minor crops from niche agricultural systems to mainstream food markets. This article addresses this gap by applying the 6Ms framework (Methods, Machines, Materials, Manpower, Measurements, and Milieu) specifically to minor crop-based novel foods, providing practical recommendations and strategies for value chain actors, and highlighting collaborative approaches for recipe development, nutritional evaluation, and consumer acceptance.

While several analytical frameworks have been applied to food systems and value chain research, including sustainable food systems models (HLPE, 2020), value chain analysis (VCA) (FAO, 2014), the multi-level perspective (MLP) on sustainability transitions (Geels, 2011), and the food-energy-water (FEW) nexus approach (Ringler et al., 2013), these approaches typically privilege one dimension of the food system. VCA, for instance, emphasizes economic transactions and efficiency but offers limited insight into technological readiness, workforce capacity, or consumer behavior. MLP frameworks focus on socio-technical transitions but often lack operational dimensions for practitioners. The 6Ms framework, by contrast, provides a structured, multi-dimensional lens that simultaneously integrates agronomic characteristics (Materials), processing technologies (Methods and Machines), human capital (Manpower), quality assurance (Measurements), and the broader socio-economic and regulatory environment (Milieu). This integrative approach is particularly suited to minor crops, where adoption barriers span multiple domains simultaneously. The 6Ms framework, originally developed in quality management and process improvement (Boca, 2015; Erkens and Stouthamer, 2020), has been successfully applied in healthcare (Wilken et al., 2017) and education (Wong, 2011), but its application to food systems represents a novel contribution. By synthesizing evidence across these six dimensions, the framework reveals trade-offs and synergies—such as the interaction between post-harvest processing methods and consumer sensory acceptance—that single-focus approaches typically overlook, enabling more context-sensitive and actionable strategies for value chain actors.

This study draws on evidence from the BioValue project, an EU-funded Horizon 2020 initiative that evaluated stakeholder interactions and consumer preferences along the value chain for underutilized crops, alongside complementary findings from related European projects. The approach encompasses recipe development and novel food products using selected minor crops, nutritional and technological analysis, sensory evaluations, focus groups, consumer surveys, and home cooking tests to measure consumer acceptance. These efforts culminate in findings that inform recommendations for integrating minor crop-based novel food products into sustainable food systems (Fig. 1), thereby supporting the transformation of food production and consumption to

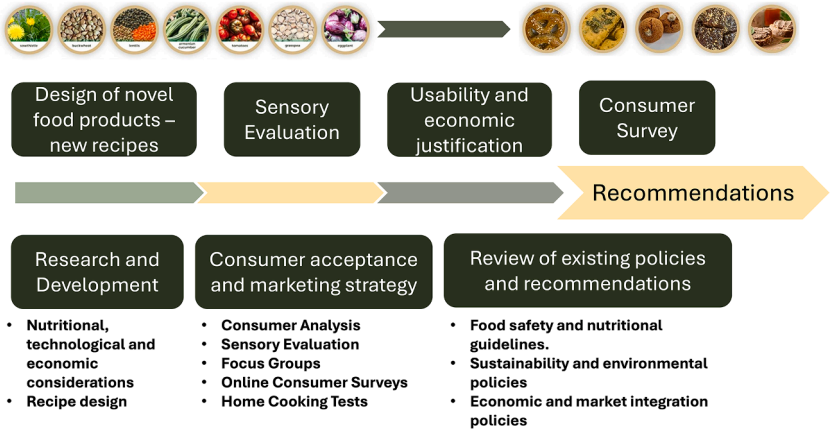


Fig. 1. Conceptual framework illustrating the research workflow leading to evidence-based.

address climate change, enhance food security, and minimize environmental impacts.

The remainder of this paper is structured as follows. Section 2 examines existing policies, legislation, and gaps relevant to minor crops and biodiversity. Section 3 discusses the importance of collaboration within the food system. Section 4 presents the methodology, detailing the data sources and analytical procedures. Section 5 presents the results and introduces the 6Ms framework as a structured analytical tool. Section 6 provides recommendations for stakeholders and discusses alignment with the SDGs. Section 7 examines challenges, limitations, and opportunities. Section 8 concludes with implications for research, policy, and practice.

2. Current policies, legislation, and gaps

Food safety policies are crucial for ensuring the security and quality of food products. These policies serve as protective measures by prohibiting harmful ingredients in food products (Laulund et al., 2017) and raising consumer awareness about their impact and implications, which requires the enforcement of these regulations (Havinga, 2006). Current policies governing minor crops and biodiversity are rooted in broader frameworks addressing agricultural sustainability, food security, and climate change mitigation.

At the international level, organizations such as the FAO promote the use of diverse and resilient crop systems to combat monoculture reliance (FAO, 2023). Initiatives like the International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA) emphasize the conservation and equitable use of plant genetic resources (Moore and Tymowski, 2005). Similarly, the Convention on Biological Diversity (CBD) sets goals to preserve genetic diversity and integrate biodiversity into national strategies, with the Kunming-Montreal Global Biodiversity Framework (2022) establishing targets to protect 30% of land and sea areas by 2030 (Chandra and Idrisova, 2011; CBD, 2022).

In the European Union, the Common Agricultural Policy (CAP) 2023–2027 includes eco-schemes and conditionality requirements aimed at promoting biodiversity and supporting sustainable farming practices (Cuadros-Casanova et al., 2023). The European Green Deal and its Farm to Fork Strategy (European Commission, 2020) set targets for reducing pesticide use by 50% and increasing organic farming to 25% of agricultural land by 2030, creating potential entry points for minor crop diversification. However, the current CAP eco-schemes remain predominantly oriented toward mainstream crops and large-scale farming operations, offering limited explicit support for underutilized species. The forthcoming CAP reform for the post-2027 period presents an opportunity to integrate minor crop cultivation into strategic plans through targeted eco-schemes, coupled income support for diversification, and investment aid for processing infrastructure tailored to small-scale, biodiversity-enhancing production systems.

Minor crops intended for European markets may fall under the EU Novel Food Regulation (EU) 2015/2283, particularly under the category of 'traditional food from a third country' when the crop has a history of safe use outside the EU (Günden et al., 2024). The regulation establishes a centralized authorization procedure managed by the European Food Safety Authority (EFSA) (Turck et al., 2016). However, the authorization process presents significant bottlenecks. The regulatory burden disproportionately affects smallholder producers and small and medium-sized enterprises (SMEs) in developing countries, who often lack the resources to compile comprehensive safety dossiers (Hermann, 2009). Furthermore, the absence of a simplified pathway for intra-European minor crops with documented traditional use—but without significant consumption history before the 1997 cut-off date—creates a regulatory gap that hinders the commercialization of landraces and regional varieties. Streamlining the authorization process and reducing database costs for SMEs could significantly accelerate market access for minor crop-based products.

National and regional policies often extend these frameworks by offering subsidies, research funding, and educational initiatives to support the adoption of biodiversity-enhancing agricultural practices (Knez et al., 2023). However, the effectiveness of these policies varies widely depending on local priorities and the level of institutional support. Governance challenges in mainstreaming minor crops include fragmented responsibility across agricultural, food safety, and environmental policy domains, weak coordination between national and EU-level instruments, and limited monitoring of biodiversity outcomes from CAP-funded interventions (Mengesha and Ayana, 2024; Onawo and Egboduku, 2025).

Despite these policies, regulations, and frameworks, significant gaps remain that hinder the adoption and commercialization of minor crops. Market integration is inadequately addressed, especially the economic barriers faced by small-scale farmers introducing minor crops to the market. Research and development in processing and optimizing minor crops require increased investment to support the development of novel food products that can compete with conventional options in terms of taste, nutrition, and price. Consumer awareness-oriented policies are required to encourage a shift toward products made from minor crops, ensuring that consumers are well-informed about their benefits and contribution to biodiversity. Finally, the lack of research on minor crops and their use in novel food products needs urgent attention. This paper aims to provide actionable recommendations to promote minor crops as nutrient-rich food sources that support biodiversity and serve as valuable ingredients in novel food products, providing sustainable benefits across the food value chain.

3. Importance of collaboration in the food system

Promoting minor crops within the food supply chain requires collaborative efforts among various actors, such as farmers, processors, retailers, researchers, and non-governmental organisations (NGOs). These stakeholders should leverage their unique strengths to enhance the visibility and integration of these crops into innovative processed food products. Minor crops, often rich in nutritional and medicinal components (Carbas et al., 2023), offer the potential to address malnutrition, enhance agricultural biodiversity, and create economic opportunities for local communities (Hunter et al., 2019; Padulosi et al., 2013). However, their adoption is hindered by challenges such as insufficient infrastructure for transport, processing, and markets; limited demand due to inadequate product and market information; and low productivity in traditional farming systems (Van Looy et al., 2008).

Collaborative partnerships can overcome these barriers by fostering knowledge sharing, addressing logistical constraints, and aligning market structures. For example, participatory exercises in local communities and data collection from consumer and trader surveys reveal that better cooperation between market chain actors and infrastructural improvements can significantly enhance the adoption of minor crops (Van Looy et al., 2008). Supply control mechanisms like origin labelling can also create niche markets, ensuring that these crops contribute to both local livelihoods and biodiversity conservation (Gruère et al., 2012).

Sustainability-oriented innovations in the agrifood supply chain, such as engaging farmers and forming partnerships among intermediaries, processors, and retailers, are critical. These collaborations can reduce costs, enhance profitability, and promote the inclusion of minor crops in processed food products (Cholez et al., 2023; Ranieri et al., 2024). Research on non-consumer actors, including suppliers and food technologists, is vital to address gaps in nutritional data and develop innovative processing techniques for these crops (Kamrath et al., 2023).

In summary, minor crops have the potential for sustainable production and diet diversification by providing unique nutrients and economic opportunities in agro-industries through supporting local food systems (Pandiyaraj et al., 2024). By exploring them, we can improve yields and quality, and fulfil nutritional needs while contributing to environmental sustainability and climate resilience (Ghosh et al., 2023; Mayes et al., 2012). Hence, developing a robust supply chain for minor crops is essential to achieve goals such as enhancing food security, improving nutrition, and income generation (Thakur, 2014).

By integrating these crops into processed food products and fostering sustainable practices, the agrifood industry can drive a more resilient and diverse food system. From a consumer perspective, promoting minor crops involves addressing awareness gaps by familiarising the consumer with the shapes, colours, and tastes of these crops. Targeted educational campaigns and labelling schemes could work as effective strategies, along with utilising physical marketing materials to highlight the nutritional, environmental, and cultural benefits of minor crop-based products. In parallel, building strong local or regional supply chains by connecting producers, processors, and retailers is crucial for emphasizing the uniqueness and added value of minor crops. Training programmes on sustainable production, logistical planning, and market entry strategies can be provided for supply chain actors to help ensure the seamless integration of these crops into the supply chain.

4. Methodology

This study is a conceptual investigation aimed at developing and illustrating the integrative 6Ms framework, comprising Methods, Machines, Materials, Manpower, Measurements, and Milieu, as a structured approach for analysing the integration of minor crop-based novel food products into sustainable food systems. The framework was developed through a multi-stage synthesis of qualitative and quantitative data, including a literature review, policy analysis, and illustrative evidence from EU-funded projects. The 6Ms framework was developed through an iterative synthesis process. Key themes and barriers affecting the adoption of minor crops were identified from the literature, policy documents and EU project evidence. These were then organised into broader dimensions representing technological, biological, human, analytical and contextual factors. The framework was further refined through discussions among researchers involved in contributing projects to ensure its relevance across different stages of the value chain.

The literature review employed a snowball sampling approach, beginning with a set of key articles on minor crops, agrobiodiversity, and food value chains identified through scientific databases including Web of Science and Scopus. Search terms included combinations of keywords related to ‘minor crops’, neglected and underutilized species’, ‘agrobiodiversity’, ‘sustainable food systems’, ‘food value chains’, ‘consumer acceptance’ and ‘novel foods’. Literature was gathered during 2024 and iteratively expanded through forward and backward citation tracking. Studies were included when they addressed at least one of the following themes: the role of minor crops or underutilised species in sustainable food systems, agrobiodiversity conservation, value-chain development, consumer acceptance, food innovation, or policy and governance aspects. Studies unrelated to food systems, biodiversity, agricultural sustainability, or the utilisation of minor crops were excluded. The screening process involved reviewing titles and abstracts of identified publications, followed by assessment of the full texts for their relevance to the conceptual development of the framework. The review covered topics at the intersection of agrobiodiversity, food value chains, consumer behaviour, food processing, and sustainability. The literature search continued iteratively until additional sources no longer provided substantially new conceptual insights. Key concepts and knowledge gaps were identified to synthesise the current understanding of minor crops, underutilised species, and their potential role in sustainable food systems. The snowballing method ensured broad interdisciplinary coverage of the relevant literature across agronomy, food science, consumer research, and sustainability studies.

Policy analysis examined documents from the Food and Agriculture Organization of the United Nations (FAO) (including The State of the World's Biodiversity for Food and Agriculture, Bélanger and Pilling, 2019; and The State of Food Security and Nutrition in the World series, FAO, 2023), the European Commission (the Farm to Fork Strategy, COM(2020)381; the EU Biodiversity Strategy for 2030; and CAP 2023–2027 documentation), the European Food Safety Authority (EFSA) (guidance on novel food applications and traditional food notifications under Regulation (EU) 2015/2283), and the Secretariat of the Convention on Biological Diversity (including the Kunming-Montreal Global Biodiversity Framework, 2022). Documents were selected based on their direct relevance to minor crops, agrobiodiversity governance, and sustainable food systems, and were analysed thematically to identify regulatory gaps, policy instruments, and governance challenges relevant to minor crop integration into European value chains.

Illustrative evidence from EU projects including BioValue, Divinfood, Diversicrop, and Radiant were incorporated to strengthen and ground the framework in empirical data. Projects were selected based on their direct relevance to minor crops, biodiversity-based food systems, value-chain development, consumer engagement and sustainable food innovation. Primary and secondary data on stakeholder interactions, consumer preferences, environmental impact, and market integration of minor crops were included. Specific methods such as focus groups, sensory evaluations, consumer surveys, and home cooking tests were used to capture the perspectives of farmers, processors, and consumers. The Agent-Based Modelling tool developed in BioValue provided additional simulation-based evidence on adoption dynamics. Together, these data sources provided an evidence-based foundation for the recommendations. Quantitative evidence, including consumer survey results, sensory evaluation outcomes, environmental assessments and model outputs, was used as illustrative evidence to support the identification of

key factors influencing minor crop adoption rather than being combined through statistical meta-analysis.

The framework also organises recommendations according to target audiences and stakeholder roles, ensuring that insights are actionable for specific actors across the value chain. The applicability of the framework was assessed by mapping evidence from different projects and value-chain contexts onto the six dimensions to examine whether the framework could capture diverse barriers, opportunities and stakeholder perspectives. By integrating conceptual, illustrative, and policy-based evidence, the 6Ms framework provides a robust, multi-dimensional foundation for guiding future research, policy development, and practical interventions in the adoption of minor crops. Although developed primarily in the context of European food systems and minor crop-based innovations, the framework provides a transferable structure that can be adapted to other food-system contexts where multiple technological, social, environmental and governance factors influence adoption (Table 1).

5. Results and the 6Ms framework

5.1. Empirical evidence from pilot studies

The pilot studies within the BioValue project provide empirical validation of the 6Ms framework. For example, in the genetic mapping study of Snake Melon (Armenian Cucumber) landraces performed in Cyprus, one of the main findings under the 'Materials' dimension is that these landraces are excellent candidates for climate-resilient agriculture.

In a cross-country study, innovative dishes based on minor crops were evaluated using a nine-point hedonic scale. Findings show high consumer-liking scores, indicating consumer acceptance and market readiness. Variations between countries and regions further suggest that processing methods should be adapted and tailored to local contexts.

Agent-based modelling simulations and consumer surveys demonstrated an increase in farmer adoption of buckwheat when technical support and training networks were provided. Behavioural reviews of Novel Food Technology Neophobia (NFTN) showed that consumers initially expressed hesitation; however, once provided with information on biodiversity conservation, willingness to pay for minor crops increased. The study implementing DNA barcoding to trace minor crops in processed goods achieved a high success rate in identifying the presence of minor crops after high-temperature processing, validating the 'Machines' dimension and providing a measurable standard for regulatory compliance and biodiversity-friendly labelling (Tsolakidou et al., 2025).

While these findings are encouraging, they should be interpreted with caution. The pilot studies were conducted in controlled settings with limited sample sizes, and the evidenced technologies have not yet been tested at industrial scale. Furthermore, findings varied across regional contexts, indicating limited transferability of uniform adoption strategies. For instance, buckwheat-enriched products achieved higher sensory acceptance in Northern European countries compared to Southern European countries, reflecting differences in culinary traditions and familiarity with buckwheat-based foods (Ranic et al., 2025). These regional variations underscore the need for context-specific product development and marketing strategies rather than a one-size-fits-all approach.

Additionally, the environmental benefits of minor crops are context dependent. Adjusted life cycle assessments (LCA) conducted across EU pilot farms indicated that certain minor crops showed lower greenhouse gas emissions compared with reference conventional crops in specific settings; however, these reductions varied substantially by crop type, cultivation method, and regional agro-climatic conditions. The nutritional advantages of minor crops are also accompanied by challenges: certain species, such as grass pea (Lathyrus sativus), contain compounds (β-ODAP) that require careful variety selection and processing to reduce to safe levels before market introduction (Solovieva et al., 2025).

Table 1
Overview of methodological approach for developing the 6Ms framework.

Methodological component	Data source / approach	Purpose / contribution
Literature review	Web of Science, Scopus; snowball sampling approach (2024)	Synthesises knowledge on agrobiodiversity, value chains and consumer behaviour; identifies gaps and concepts for the framework
Policy analysis	FAO, European Commission, EFSA, CBD Secretariat reports and policy documents	Summarises global and regional state of biodiversity, regulatory gaps and sustainability opportunities
Illustrative evidence	EU projects (BioValue, Divinfood, Radiant, Diversicrop)	Provides real-world examples of minor crop adoption, value chain dynamics and stakeholder interactions
Stakeholder engagement	Focus groups, consumer surveys, home cooking tests, Agent-Based Modelling tool	Captures consumer preferences, behavioural insights and actor perspectives to inform practical recommendations
Recommendation structuring	BioValue objectives, stakeholder mapping	Aligns recommendations with specific target audiences across the value chain
Framework development	Synthesis of all above components	Constructs the 6Ms framework as a conceptually grounded, evidence-informed and structured tool for minor crop integration

5.2. The pathway to recommendations and the 6Ms framework

In a market overloaded with different products promoted to serve the same goal, the challenge is to create novel products to attract new consumers and penetrate the market (Simeone and Marotta, 2010). However, despite the large amount of research on optimising the product development process, the majority of new food products (72–88%) continue to fail (Buisson, 1995; Lord, 2007; Rudolph, 2007). Only 7–25% of products considered 'new' food goods are truly new to consumers (Lord, 2007; Rudolph, 2007). This low rate of innovation, combined with the high failure rate of food products, requires the process to become more 'focused, quantitative, rapid, and knowledge-based' (Earle, 1997). This process is usually described as a five-to-eight step process, including idea or concept generation and screening, research, development, product testing, and marketing launch activities (Rudder et al., 2001). Research focusing on food product development has indicated certain success factors, such as market knowledge, consumer insights, and retailer involvement. Hence, input and feedback from various sources, including retailers, suppliers, food and research centres, consumers, and other chain actors, is required to avoid and solve problems that may arise in the development process (Stewart-Knox and Mitchell, 2003). Accordingly, incorporating the consumer perspective at the very early stages of new product development has been identified as an important success factor for the entire process (Van Kleef et al., 2005).

The term 'recommendation' in this context refers to a targeted action or strategy proposed to improve certain aspects of processed food production, such as nutrition, sustainability, and market acceptance. These recommendations are not merely suggestions; they present essential tools for enhancing the implementation strategies across the 6Ms (Materials, Machines, Methods, Manpower, Measurements, Milieu). The 6Ms framework is commonly used in quality management and process improvement, providing a structured approach to enhance production efficiency (Erkens and Stouthamer, 2020), and has also been successfully applied in different fields outside manufacturing, such as healthcare, management, and education (Boca, 2015; Wilken et al., 2017; Wong, 2011)(Fig. 2).

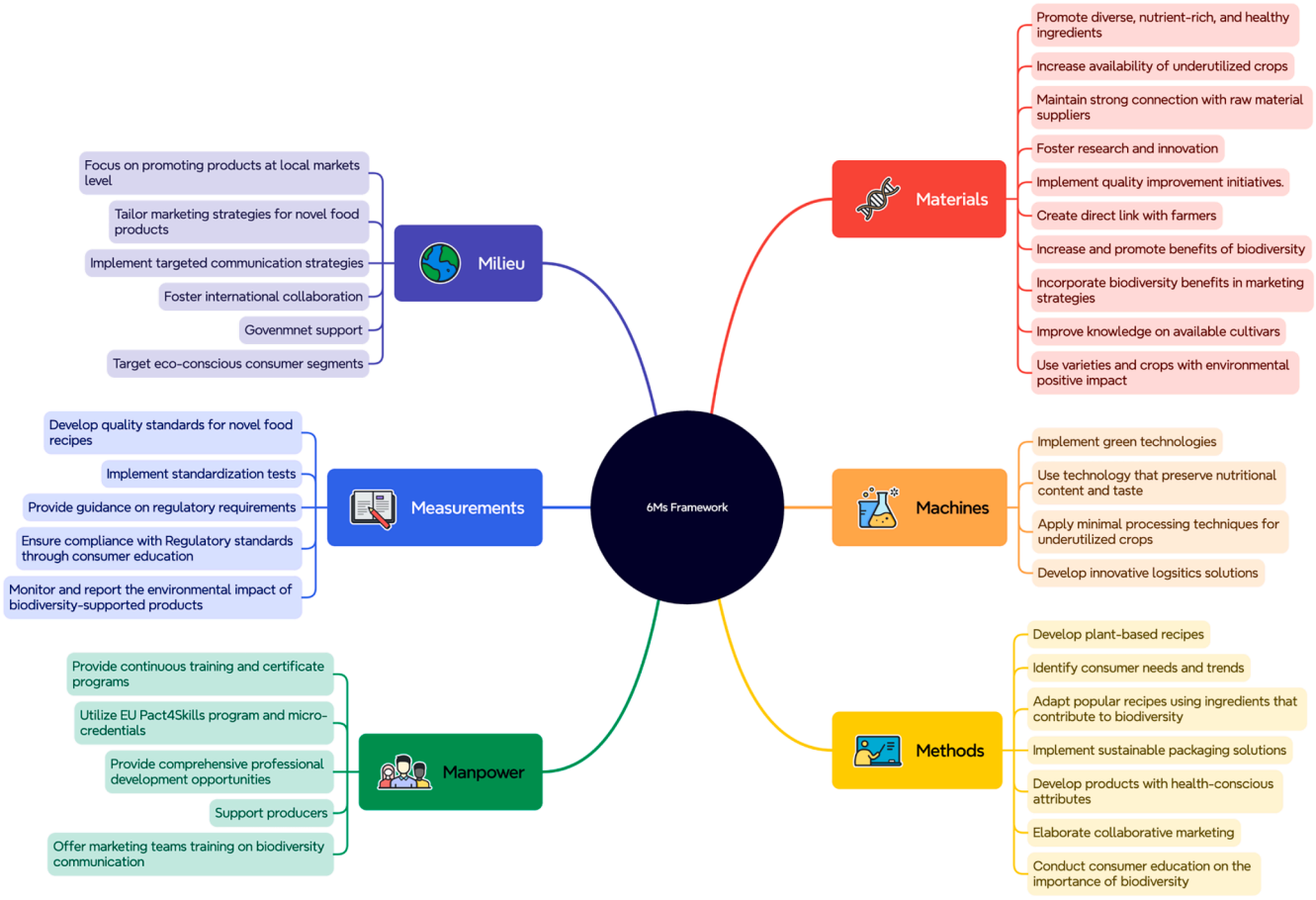


Fig. 2. Overview of the 6Ms framework and related recommendations for minor crop adoption.

By applying this framework, we aim for a systematic integration of minor crops into the supply chain, addressing challenges related to resource availability, technological adaptation, workforce training, and environmental considerations (Boca, 2015). By categorising recommendations into these six dimensions, we make them practical, relevant, and adaptable for a wide range of stakeholders. This structured approach allows for clear, targeted interventions under each section, providing a pathway for effective implementation with short- and long-term impact in the value chain.

Each recommendation highlights the expected impact, identifies the target audience, and addresses potential challenges, ensuring their effective implementation by stakeholders. This holistic approach ensures that the recommendations serve as a bridge between innovation and the practical realities of the food production value chain. A comprehensive overview of the 6Ms framework, supported by integrated evidence, is presented in Table 2 and the Supplementary Material.

5.3. *Comparative analysis: 6Ms framework and existing food systems approaches*

To demonstrate the distinctive contribution of the 6Ms framework, we compare it with four established analytical approaches commonly applied to food systems and value chain research: (i) Value Chain Analysis (VCA), (ii) the Multi-Level Perspective (MLP) on socio-technical transitions, (iii) the Food-Energy-Water (FEW) nexus approach, and (iv) the FAO Sustainable Food Value Chain (SFVC) framework.

Value Chain Analysis, as formalised by the FAO (2014) and widely applied in agri-food studies, maps the flow of products, information, and finance from production to consumption. While VCA effectively identifies economic bottlenecks, governance structures, and value distribution, it typically treats technology, workforce capacity, and consumer behaviour as exogenous factors. The 6Ms framework extends VCA by explicitly integrating technological readiness (Machines), human capital (Manpower), and sensory and regulatory metrics (Measurements) as endogenous dimensions that shape value chain performance.

The Multi-Level Perspective on sustainability transitions, developed by Geels (2011), examines how niche innovations interact with established socio-technical regimes and broader landscape pressures. The MLP is valuable for understanding long-term system transformation but operates at a high level of abstraction, offering limited operational guidance for practitioners. The 6Ms framework complements the MLP by providing concrete, actionable dimensions within which niche innovations like minor crops can be operationalised. Where the MLP asks 'how do regimes change?', the 6Ms asks 'what specific interventions across materials, methods, machines, manpower, measurements, and milieu enable that change?'.

The Food-Energy-Water nexus approach (Ringler et al., 2013) examines the interconnections between resource systems, highlighting trade-offs and synergies in resource allocation. While the FEW nexus captures critical resource interactions, it does not address the socio-economic and behavioural dimensions of food system transformation, such as consumer acceptance, workforce training, or regulatory frameworks, that are essential for minor crop adoption. The 6Ms framework incorporates these dimensions through the Milieu and Manpower components, bridging the gap between resource-based analysis and implementation-oriented strategies.

The FAO Sustainable Food Value Chain framework (FAO, 2014; Neven, 2014) offers a multi-dimensional approach that integrates

Table 2
Comprehensive overview of the 6Ms framework for minor crop adoption with integrated evidence.

6Ms dimension	Focus / scope	Example recommendation	Identified gap / opportunity
Materials	Ingredients used in processed food products	Develop low-ODAP grass pea varieties; innovate buckwheat-based dishes	Crop safety and nutritional quality limits adoption
Machines	Technologies and equipment used in food processing	Introduce small-scale processing equipment; deploy DNA barcoding for traceability	Lack of processing tools limits efficiency and scalability
Methods	Development of food combinations and recipes	Improve post-harvest processing techniques; develop appealing novel dishes	Nutrient loss and inconsistent product quality reduce appeal
Manpower	Training and support for food industry professionals	Farmer training programmes; peer-to-peer learning networks	Limited technical knowledge reduces adoption
Measurements	Compliance with regulatory standards, sensory and consumer testing, technological validation	Conduct sensory tests, DNA barcoding, and consumer surveys	Low consumer awareness and unknown preferences hinder market uptake
Milieu	Market introduction while respecting traditional culinary practices and consumer preferences	Policy incentives, transparent labelling, and biodiversity awareness campaigns	Regulatory and market barriers restrict scaling; Novel Food Technology Neophobia exists

Note: Supporting evidence, measurable outcomes, and interactions across dimensions are detailed in Supplementary Tables S3 and S4.

economic, social, and environmental sustainability into value chain development. While the SFVC framework provides a comprehensive sustainability lens, it does not explicitly disaggregate the technological and methodological dimensions required for processing novel food products from underutilised crops. The 6Ms framework addresses this limitation by providing a finer-grained taxonomy of production and processing dimensions (Methods, Machines, Materials) that are directly relevant to product development and quality assurance. Table 3 summarises the comparative strengths of each framework.

5.4. Synthesis of evidence across the 6Ms

The 6Ms framework has been chosen to structure this work as it is a well-known robust tool for quality management; however, its application in the agri-food sector has not been previously demonstrated. By drawing on findings from the BioValue project and related European initiatives, we demonstrate how specific data sources serve as direct inputs for each dimension in the framework. This integration ensures that the recommendations provided are grounded in technological, nutritional, and consumer-focused research.

Pilot studies within the BioValue project indicated that mild processing techniques preserved higher nutrient levels in buckwheat products compared with conventional high-temperature methods. Additionally, agent-based modelling functions as a decision-support tool for farmers and processors, simulating adoption pathways under different policy and market scenarios. On the manpower side, the involvement of chefs, food technologists, and farmers in collaborative, fork-to-farm engagement ensures that novel recipes are nutritionally optimised and commercially viable.

Through regional comparative analysis, the findings further indicate that while minor crops offer a universal contribution to biodiversity, their integration strategies must be customised based on regional socio-technical landscapes. Case studies within Mediterranean contexts suggested a stronger need for contractual formalisation between farmers and processors, whereas Northern European pilot cases highlighted consumer-oriented marketing challenges and culinary education needs (Solovieva et al., 2025). These findings are based on multi-country evidence across European regions and value chain stages, although contextual variation limits the generalisability of specific policy prescriptions.

Recent literature highlights both the potential and persistent

Table 3
Comparative analysis of food systems frameworks and the 6Ms contribution.

Framework	Primary focus	Key dimensions	Limitations for minor crops	6Ms added value
Value Chain Analysis (VCA) (FAO, 2014; Neven, 2014)	Economic transactions, governance structures, and value distribution along the chain	Input supply, production, processing, distribution, consumption	Treats technology, workforce capacity, and consumer behaviour as exogenous factors; offers limited insight into product innovation or multi-dimensional adoption barriers	Extends VCA by endogenising Machines, Manpower, and Measurements; explains how technological readiness and consumer acceptance interact with economic performance
Multi-Level Perspective (MLP) (Geels, 2011; El Bilali, 2019)	Socio-technical transitions; niche innovation interactions with established regimes and landscape pressures	Niche innovations, socio-technical regimes, landscape developments	Operates at a high level of abstraction with limited operational guidance for practitioners; does not provide granular dimensions for product-level innovation	Complements MLP by translating transition theory into concrete dimensions (Materials, Methods, Machines) for operationalising niche innovations in food systems
Food-Energy-Water (FEW) Nexus (Ringler et al., 2013; FAO, 2014)	Resource interconnections, cross-sectoral trade-offs, and synergies in resource allocation	Food production, energy consumption, water use	Captures critical resource interactions but does not address socio-economic, behavioural, or regulatory dimensions essential for adoption	Incorporates Milieu (regulatory, cultural, market factors) and Manpower (skills, training, institutional capacity) to bridge resource analysis with implementation strategies
FAO Sustainable Food Value Chain (SFVC) (FAO, 2014; Neven, 2014)	Economic, social, and environmental sustainability integrated across value chain stages	Economic viability, social inclusiveness, environmental performance	Comprehensive sustainability lens but does not disaggregate technological and methodological processing dimensions for novel foods from underutilised crops	Provides finer-grained taxonomy of production dimensions (Materials, Methods, Machines) directly relevant to minor crop product development and quality assurance
6Ms Framework (this study) (Boca, 2015; Erkens and Stouthamer, 2020)	Multi-dimensional integration of technical, human, organisational, and contextual factors for food system innovation	Materials, Methods, Machines, Manpower, Measurements, Milieu	Simplifies complex socio-ecological systems; limited capacity to capture feedback loops, power asymmetries, and institutional inertia; requires further empirical validation	Holistic, practitioner-oriented lens; reveals trade-offs and synergies across dimensions; provides a structured basis for context-sensitive, evidence-based recommendations

challenges of underutilised and neglected crops. Systematic reviews (Chimonyo et al., 2022) indicate a lack of integrated frameworks capturing the interactions among agronomic, nutritional, market, and socio-cultural factors, while nutrition-focused studies (Ali and Bhattacharjee, 2023) reveal contradictions between the high micronutrient density of minor crops and their low consumer adoption due to safety concerns, limited awareness, and post-harvest constraints. Regional analyses (Mengesha and Ayana, 2024; Onawo and Egboduku, 2025) further identify gaps in institutional support and policy frameworks. Synthesising these findings, the 6Ms framework offers a multi-dimensional lens that integrates technical, behavioural, organisational, and environmental factors, enabling identification of gaps and opportunities that single-focus approaches may overlook. This framework also illustrates specific trade-offs and synergies—for instance, how improved post-harvest methods require trained manpower, or how consumer acceptance interacts with crop traits—providing a structured basis for minor crop adoption strategies.

6. Recommendations for the integration of minor crops and expected impact

Integrating minor crops into current food systems presents opportunities to enhance agrobiodiversity, promote sustainable agricultural practices, and enrich global diets. However, this road is marked with limitations due to policy gaps, market constraints, and consumer unfamiliarity. To address these challenges, a multi-faceted approach is needed, addressing all stakeholders across food chains by combining policy support, industry commitment, and consumer education. Recommendations presented in this paper aim to pave the road for minor crops to be integrated into novel processed food products, facilitating their market entry with consumer acceptance. This approach ensures their economic viability while contributing to global sustainability goals, particularly Sustainable Development Goals (SDGs) 2 (Zero Hunger), 3 (Good Health and Well-Being), 12 (Responsible Consumption and Production), 13 (Climate Action), and 15 (Life on Land) (United Nations, 2015).

Governments should offer financial incentives such as subsidies, grants, and tax reductions to mitigate the risks associated with growing crops that currently have limited market presence (Amaglobeli, 2024; El Bilali et al., 2024). These interventions can encourage diversification in agricultural production, strengthening food security while promoting climate-resilient crops that require fewer inputs (Amaglobeli, 2024). Aligning with SDG 2 and SDG 13 (United Nations, 2015), these measures will not only enhance farmers' incomes (Morris et al., 2007) but also contribute to climate adaptation strategies.

Research and development (R&D) is essential for improving productivity, resilience, and processing potential of minor crops (Mabhaudhi et al., 2017). R&D should focus on studying and identifying supply chain flaws and improving processing methods to make these crops more acceptable and convenient for consumers and the food industry (El Bilali et al., 2023). Ensuring sustained demand through public procurement policies—integrating minor crops into national school meal programmes, hospital catering, and institutional food services—creates stable markets while raising public awareness (El Bilali et al., 2023). This approach supports SDG 2 and SDG 3 (United Nations, 2015) and encourages healthier dietary patterns.

The food industry plays an essential role in translating these initiatives into market success. Strong collaboration between agricultural producers, food manufacturers, and retailers is necessary to develop novel products that are appealing, convenient for consumers, and rich in nutrients using minor crops (Donkor et al., 2020; El Bilali et al., 2024; Haggblade et al., 2017). Large retailers should dedicate shelf space to minor crop-based products and increase promotional efforts to enhance visibility.

Building strong supply chains that connect smallholder farmers with larger markets is equally important (Darko-Koomson et al., 2020; Donkor et al., 2018; Etongo et al., 2015; Mbosso et al., 2020). Farmers should benefit from increasing demand through fair trading practices and cooperative farming models. Long-term partnerships between retailers, food brands, and farmers should provide technical support, logistical assistance, and market access.

Raising consumer awareness (Jena et al., 2018) and improving education will ensure the long-term success of these interventions. Large-scale awareness campaigns that highlight the health, environmental, cultural, and economic benefits of minor crops are needed. Labelling initiatives can help consumers make informed choices (Bhatt et al., 2018; de Magistris et al., 2015), aligning with SDG 12 and SDG 15 (United Nations, 2015). Social media, culinary influencers, and chef partnerships can attract consumer interest. Long-term strategies such as integrating crop diversity and sustainable food systems into school curricula (Hilimire et al., 2014) can yield lasting benefits by fostering healthy and sustainable eating habits from a young age.

Achieving successful integration of minor crops requires coordinated efforts across all supply chain actors, at the policy, industry, and consumer levels. Policies supporting farmers, investments in R&D and supply chains, and consumer-oriented initiatives should collaborate to create a sustainable, resilient food ecosystem (Table 4).

Table 4
Contribution of minor crops to selected SDGs.

SDG	Relevance to minor crops	Specific examples
SDG 2 — Zero Hunger	Diversify food sources and improve food security	Green leafy vegetables (amaranth, chard, wild greens) provide iron and folate. Lentils and buckwheat add plant-based protein. Armenian cucumber and eggplant provide nutritious, locally adapted vegetables
SDG 3 — Good Health and Well-Being	Support healthier diets and nutritional outcomes	Green leafy vegetables and Sonchus are rich in vitamins and antioxidants; traditional tomatoes provide lycopene. Lentils and buckwheat improve dietary protein and micronutrient intake
SDG 8 — Decent Work and Economic Growth	Create income and employment opportunities	Value-chain development for minor crops (tomatoes, lentils, buckwheat, eggplant) supports small-scale farmers and processors. Local marketing of Armenian cucumber and wild greens generates new income
SDG 9 — Industry, Innovation and Infrastructure	Encourage innovation in food systems	Processing technologies and novel products using minor crops (tomato landraces, buckwheat, eggplant) stimulate innovation. Minor crop integration into local food supply chains
SDG 12 — Responsible Consumption and Production	Promote sustainable production and diverse diets	Locally adapted minor crops (green leafy vegetables, Armenian cucumber, tomato landraces) reduce reliance on major global crops, lower input requirements and support sustainable farming
SDG 13 — Climate Action	Enhance climate resilience	Drought- and heat-tolerant crops (buckwheat, Armenian cucumber, eggplant, tomato landraces) increase resilience to climate change, reduce dependence on high-input systems
SDG 15 — Life on Land	Support biodiversity and ecosystem health	Minor crops (green leafy vegetables, Sonchus, buckwheat, lentil, eggplant) increase agrobiodiversity, reduce monocropping, improve soil health and pollinator habitats

7. Challenges, limitations, and opportunities

The successful integration of minor crops and novel processed food products will face numerous challenges, including consumer resistance, limited industry collaboration, supply chain inefficiencies, regulatory barriers, and financial limitations.

A significant barrier to acceptance stems from misconceptions, limited accessibility, and a lack of awareness regarding nutritional properties and health benefits. Many consumers remain unfamiliar with these crops and perceive them as inferior or difficult to prepare, reinforcing psychological barriers such as Novel Food Technology Neophobia (NFTN) (Ross et al., 2022). Feelings of disgust toward unfamiliar foods can further reduce motivation to adopt sustainable dietary choices (Ribeiro et al., 2022; Sogari et al., 2019). Enhancing public knowledge through transparent labelling, educational campaigns, and promotional marketing is crucial (Günden et al., 2024; Knez et al., 2023). Improving supply chain infrastructure and involving influential actors such as chefs and food bloggers can help shift consumer perceptions.

Hesitation to innovate in the food industry is often caused by fear of failure, financial risks, and a focus on safe choices dictated by the existing market. These challenges can be addressed by encouraging public-private partnerships and subsidised pilot programmes.

Supply chain gaps—limited availability of raw materials, logistical constraints, and lack of processing facilities—disrupt the flow from production to market (Kaur et al., 2025). Cooperative farming and appropriate processing and storage technologies can stabilise supply and reduce costs (Knez et al., 2023).

Regulatory barriers slow market access, especially for novel food products from minor crops. Streamlined approval processes, accessible regulatory guidance, and tax incentives can facilitate integration. Strengthening multi-stakeholder collaboration across jurisdictions is essential.

Several limitations of the present study should be acknowledged. First, the 6Ms framework, while providing a structured multi-dimensional lens, simplifies complex socio-ecological systems and has limited capacity to capture feedback loops, power asymmetries, and institutional inertia within food systems. Second, the empirical evidence supporting the framework derives predominantly from EU-funded projects in European contexts, which may affect the applicability of findings to other regions with different agro-ecological and socio-economic conditions. Third, the literature review employed a snowball sampling approach rather than a formal systematic review protocol, which may have introduced selection bias despite ensuring broad thematic coverage. Fourth, expanding minor crop cultivation carries potential risks, including the possibility of monocropping of formerly diverse species and new social inequalities in access to genetic resources. These limitations underscore the importance of continued empirical testing, adaptive management, and inclusive governance in the further development and application of the 6Ms framework.

8. Conclusion

This study has examined the potential of minor crops to address contemporary challenges of food security, biodiversity loss, and climate change through the systematic application of the 6Ms framework. Our analysis demonstrates that the integration of minor crops into European food value chains requires coordinated action across multiple dimensions—from crop selection and breeding (Materials) to processing technologies (Methods and Machines), workforce development (Manpower), quality assurance and consumer testing (Measurements), and the broader policy and market environment (Milieu). The 6Ms framework provides a structured lens through which these interdependencies can be understood and addressed.

Several key findings emerge from this analysis. First, the adoption of minor crops is constrained not by a single barrier but by a constellation of interacting factors: agronomic limitations, technological gaps, knowledge deficits, and market failures. The 6Ms framework reveals that addressing any single dimension in isolation is unlikely to succeed; interventions must be coordinated across multiple dimensions. For example, improved post-harvest processing methods (Methods) require trained personnel (Manpower), and consumer acceptance (Measurements) depends on both product quality (Materials) and effective communication strategies (Milieu).

Second, empirical evidence from BioValue and related projects indicates promising consumer acceptance of minor crop-based products when developed with attention to sensory quality, cultural familiarity, and transparent labelling. However, these findings are context-dependent and vary across regions, crops, and consumer segments, warranting caution in generalisation.

Third, the policy landscape for minor crops in the EU remains fragmented. While the CAP 2023–2027, the European Green Deal, and the Farm to Fork Strategy provide broad frameworks for sustainable agriculture, explicit provisions for minor crops are limited. The forthcoming CAP reform post-2027 and the ongoing implementation of the Novel Food Regulation present critical windows of opportunity to embed minor crop diversification into EU agricultural and food safety policy. We recommend: (i) introducing eco-schemes specifically rewarding minor crop cultivation under the CAP; (ii) establishing a simplified authorisation pathway under the Novel Food Regulation for crops with documented traditional use; (iii) integrating minor crop targets into national biodiversity strategies; and (iv) creating dedicated funding streams for minor crop value chain development under Horizon Europe and its successor programmes.

Farmers face significant financial constraints; targeted support measures and incentive schemes are recommended to encourage adoption among farmers. R&D investment with a long-term scope benefits the entire value chain. The education and health sectors can integrate minor crops into school meals and hospital catering. Social media campaigns, educational activities, and partnerships with chefs can guide consumer demand toward minor crop-based products.

Implementation will face obstacles including consumer resistance, supply chain gaps, and regulatory barriers. Coordinated multi-stakeholder efforts and innovative technological solutions are needed. Alignment with the SDGs can attract global attention and promote the transition toward more sustainable practices.

The concept of promoting minor crops is not merely a strategy to improve food security but an avenue toward environmental sustainability, economic opportunity, and cultural diversity. Future research should prioritise: (i) longitudinal studies tracking economic and environmental outcomes of minor crop adoption; (ii) comparative analyses of regulatory pathways for novel foods across jurisdictions; (iii) large-scale consumer studies examining communication strategies in shifting dietary preferences; and (iv) refinement of the 6Ms framework through integration with quantitative sustainability metrics and participatory modelling. With this approach, we can work toward a sustainable future and a long-term solution to food security challenges.

In conclusion, by integrating minor crops into our food systems, we not only address current challenges but also pave the way for a more resilient, equitable, and sustainable global food network that supports both people and the planet.

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Amine Zouaghi: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Marija Knez:** Writing – review & editing, Validation, Supervision, Conceptualization. **Konstadinos Mattas:** Validation, Supervision, Methodology, Funding acquisition, Conceptualization. **George Baourakis:** Validation, Supervision, Funding acquisition. **Eleni Stamataki:** Writing – review & editing, Validation, Project administration. **Mirjana Gurinovic:** Resources, Investigation, Data curation. **Cyril Tisseyre:** Writing – review & editing, Investigation, Data curation. **Burkhard Schaer:** Validation, Resources, Investigation, Formal analysis, Data curation.

Declaration of competing interest

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

Supplementary materials

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Data availability

Data will be made available on request.

References

Ali, A., Bhattacharjee, B., 2023. Nutrition security, constraints, and agro-diversification strategies of neglected and underutilized crops to fight global hidden hunger. Front. Nutr. 10, 1221832. https://doi.org/10.3389/fnut.2023.1221832.

Amaglobeli, D., 2024. Agricultural producer subsidies. IMF Notes 2024 (1), 1. https://doi.org/10.5089/9798400285950.068.

Bélanger, J., Pilling, D., 2019. The State of the World's Biodiversity for Food and Agriculture. FAO. https://doi.org/10.4060/CA3129EN.

Bhatt, S., Lee, J., Deutsch, J., Ayaz, H., Fulton, B., Suri, R., 2018. From food waste to value-added surplus products (VASP): consumer acceptance of a novel food product category. J. Consum. Behav. 17, 57–63. https://doi.org/10.1002/cb.1689.

Boca, G., 2015. 6M in management education. Procedia – Soc. Behav. Sci. 182, 4–9. https://doi.org/10.1016/j.sbspro.2015.04.727.

Buisson, D., 1995. Developing new products for the consumer. Food Choice and the Consumer, pp. 182–215.

Carbas, B., Machado, N., Pathania, S., Brites, C., Rosa, E., Barros, A., 2023. Potential of legumes: nutritional value, bioactive properties, innovative food products, and application of eco-friendly tools for their assessment. Food Rev. Int. 39, 160–188. https://doi.org/10.1080/87559129.2021.1901292.

CBD, 2022. Kunming-Montreal global biodiversity framework. Convention on Biological Diversity. Montreal.

Chandra, A., Idrisova, A., 2011. Convention on biological diversity: a review of national challenges and opportunities for implementation. Biodivers. Conserv. 20, 3295–3316. https://doi.org/10.1007/s10531-011-0141-x.

Chimonyo, V.G.P., Chibarabada, T.P., Choruma, D.J., 2022. Modelling neglected and underutilised crops: a systematic review of progress, challenges, and opportunities. Sustainability 14 (21), 13931. https://doi.org/10.3390/su142113931.

Chivenge, P., Mabhaudhi, T., Modi, A.T., Mafongoya, P., 2015. The potential role of neglected and underutilised crop species as future crops under water scarce conditions in sub-Saharan Africa. Int. J. Env. Res. Public Health 12, 5685–5711. https://doi.org/10.3390/ijerph120605685.

Cholez, C., Pauly, O., Mahdad, M., Mehrabi, S., Giagnocavo, C., Bijman, J., 2023. Heterogeneity of inter-organizational collaborations in agrifood chain sustainability-oriented innovations. Agric. Syst. 212, 103774. https://doi.org/10.1016/j.agsy.2023.103774.

Collins, W., Qualset, C., 1998. Biodiversity in Agroecosystems. CRC Press. https://doi.org/10.1201/9781003040668.

Coulter, J., 2004. World agriculture: towards 2015/2030. An FAO perspective (ed. J. Bruinsma). Exp. Agric. 40, 269. https://doi.org/10.1017/S0014479704211796.

Cuadros-Casanova, I., et al., 2023. opportunities and challenges for common agricultural policy reform to support the European Green Deal. Conserv. Biol. 37, e14052. https://doi.org/10.1111/cobi.14052.

Darko-Koomson, S., Aidoo, R., Abdoulaye, T., 2020. Analysis of cassava value chain in Ghana: implications for upgrading smallholder supply systems. J. Agribus. Dev. Emerg. Econ. 10, 217–235. https://doi.org/10.1108/JADEE-05-2019-0066.

de Magistris, T., Pascucci, S., Mitsopoulos, D., 2015. Paying to see a bug on my food: how regulations and information can hamper radical innovations in the European Union. Br. Food J. 117, 1777–1792. https://doi.org/10.1108/BFJ-06-2014-0222.

Devos, Y., et al., 2022. Addressing the need for safe, nutritious and sustainable food: outcomes of the 'One – Health, Environment & Society – Conference 2022'. Trends. Food Sci. Technol. 129, 164–178. https://doi.org/10.1016/j.tifs.2022.09.014.

Donkor, E., Donkor, E., Owusu-Sekyere, E., Owusu, V., 2020. The development and promotion of sweet potato yoghurt in Ghana: implications for sustainable production and consumption policies. Sustainability 12, 3336. https://doi.org/10.3390/su12083336.

Donkor, E., Onakuse, S., Bogue, J., de los Ríos Carmenado, I., 2018. Determinants of farmer participation in direct marketing channels: a case study for cassava in the Oyo State of Nigeria. Span. J. Agric. Res. 16, e0106.

Earle, M., 1997. Changes in the food product development process. Trends. Food Sci. Technol. 8, 19–24. https://doi.org/10.1016/S0924-2244(96)20009-3.

El Bilali, H., 2019. The multi-level perspective in research on sustainability transitions in agriculture and food systems: a systematic review. Agriculture 9 (4), 74. https://doi.org/10.3390/agriculture9040074.

El Bilali, H., et al., 2024. Conservation and promotion of neglected and underutilized crop species in West Africa: policy and governance. Sustainability 16, 6194. https://doi.org/10.3390/su16146194.

El Bilali, H., Cardone, G., De Falcis, E., Naino Jika, A., Rokka, S., Diawara, A., Ghione, A., 2023. Neglected and underutilised species (NUS): an analysis of strengths, weaknesses, opportunities and threats (SWOT). AGROFOR Int. J. 8 (1), 19–29. https://doi.org/10.7251/AGRENG2301019E.

Erkens, G., Stouthamer, E., 2020. The 6M approach to land subsidence. Proc. IAHS 382, 733–740. https://doi.org/10.5194/piahs-382-733-2020.

Etongo, D., Djenontin, I., Kanninen, M., Fobissie, K., 2015. Smallholders' tree planting activity in the Ziro Province, southern Burkina Faso: impacts on livelihood and policy implications. Forests 6, 2655–2677. https://doi.org/10.3390/f6082655.

European Commission, 2020. Farm to fork strategy: for a fair. Healthy Environ.-Friendly Food Syst. COM (2020), 381 final.

FAO, 2014. Developing Sustainable Food Value Chains: Guiding Principles. Food and Agriculture Organization, Rome.

FAO, 2022. Agricultural Production Statistics 2000–2021. FAO. https://doi.org/10.4060/cc3751en.

FAO, 2023. Urbanization, agrifood systems transformation and healthy diets across the rural-urban continuum. The State of Food Security and Nutrition in the World. FAO, Rome.

Garn, S.M., Leonard, W.R., 1989. What did our ancestors eat? Nutr. Rev. 47, 337–345. https://doi.org/10.1111/j.1753-4887.1989.tb02765.x.

Geels, F.W., 2011. The multi-level perspective on sustainability transitions: responses to seven criticisms. Environ. Innov. Soc. Transit. 1 (1), 24–40. https://doi.org/10.1016/j.eist.2011.02.002.

Ghosh, S., Sarkar, T., Chakraborty, R., 2023. Underutilized plant sources: a hidden treasure of natural colors. Food Biosci. 52, 102361. https://doi.org/10.1016/j.fbio.2023.102361.

Gruère, G., Giuliani, A., Smale, M., 2012. Marketing Underutilized Plant Species for the Benefit of the Poor: A Conceptual Framework. International Food Policy Research Institute.

Günden, C., Atakan, P., Yercan, M., Mattas, K., Knez, M., 2024. Consumer response to novel foods: a review of behavioral barriers and drivers. Foods 13, 2051. https://doi.org/10.3390/foods13132051.

Haggblade, S., Me-Nsope, N., Staatz, J., 2017. Food security implications of staple food substitution in Sahelian West Africa. Food Policy 71, 27–38.

Havinga, T., 2006. Private regulation of food safety by supermarkets. Law Policy 28, 515–533. https://doi.org/10.1111/j.1467-9930.2006.00237.x.

Hermann, M., 2009. The impact of the European Novel Food Regulation on trade and food innovation based on traditional plant foods from developing countries. Food Policy 34 (6), 499–507.

Hilimire, K., Gillon, S., McLaughlin, B., Dowd-Uribe, B., Monsen, K., 2014. Food for thought: developing curricula for sustainable food systems education programs. Agroecol. Sustain. Food Syst. 38, 722–743. https://doi.org/10.1080/21683565.2014.881456.

HLPE, 2020. Food Security and Nutrition: Building a Global Narrative Towards 2030. High Level Panel of Experts on Food Security and Nutrition, Rome.

Hunter, D., et al., 2019. The potential of neglected and underutilized species for improving diets and nutrition. Planta 250, 709–729. https://doi.org/10.1007/s00425-019-03169-4.

Idowu, O., 2009. Contribution of neglected and underutilized crops to household food security and health among rural dwellers in Oyo State, Nigeria. In: International Symposium on Underutilized Plants for Food Security, Nutrition, Income and Sustainable Development, pp. 49–56. https://doi.org/10.17660/ActaHortic.2009.806.3.

IPBES Díaz, S., et al., 2019. Summary for policymakers of the global assessment report on biodiversity and ecosystem services. https://doi.org/10.5281/ZENODO.3553579.

Jena, A., Deuri, R., Sharma, P., Singh, S., 2018. Underutilized vegetable crops and their importance. J. Pharmacogn. Phytochem. 7, 402–407.

Kalmpourtzidou, A., Boussetta, S., Al-Naqeb, G., De Giuseppe, R., Cena, H., 2025. Novel foods, neglected and alien species to increase food biodiversity of diets in Europe. Future Foods 11, 100596. https://doi.org/10.1016/j.fufo.2025.100596.

Kamrath, C., Wesana, J., Steur, H., Gellynck, X., Bröring, S., 2023. Evaluation of food technologies across supply chain actors: a systematic review of explanatory models. IJISD 17, 244–288. https://doi.org/10.1504/IJISD.2023.131798.

Kaur, S., et al., 2025. Resurrecting forgotten crops: food-based products from potential underutilized crops – a path to nutritional security and diversity. Future Foods 11, 100585. https://doi.org/10.1016/j.fufo.2025.100585.
Knez, M., et al., 2023. Causes and conditions for reduced cultivation and consumption of underutilized crops: is there a solution? Sustainability 15, 3076. https://doi.org/10.3390/su15043076.
Knez, M., Mattas, K., Gurinovic, M., Gkotzamani, A., Koukounaras, A., 2024b. Revealing the power of green leafy vegetables: cultivating diversity for health, environmental benefits, and sustainability. Glob. Food Sec. 43, 100816.
Knez, M., Ranić, M., Gurinović, M., 2024a. Underutilized plants increase biodiversity, improve food and nutrition security, reduce malnutrition, and enhance human health and well-being. Let's put them back on the plate! Nutr. Rev. 82 (8), 1111–1124.
Lachat, C., et al., 2018. Dietary species richness as a measure of food biodiversity and nutritional quality of diets. Proc. Natl. Acad. Sci. U.S.A. 115, 127–132. https://doi.org/10.1073/pnas.1709194115.
Lara, S.W., Tsiami, A., Cross, P., 2023. Discovering and mapping colloquial terminologies describing underutilized and neglected food crops – A comprehensive review. Foods 12 (12), 2428.
Laulund, S., Wind, A., Derkx, P., Zuliani, V., 2017. Regulatory and safety requirements for food cultures. Microorganisms 5, 28. https://doi.org/10.3390/microorganisms5020028.
Li, X., Siddique, K., 2018. Future Smart Food: Rediscovering Hidden Treasures of Neglected and Underutilized Species for Zero Hunger in Asia. FAO.
Lord, J., 2007. New product failure and success. Developing New Food Products for a Changing Marketplace. CRC Press, pp. 47–74.
Mabhaudhi, T., Chimonyo, V., Chibarabada, T., Modi, A., 2017. Developing a roadmap for improving neglected and underutilized crops: a case study of South Africa. Front. Plant Sci. 8, 2143. https://doi.org/10.3389/fpls.2017.02143.
Mayes, S., Massawe, F., Alderson, P., Roberts, J., Azam-Ali, S., Hermann, M., 2012. The potential for underutilized crops to improve security of food production. J. Exp. Bot. 63, 1075–1079. https://doi.org/10.1093/jxb/err396.
Mazac, R., Järviö, N., Tuomisto, H., 2023. Environmental and nutritional life cycle assessment of novel foods in meals as transformative food for the future. Sci. Total Environ. 876, 162796. https://doi.org/10.1016/j.scitotenv.2023.162796.
Mbosso, C., et al., 2020. Fonio and bambara groundnut value chains in Mali: issues, needs, and opportunities for their sustainable promotion. Sustainability 12, 4766. https://doi.org/10.3390/su12114766.
Mengesha, D., Ayana, B., 2024. Status of underutilized crops in Ethiopia: opportunities, challenges and policy recommendations. Int. J. Agric. Biol. Sci. https://doi.org/10.5281/zenodo.14845355.
Moore, G., Tymowski, W., 2005. Explanatory Guide to the International Treaty on Plant Genetic Resources for Food and Agriculture. IUCN.
Morris, M., Kelly, V., Kopicki, R., Byerlee, D., 2007. Fertilizer Use in African Agriculture: Lessons Learned and Good Practice Guidelines. The World Bank.
Neven, D., 2014. Developing Sustainable Food Value Chains: Guiding Principles. FAO, Rome.
Onawo, O.L., Egboduku, W.O., 2025. Highlighting the untapped potential of neglected and underutilized crop species for sustainable food security. J. Underutilized Legumes 7 (2), 73–93.
Padulosi, S., Eyzaquirre, P., Hodgkin, T., 1999. Challenges and strategies in promoting conservation and use of neglected and underutilized crop species. Perspect. New Crops New Uses 140–145.
Padulosi, S., Thompson, J., Rudebjer, P., 2013. Fighting poverty, hunger and malnutrition with neglected and underutilized species (NUS): needs. Chall. Way Forw. https://doi.org/10.13140/RG.2.1.3494.3842.
Pandiyaraj, P., et al., 2024. Underutilized vegetable crops: potential sources of nutrition and livelihood security. Eur. J. Nutr. Food Saf. 16, 248–254. https://doi.org/10.9734/ejnfs/2024/v16i71473.
Pongsiri, M., Roman, J., 2007. Examining the links between biodiversity and human health: an interdisciplinary research initiative at the U.S. Environmental Protection Agency. EcoHealth 4, 82–85. https://doi.org/10.1007/s10393-007-0087-3.
Ranic, M., et al., 2025. Exploring buckwheat's potential—developing innovative dishes, sensory evaluation, consumer acceptance and market integration in Europe: a cross-country analysis. Front. Sustain. Food Syst. 9, 1673883.
Ranieri, A., Tregua, M., Di Bernardo, I., 2024. From land to table: a sustainable chain towards collaborative consumption. Understanding Collaborative Consumption. Edward Elgar Publishing, pp. 168–184. https://doi.org/10.4337/9781035307531.00022.
Read, Q., Hondula, K., Muth, M., 2022. Biodiversity effects of food system sustainability actions from farm to fork. Proc. Natl. Acad. Sci. U.S.A. 119, e2113884119. https://doi.org/10.1073/pnas.2113884119.
Ribeiro, J., Gonçalves, A., Moura, A., Varela, P., Cunha, L., 2022. Insects as food and feed in Portugal and Norway – cross-cultural comparison of determinants of acceptance. Food Qual. Prefer. 102, 104650. https://doi.org/10.1016/j.foodqual.2022.104650.
Ringler, C., Bhaduri, A., Lawford, R., 2013. The nexus across water, energy, land and food (WELF): potential for improved resource use efficiency? Curr. Opin. Env. Sustain 5 (6), 617–624. https://doi.org/10.1016/j.cosust.2013.11.002.
Roe, D., Seddon, N., Elliott, J., 2019. Biodiversity Loss is a Development Issue. International Institute for Environment and Development.
Ross, M., Collins, A., McCarthy, M., Kelly, A., 2022. Overcoming barriers to consumer acceptance of 3D-printed foods in the food service sector. Food Qual. Prefer. 100, 104615. https://doi.org/10.1016/j.foodqual.2022.104615.
Rudder, A., Ainsworth, P., Holgate, D., 2001. New food product development: strategies for success? Br. Food J. 103, 657–671. https://doi.org/10.1108/00070700110407012.
Rudolph, M., 2007. The food product development process. Developing New Food Products for a Changing Marketplace. CRC Press, pp. 75–89.
Scaffardi, L., Formici, G. (Eds.), 2022. Novel Foods and Edible Insects in the European Union: An Interdisciplinary Analysis. Springer. https://doi.org/10.1007/978-3-031-13494-4.
Shroff, R., Cortés, C., 2020. The biodiversity paradigm: building resilience for human and environmental health. Development 63, 172–180. https://doi.org/10.1057/s41301-020-00260-2.
Simeone, M., Marotta, G., 2010. Towards an integration of sensory research and marketing in new food products development: a theoretical and methodological review. Afr. J. Bus. Manag. 4, 4207–4216.
Sogari, G., Bogueva, D., Marinova, D., 2019. Australian consumers' response to insects as food. Agriculture 9, 108. https://doi.org/10.3390/agriculture9050108.
Solovieva, I., et al., 2025. Exploring the potential and challenges of Lathyrus sativus (grass pea) in European agri-food value chains: a cross-country analysis. Sustainability 17 (8), 3283. https://doi.org/10.3390/su17083283.
Stewart-Knox, B., Mitchell, P., 2003. What separates the winners from the losers in new food product development? Trends. Food Sci. Technol. 14, 58–64. https://doi.org/10.1016/S0924-2244(02)00239-X.
Thakur, M., 2014. Underutilized food crops: treasure for the future India. Food Sci. Res. J. 5 (2), 174–183. https://doi.org/10.15740/HAS/FSRJ/5.2/174-183.
Timaeus, J., Ruigrok, T., Siegmeier, T., Finckh, M.R., 2022. Adoption of food species mixtures from farmers' perspectives in Germany: managing complexity and harnessing advantages. Agriculture 12 (5), 697.
Tsolakidou, M.-D., et al., 2025. DNA barcoding for tracing biodiversity in mixed crop food products: a proof of concept within the BioValue project. Foods 14 (18), 3256. https://doi.org/10.3390/foods14183256.
Turck, D., et al., 2016. Dietary reference values for potassium. EFSA J. 15, e04592. https://doi.org/10.2903/j.efsa.2017.4780.
United Nations, 2015. Transforming our world: the 2030 agenda for sustainable development.
United Nations, 2022. World Population Prospects 2022: Summary of Results. UN DESA, New York.
van der Sluis, M., et al., 2022. The Need to Enhance Crop, Livestock and Aquatic Genetic Diversity in Food Systems. Wageningen Livestock Research. https://doi.org/10.18174/575252.
Van Kleef, E., Trijp, H., Luning, P., 2005. Consumer research in the early stages of new product development: a critical review of methods and techniques. Food Qual. Prefer. 16, 181–201. https://doi.org/10.1016/j.foodqual.2004.05.012.
Van Looy, T., Carrero, G., Mathijs, E., Tollens, E., 2008. Underutilized agroforestry food products in Amazonas (Venezuela): a market chain analysis. Agroforest Syst. 74, 127–141. https://doi.org/10.1007/s10457-008-9110-0.
Wilken, M., Hüske-Kraus, D., Klausen, A., Koch, C., Schlauch, W., Röhrig, R., 2017. Alarm fatigue: causes and effects. German Medical Data Sciences: Visions and Bridges. IOS Press, pp. 107–111.
Wong, K., 2011. Using an Ishikawa diagram as a tool to assist memory and retrieval of relevant medical cases from the medical literature. J. Med. Case Rep. 5, 1–3. https://doi.org/10.1186/1752-1947-5-120.