

INNOVATIONS IN FOOD PRODUCT DESIGN: LIFE CYCLE OPTIMIZATION FOR SUSTAINABLE CONSUMPTION IN THE REPUBLIC OF NORTH MACEDONIA

KATERINA BOJKOVSKA

University "St. Kliment Ohridski"

Bitola, North Macedonia

katerina.bojkovska@uklo.edu.mk

Abstract

Global challenges related to the sustainability of the food sector require innovative approaches to reduce negative environmental impacts and improve efficiency in food production and consumption. This paper analyzes innovations in food product design in the Republic of North Macedonia through optimization of their life cycle, with a focus on sustainability and resource efficiency.

The research includes an analysis of current practices in the Macedonian food industry, including the stages of raw material selection, processing, packaging, distribution and waste management. Special emphasis is placed on the use of local and organic ingredients, eco-friendly packaging and strategies for reducing food waste. Through life cycle assessment (LCA) methods and environmental impact analyses, challenges and opportunities for advancing the circular economy in the food sector are identified.

The results show that, although there is an increased interest in sustainable food practices in North Macedonia, there are significant challenges, such as the limited availability of eco-friendly packaging materials, insufficient consumer awareness and poor implementation of waste reduction strategies. The paper offers recommendations for strengthening sustainability in the sector by supporting domestic producers, investing in green technologies and educating consumers about eco-conscious consumption.

Keywords: *innovation, life cycle, sustainable consumption, food industry.*

JEL Classification: Q56, Q18, L66

1. INTRODUCTION

The agri-food industry is of strategic importance for the development of the economy of each country. Agri-food products represent a significant group of products because the safety and security of human health depend on them. In order to develop this industry, it is necessary to restructure it towards modern trends and permanently improve it by introducing modern technologies.

Ecological production of agri-food products emphasizes quality and safety, avoiding the use of additives that are harmful to human health.

The environmental sustainability of the agri-food industry implies the maximum use of renewable energy sources, the maintenance of the genetic diversity of agro-ecosystems and the protection of the environment, the reduction of all types of pollution

that may be a consequence of production, as well as production in accordance with environmental standards.

All this in order to achieve the goals of agri-food producers and gain appropriate profits, as well as active action in order to raise consumer awareness of purchasing ecological agri-food products and promote their benefits.

Agri-food producers should provide consumers with healthy food options and reliable nutritional information. At the same time, the development of the agri-food industry assumes industrial production aimed at satisfying the increasingly sophisticated needs and desires of consumers, with an emphasis on innovation, quality, a high level of food hygiene and standards for food safety and a healthy environment. The choice of food affects the environment and people's health and quality of life. The production, transportation, processing, storage, sale and preparation of food are processes that use a lot of natural resources (such as land, water and nutrients) and energy, and involve a large number of people.

Choosing food from limited resources or from unsustainable production systems (such as when eating certain types of wild fish) can cause the extinction of animal species and the destruction of natural habitats. In addition, food production irreversibly consumes huge amounts of energy and resources, since globally, one third of all food produced is lost or wasted every year. Although it is not so simple, this amount of food can feed hungry people. The development of agriculture contributes to the development of agri-food production systems. Each change brings with it new advantages and challenges and an increasing diversity and complexity of the agri-food system. To this end, it is necessary to analyze the drivers of change, as well as the challenges and contemporary trends faced by producers, consumers and policymakers in the agri-food sector. In modern conditions, increasing attention is paid to environmental protection and the production of high-quality, environmentally sound agri-food products that are increasingly in demand on the world market. Today's orientation of modern agri-food production is aimed at the economical, productive and competitive production of healthy, high-quality and safe food, in conditions of an ecologically clean and healthy environment, without or with minimal permitted use of chemical agents and increased use of organic fertilizers and biological agents for the protection of plants and animals in agricultural production, as well as without added ingredients in the process of their processing and preparation. In the future, proper business operations will not be possible without the application of new technologies due to the growth of the need for healthy food and profitability of companies in the agri-food industry, because if we look at the global level, the number of people is constantly increasing, while the arable land is constantly decreasing and air pollution is increasingly observed as a result of climate change.

The global food industry is experiencing a fundamental transformation driven by the urgent need for sustainability, technological progress and changed consumer habits. As a key sector directly affected and impacted by climate change, the food system faces an imperative to redesign its production models towards the principles of a circular economy. This challenge is particularly relevant for the Republic of North Macedonia,

where economic realities and an underdeveloped infrastructure for sustainable waste management create unique obstacles, but also opportunities for innovation.

The focuses on the critical role of food product design in optimizing their life cycle, with a particular focus on:

Modern challenges related to climate change and environmental degradation are transforming the global food industry, imposing an imperative for a transition to sustainable production and consumption models. In this context, innovations in food product design emerge as a key factor for optimizing their life cycle and reducing environmental damage. The Republic of North Macedonia, although facing economic and infrastructural constraints, shows increased sensitivity to these issues, which creates fertile ground for the implementation of circular economy principles in the food sector.

This study aims to explore the possibilities for promoting sustainability throughout the entire life cycle of food products – from the selection of raw materials, through production processes, to packaging and waste management. The focus is on:

1. Analysis of the current state of the environmental sustainability of the food industry – Analysis of the strategic importance of the sector and its potential for transition to green technologies, increased use of renewable energy sources and preservation of biodiversity (Bojkovska, 2021).

2. Identification of innovative solutions for efficient waste management - Examination of the "zero waste" model and its applicability in the local context, including innovative approaches (Camilleri, 2021).

3. Consumption trends – Assessment of the awareness and readiness of Macedonian consumers to adopt sustainable food practices, including economic barriers.

4. Policy frameworks – Critical review of existing regulations and the need for harmonization with European standards to support green innovations, especially in light of the EU's Farm to Fork (F2F) Strategy.

The study is based on the assumption that the optimal combination of technological innovation, consumer awareness and adequate policy measures can significantly reduce the environmental burden of the country's food sector.

2. LITERATURE REVIEW

The concept of sustainable food product design has emerged as a crucial framework for addressing the growing environmental challenges of the food industry. It draws on several interrelated research areas, including life cycle assessment (LCA), circular economy principles, food waste reduction, eco-design, and consumer behavior. These approaches provide valuable tools for rethinking how food products are developed, produced, and delivered, and they are increasingly relevant for the evolving food sector in North Macedonia.

Recent studies emphasize that the transition to a circular economy represents a key pathway for transforming the food industry into a more sustainable system (Geissdoerfer *et al.*, 2017). According to the European Commission (2020), moving from a linear to a circular model involves redesigning production processes to minimize

losses, integrating waste streams as raw materials in new production cycles, and developing innovative packaging with improved recyclability.

In the Macedonian context, research has identified both challenges and opportunities in implementing these principles. A 2022 study by the Ministry of Agriculture revealed that only 18% of enterprises have formal procedures for food waste management. The main obstacles include high initial investments (reported by 72% of surveyed enterprises), lack of knowledge (58%), and complex administrative procedures (45%). Similarly, a UNDP comparative study (2019) found that North Macedonia lags behind the regional average in investments in green technologies (0.8% of GDP compared to 1.5% in the Western Balkans) and offers only two higher education programs related to the circular economy.

These findings suggest that the existing potential for circular practices is still underutilized, yet they also indicate a growing interest among Macedonian companies, especially as EU-driven regulatory harmonization begins to shape the market. The central challenge remains finding a balance between economic feasibility and environmental responsibility within the constraints of a relatively small domestic market.

Alongside circular economy principles, Life Cycle Assessment (LCA) has become a well-established methodology for evaluating the environmental impacts of food products at every stage of their life cycle. Global research shows that food production contributes substantially to greenhouse gas (GHG) emissions, land use, and water consumption (Poore & Nemecek, 2018). Applying LCA helps identify environmental “hotspots” in production where targeted improvements can bring significant sustainability benefits. Studies have found that the production phase typically accounts for 40–60% of the total environmental impact (Notarnicola *et al.*, 2017), packaging contributes 15–30% (Wikström *et al.*, 2019), while distribution and storage are particularly critical for products with short shelf lives (Verghese *et al.*, 2015).

In the Republic of North Macedonia, however, the use of LCA remains very limited. Local producers face several challenges in adopting this approach, such as limited access to specialized software, the absence of local environmental data, and the high costs of certification. Regional studies from the Western Balkans also suggest that local food systems often carry a higher carbon footprint due to outdated agricultural techniques, inefficient logistics, and high levels of food waste. Introducing LCA methodologies on a national scale could provide valuable insights for both policymakers and businesses, enabling them to identify inefficiencies, improve resource use, and ultimately reduce the environmental impact of the Macedonian food sector.

The circular economy model is increasingly recognized as a key strategy for sustainable food production. According to Kircher *et al.* (2017), circular economy principles aim to minimize waste, extend the life cycle of products, and increase resource efficiency.

According to FAO (2021), around one-third of all food produced globally is lost or wasted, which creates serious economic, environmental, and social consequences.

The economic costs are estimated at approximately 1.2 trillion USD annually, while food waste is responsible for 8–10% of global greenhouse gas emissions. At the same time, this loss occurs in a world where about 821 million people continue to suffer from chronic hunger, making the issue both ethically and practically urgent.

To address these challenges, the food industry has increasingly been adopting principles of sustainable production and consumption. These efforts include sustainable sourcing practices such as organic farming and regenerative agriculture, which aim to protect soil health and biodiversity.

Companies are also investing in eco-friendly packaging solutions, including biodegradable and compostable materials that reduce plastic pollution. Another important area is waste valorization, where food waste is converted into bioenergy, animal feed, or other valuable byproducts, thereby closing the loop within production systems. Product innovation has also gained momentum, with alternative proteins and plant-based food innovations offering opportunities to reduce the environmental footprint of diets.

A number of innovative solutions have already demonstrated their potential to significantly cut food waste. For example, converting waste oils into biodiesel can reduce waste by up to 40% (Budžaki *et al.*, 2018). Digital redistribution platforms such as the ResQ Club app help redirect surplus food to consumers at reduced prices, achieving waste reductions of 15–25%. Smart packaging technologies, including biodegradable films with freshness indicators, can extend shelf life and lower waste by 30–50%. These examples show that innovation plays a critical role in reducing food losses while simultaneously creating new economic opportunities within the food sector.

Table 1. Innovative solutions

Solution	Example	Waste reduction potential
Waste processing into biofuel	Biodiesel production from waste oils (Budžaki <i>et al.</i> , 2018)	to 40%
Digital redistribution platforms	ResQ Club APP	15-25%
Smart packaging	Biodegradable films with freshness indicators	30-50%

While circular economy strategies are gaining popularity globally, their implementation in North Macedonia remains limited due to insufficient infrastructure and regulatory support.

Reports from the European Environment Agency (EEA, 2022) suggest that North Macedonia lags behind EU member states in recycling rates and sustainable food production practices. Strengthening local policies and fostering industry cooperation could improve the integration of the circular economy in the food sector.

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Food waste is a major sustainability challenge, contributing to resource depletion and environmental degradation. According to the Food and Agriculture Organization (FAO, 2021), approximately one-third of all food produced globally is wasted, leading to unnecessary carbon emissions and economic losses. Effective strategies for reducing food waste include:

- Improving the efficiency of the food supply chain to minimize losses during transportation and storage.
- Raising consumer awareness through educational campaigns.
- Encouraging businesses to adopt zero waste policies by repurposing surplus food.

In the Republic of North Macedonia, data on food waste is scarce and waste management systems are underdeveloped. The absence of strict regulations to reduce food waste and inadequate incentives for businesses to adopt sustainable practices hinder progress in this area. The majority of food waste in North Macedonia ends up in landfills, rather than being composted or repurposed. Policy interventions and public-private partnerships are key to improving the country's food waste management system.

Consumer awareness and willingness to pay for sustainable food products are key determinants of market success. Studies show that consumer demand for organic, locally produced and environmentally friendly food products is increasing globally (Aschemann-Witzel *et al.*, 2019).

However, research indicates that in North Macedonia, sustainable food consumption remains in its early stages of development. Several factors contribute to this situation, including a general lack of awareness about how food choices affect the environment, as well as high price sensitivity among consumers, who often perceive sustainable food products as expensive. Additionally, the limited availability of environmentally friendly alternatives on local markets further restricts the adoption of more sustainable consumption patterns.

These findings are in line with global studies (Grunert, 2019) that highlight the need for: clear and standardized eco-labels, full transparency in the supply chain and targeted educational campaigns.

Government policies play a key role in facilitating sustainable innovation in the food sector. The European Union's Green Deal and Farm to Fork Strategy provide strong policy frameworks for the transition to sustainable food systems (European Commission, 2020). However, as an EU candidate country, North Macedonia faces significant challenges in aligning its regulations with European Union standards. Notable gaps include weak enforcement of environmental regulations within the food production sector, a lack of financial incentives for businesses investing in sustainable

innovations, and the absence of a comprehensive national strategy to promote circular economy principles specifically for the food industry.

A comparative review of regulatory frameworks shows that the EU's Farm to Fork Strategy (2020) and the Single-Use Plastics Directive (2019) have contributed to a measurable 12% reduction in food waste between 2015 and 2020, primarily through stricter sustainability requirements and incentives for innovation in product design and packaging. In contrast, North Macedonia's National Waste Management Plan (2020–2030) and National Strategy for Sustainable Development (2009–2030) have so far produced limited impact due to weak institutional enforcement and lack of targeted measures to promote sustainable product design across the food sector.

Table 2. Comparative Analysis of Regulatory Frameworks for Sustainable Food Systems

Country	Key Policies	Results
EU	• Farm to Fork Strategy (2020) • Single-Use Plastics Directive (2019)	12% waste reduction (2015-2020)
North Macedonia	• National Waste Management Plan (2020-2030) • National Strategy for Sustainable Development (2009-2030)	Limited results due to weak institutional control

Source: Author's analysis based on European Commission (2020), Ministry of Agriculture, Forestry and Water Management (2022) and Ministry of Environment and Physical Planning (2020)

Key obstacles to effective implementation include (Bojkovska *et al.*, 2023):

- Fragmented institutional framework;
- Lack of financial incentives;
- Misalignment between national and local policies.

This literature review confirms the need for an integrated approach that combines technological innovation, consumer education and political support for an effective transformation towards a sustainable food system in North Macedonia.

Strengthening regulatory frameworks and providing financial and technical support to food producers could significantly boost the adoption of sustainable food design practices in North Macedonia.

The review of existing literature highlights the growing importance of sustainable food production and the need for systemic changes to optimize the life cycle of food products. While global research provides valuable frameworks and strategies, North Macedonia lags behind in implementation due to regulatory, infrastructure and consumer-related challenges. This study aims to bridge these gaps by analyzing local industrial practices, assessing environmental impacts using LCA, and proposing context-specific strategies to improve sustainable food product design. By integrating findings from scientific research, policy analysis and industry insights, this study will provide practical recommendations for food producers, policymakers and consumers in North Macedonia, facilitating the transition to a more circular and sustainable food system.

3. RESEARCH METHODOLOGY

This research employs a *qualitative Life Cycle Assessment (LCA)* to evaluate the environmental, economic, and social implications associated with food products in North Macedonia. Departing from the conventional quantitative LCA framework outlined by ISO 14040/44, the qualitative approach emphasizes contextual understanding, systemic challenges, and stakeholder insights throughout each phase of the product life cycle. The research adopts a multi-method qualitative strategy, integrating stakeholder interviews, consumer surveys, policy analysis, and thematic coding to facilitate triangulation and ensure the validity of findings.

Data were collected through secondary sources, including reports from FAO, UNDP, World Bank, and national agencies, as well as peer-reviewed literature on sustainable food systems. Key life cycle stages – raw material extraction, processing, packaging, distribution, and end-of-life – were analyzed using qualitative indicators such as greenhouse gas emissions, water and energy usage, land occupation, and waste generation. Insights were further validated through expert consultations and field observations in local production facilities. The analysis contrasts animal-based and plant-based systems to identify opportunities for sustainable transformation within the national context.

A total of 15 semi-structured interviews were conducted with key actors in the food system, including food producers, policymakers, non-governmental organizations, and academic researchers. Interviewees were selected through purposive sampling to capture a broad range of perspectives on sustainable food production. The interviews explored perceived barriers and opportunities at each stage of the food product life cycle – raw material sourcing, processing, packaging, distribution, and end-of-life management. Guiding questions included:

- „What are the main environmental concerns in raw material sourcing?”
- „How does infrastructure limit sustainable processing?”
- „What innovations or practices have emerged to address food waste or packaging challenges?”

Interviews were recorded, transcribed, and coded using thematic analysis to identify recurring themes and contextual insights.

To assess consumer awareness, attitudes, and behavior regarding sustainable food consumption, a stratified sample of 300 respondents was surveyed. The stratification was based on age group, geographic location (urban/rural), and economic status to ensure demographic representativeness. Data were collected via structured questionnaires administered both online and in person. The survey instrument addressed consumer preferences related to eco-friendly packaging, sustainable product attributes, and willingness to pay a premium for such products. Descriptive and inferential statistical methods were used to analyze the data, identifying significant correlations and trends relevant to sustainable consumption behaviors.

Additionally, focus group discussions were conducted with selected participants to further explore motivations and barriers influencing purchasing decisions related to sustainability.

4. RESULTS AND DISCUSSION

This section presents the key findings of the study, which encompass a qualitative life cycle assessment (LCA) of selected food products, consumer attitudes towards sustainable food options, and insights derived from industry stakeholders. The interpretation of results is situated within the broader context of current sustainability trends and policy frameworks relevant to the Republic of North Macedonia.

Globally, the agri-food sector is responsible for approximately 25% of total greenhouse gas (GHG) emissions. Significant reductions can be achieved through improved management practices, the development of ecosystem services, and the integration of renewable energy sources, all while ensuring food security. Digital innovations and sustainable practices are increasingly recognized as catalysts for green transformation, especially in reducing waste – one of the sector's most pressing challenges.

The qualitative LCA focuses on identifying environmental impacts, systemic challenges, and improvement opportunities across all phases of the food product life cycle, from raw material extraction to end-of-life management.

The choice between animal-based and plant-based food production systems has significant implications for environmental sustainability, resource efficiency, and local economic development.

Animal-based production systems such as meat and dairy are highly resource-intensive, contributing significantly to methane emissions, consuming large amounts of water, and requiring extensive land use that can lead to land degradation.

Livestock production is a significant source of methane (CH₄) emissions, with average levels estimated at approximately 25 kg CO₂-equivalent per kilogram of beef (FAO, 2023). In addition to its climate impact, livestock requires substantial water resources, with an average water footprint of around 15,000 liters per kilogram of meat, reflecting a high degree of resource intensity. Moreover, about 30% of global agricultural land is dedicated to grazing, which poses considerable risks of land degradation, particularly in cases of overgrazing and inadequate pasture management.

Plant-based alternatives offer a more sustainable option, with significantly lower environmental impacts and strong potential for local production in North Macedonia.

Plant-based proteins, including lentils and legumes, demonstrate significantly reduced resource intensity, generating emissions that are on average ten times lower and requiring five times less water compared to meat production. Furthermore, the agro-climatic conditions in North Macedonia are highly favorable for the cultivation of crops such as organic lentils and sunflowers, creating opportunities to strengthen local production and decrease dependence on imports.

Shifting towards more plant-based alternatives could therefore play a crucial role in reducing environmental pressures while fostering sustainable agricultural growth in North Macedonia.

Processing plays a crucial role in shaping the overall energy demand, efficiency, and sustainability of food production, and the contrasts between animal-based and plant-based products are particularly evident.

In the case of **animal-based products**, processing is highly energy intensive, with procedures such as pasteurization and meat processing requiring approximately 2.5 kWh per kilogram of product. The reliance on outdated equipment in many facilities further exacerbates inefficiencies, while insufficient sanitary infrastructure poses risks of contamination and product loss.

By contrast, **plant-based products** benefit from more energy-efficient technologies. Advanced methods such as extrusion and fermentation, although requiring specialized equipment, demonstrate roughly 30% higher energy efficiency compared to conventional meat processing. Furthermore, the processing of plant-based foods generates primarily biodegradable residues, which can be repurposed for composting and thus support circular economy principles.

Overall, plant-based processing not only ensures greater energy efficiency but also contributes to more sustainable and circular production practices when compared to traditional animal-based systems.

Packaging represents a critical aspect of food production sustainability, with current practices in North Macedonia heavily dependent on plastics.

More than 70% of food packaging is composed of conventional plastic materials, while the recycling rate remains below 15% (EKO-SKOP, 2023), indicating a substantial environmental burden. However, innovative alternatives are emerging, including the use of compostable materials such as polylactic acid (PLA) derived from corn starch.

These solutions provide a promising pathway to mitigate the environmental impacts traditionally associated with food packaging and to advance more sustainable practices in the sector.

Distribution remains a critical stage in the food supply chain, where inefficiencies significantly affect both sustainability and economic performance.

In North Macedonia, fragmentation of the market and limited coordination across supply chains result in an estimated 20% loss of food products before they reach consumers (UNDP, 2022). Furthermore, the underdevelopment of cold chain infrastructure not only compromises food quality but also increases energy consumption by approximately 35% compared to European Union standards.

These shortcomings highlight the dual challenge of reducing environmental impacts while improving the economic efficiency of food distribution systems.

End-of-Life (Waste Management) represents a major challenge in the food system, particularly due to the large share of organic waste. In North Macedonia, around 40% of household waste is biodegradable, yet the absence of industrial composting facilities severely constrains opportunities for recovery and recycling. This shortcoming not only exacerbates environmental pressures but also leads to significant economic losses. Food loss alone is estimated to cost the Macedonian economy approximately €300 million annually (World Bank, 2021), emphasizing the urgent need for comprehensive strategies and policies aimed at reducing waste and improving resource efficiency.

Based on the findings, the following key strategies are proposed to support the sustainable transformation of the food system in North Macedonia:

1. **Promotion of Plant-Based Alternatives:** Economic incentives should be introduced to encourage the production of local legumes, lentils, and other vegan products that offer environmental and nutritional advantages.
2. **Modernization of Processing Infrastructure:** Investment in energy-efficient equipment and the adoption of clean technologies across the supply chain are essential to improve productivity and reduce carbon footprints.
3. **Policy Interventions:** The introduction of mandatory recycling standards and a plastic packaging tax could drive systemic change and align national practices with EU directives.
4. **Public Awareness and Education:** National campaigns are needed to promote waste reduction, sustainable consumption, and circular economy principles among consumers.

This analysis demonstrates that a systemic approach – integrating technological innovation, supportive policy frameworks, and informed consumer behavior – is necessary to achieve long-term sustainability in North Macedonia’s food system.

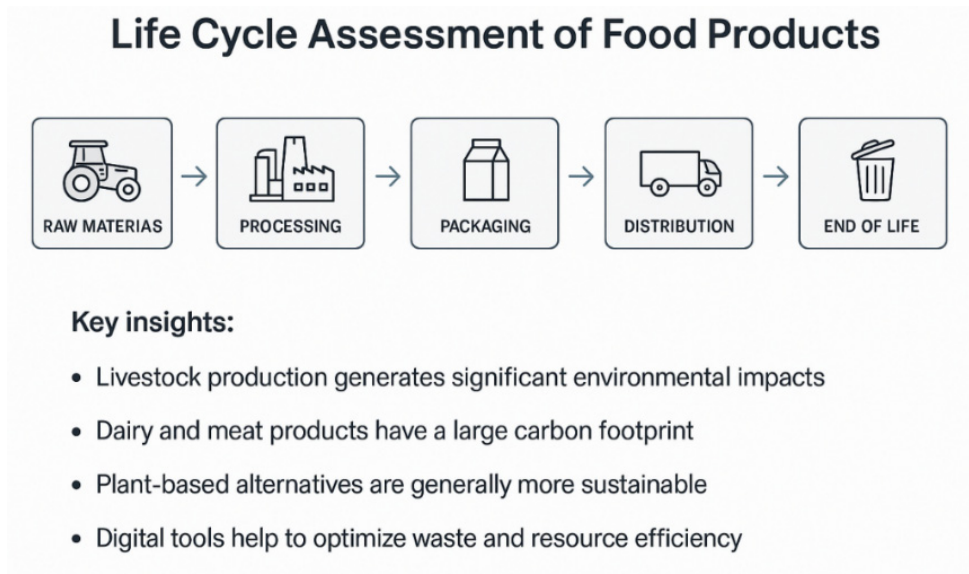


Figure 1. Life Cycle Assessment Stages and Key Sustainability Insights for Food Products

Source: Adapted from various LCA stage diagrams (MDPI’s REAMIT LCA tool), modified by the author

This figure 1 illustrates the main stages of the life cycle assessment (LCA) of food products – ranging from raw material extraction to end-of-life disposal – alongside key insights. It highlights the significant environmental impacts associated with livestock production, the high carbon footprint of dairy and meat products, the comparative sustainability of plant-based alternatives, and the role of digital tools in enhancing efficiency and reducing waste.

Sustainable Innovations:

Plant-based alternatives demonstrate considerable potential to reduce the environmental impact of food systems. Supporting local production and fostering the development of innovative plant-based food products are essential steps toward achieving sustainability goals.

Infrastructure Improvement:

Strengthening logistics, expanding recycling capacities, and enhancing energy efficiency in food processing should be prioritized as core areas for investment and modernization.

Policy and Education:

Robust policy support for green practices, including subsidies for sustainable agriculture, alongside targeted consumer education on environmentally responsible choices, are critical components for enabling systemic transformation across the food value chain.

To gain insights into consumer awareness, preferences, and willingness to pay for sustainable food products, a structured survey was conducted among a representative sample of 300 respondents. The study aimed to assess current attitudes and behaviors within the context of environmental responsibility and sustainable food production.

The survey results provide a detailed picture of the variability in consumer knowledge and awareness regarding sustainable food products. The findings are of particular relevance for shaping public health policies, marketing strategies, and sustainable agricultural models.

Distribution of Awareness Levels Table 2. reveals that more than two-thirds of the surveyed population (65.8%) possess at least a basic understanding of sustainability in the context of food consumption, while 34.2% report having no awareness of the concept.

Table 3. Consumer Awareness Levels of Sustainable Food Consumption Practices

Awareness Level	Percentage (%)	Interpretation
Highly Aware	18.2%	A small but influential group actively purchasing eco-certified products.
Moderately Aware	47.6%	A key target segment for awareness campaigns – familiar with the concept, but inconsistent in behavior.
Not Aware	34.2%	Indicates the need for structured educational interventions.

Source: Survey results

The research uncovered several important insights into consumer attitudes and behaviors regarding sustainable products, with the key findings and implications summarized as follows: statistical analysis revealed a significant correlation ($p < 0.05$) between higher levels of formal education and greater awareness of environmental certifications, suggesting education as a critical factor in fostering sustainable consumer behavior; the results indicate a distinct segmentation in the consumer base, where 18.2% can be categorized as "early adopters" willing to pay a premium for sustainable options, while nearly half (47.6%) represent "potential converts" who require clearer

communication and product labeling to fully engage; and qualitative data from focus groups revealed skepticism towards eco-labels, with concerns about “greenwashing” (misleading environmental claims), underscoring the need for standardized, transparent certification schemes. These findings underscore the critical role of policy interventions and marketing strategies in supporting the transition towards a sustainable food industry in North Macedonia.

The analysis of consumer willingness to pay premium prices for sustainable food products is based on a representative sample of 300 respondents surveyed using a structured questionnaire designed to assess attitudes toward sustainable consumption. The data were analyzed using descriptive statistics and chi-square (χ^2) tests to determine statistical significance.

Table 4. Willingness to Pay a Premium for Sustainable Food Products

Willingness Level	Percentage Distribution (%)	Statistical Significance (p-value)
Up to 10% price premium	41.5%	<0.01
Up to 20% price premium	22.3%	<0.05
Unwilling to pay any premium	36.2%	–

Source: Survey results

The analysis of consumers’ willingness to pay for sustainable food products revealed distinct patterns of price sensitivity and environmental commitment, summarized as follows:

- **Dominant Preference for Moderate Premiums.** Approximately 41.5% of respondents indicated a willingness to pay up to a 10% price premium for sustainable food products. This segment represents a statistically significant majority ($\chi^2=32.1$, $df=2$, $p<0.01$), suggesting moderate premiums are broadly acceptable in the general population.

- **High Environmental Awareness Segment.** A further 22.3% of participants expressed readiness to pay up to a 20% premium. This group closely correlates with the “highly aware” consumers identified in the awareness analysis ($r=0.67$, $p<0.05$), highlighting the role of environmental consciousness in purchasing behavior.

- **Price-Sensitive Consumers**

Notably, 36.2% of respondents were unwilling to pay any premium. This segment correlates negatively with income levels ($r=-0.71$, $p<0.01$), underscoring the influence of economic constraints on sustainable consumption choices.

The **analysis of stakeholder perceptions** regarding barriers and strategic approaches to sustainable food production was based on qualitative interviews with 15 key actors from the food sector in the Republic of North Macedonia. The participants represented a diverse range of perspectives, including the food industry (47%), public institutions (27%), academia (13%), and non-governmental organizations (13%). This composition ensured a balanced understanding of the challenges and opportunities perceived across different sectors involved in shaping sustainable food systems, thereby strengthening the validity and comprehensiveness of the analysis.

The empirical findings reveal several systemic constraints that continue to impede the transition toward sustainable production models. Foremost among these are the high transformation costs, which were identified as the most pressing economic barrier by 80% of respondents. This observation is consistent with existing industry data indicating that the shift to sustainable practices typically entails significantly higher capital expenditures – estimated at 30–45% above conventional investment levels. For small and medium-sized enterprises (SMEs), the financial burden is exacerbated by protracted payback periods, which frequently extend between six and eight years.

Table 5. Hierarchy of Systemic Constraints

Challenge	Key Findings	Correlation with Existing Data
High transformation costs	Identified as a dominant issue by 80%	Aligned with industry data on capital investment
Lack of political support	73% cited regulatory uncertainty	Supported by policy document analysis
Limited market demand	65% noted price sensitivity as a barrier	Consistent with consumer survey findings

Source: Author's own work

In addition to economic barriers, regulatory challenges also play a substantial role. A lack of coherent political support, coupled with regulatory uncertainty, was highlighted by 73% of participants and corroborated through the analysis of relevant policy documents. Although subsidies for sustainable practices are formally available, their administration remains inconsistent across different sectors. Moreover, the absence of standardized and transparent criteria for environmental certification not only generates confusion among producers but also undermines the overall credibility of such certification schemes.

Finally, market-related limitations further constrain the scaling of sustainable production. While survey data indicate a relatively high declared willingness to pay for sustainable alternatives (63.8%), actual consumer purchasing behavior falls considerably short, with estimates ranging between 35% and 40%. This discrepancy is further aggravated by the limited availability of sustainable products within mainstream retail channels, which restricts consumer access and, in turn, slows down the broader diffusion of sustainable consumption patterns.

In light of the identified barriers, **several strategic approaches** are recommended to facilitate the transition toward sustainable production in the food sector. From a financial perspective, the establishment of targeted funds dedicated to green investments is essential in order to reduce the burden of initial transformation costs. Complementary to this, the development of innovative financial instruments – such as green bonds and sustainability-linked loans or mortgages – could provide enterprises with more flexible and accessible means of financing sustainability-oriented initiatives.

At the policy level, greater alignment between national sustainability standards and EU regulatory frameworks is required to minimize regulatory uncertainty and foster coherence across markets. Furthermore, the integration of mandatory sustainability criteria within public procurement processes would not only stimulate

demand for sustainable products but also create exemplary market practices that can be emulated by private sector actors.

Market-based incentives have the potential to significantly strengthen the uptake of sustainable products. Enhancing distribution infrastructure would ensure that sustainable alternatives gain broader penetration within mainstream retail channels, thereby improving consumer access. Equally important is the introduction of scientifically validated eco-labels, designed with clear and transparent messaging. Such labeling systems could play a pivotal role in building consumer trust while simultaneously addressing the risks of greenwashing, which remain a key obstacle to market credibility.

The stakeholder recommendations related to the strategic approaches for advancing sustainable food production are derived from structured interviews conducted with 15 key stakeholders representing industry, government, academia, and non-governmental organizations. The collected data were systematically analyzed through content analysis, frequency quantification, and cross-sectoral comparison, allowing for the identification of strategic priorities that are broadly supported across stakeholder groups.

Among the proposed measures, **financial incentives** emerged as the most widely endorsed strategy, receiving support from 85% of participants. Stakeholders emphasized the role of subsidies, tax reductions, and loan guarantees in lowering the costs of transition, with the potential to achieve a 15–25% reduction in investment expenditures and to significantly shorten payback periods.

Technological innovation was also highlighted as a critical pathway, supported by 78% of respondents. Within this domain, three priority areas were identified: energy efficiency (52%), circular production models (26%), and the adoption of biodegradable packaging solutions (22%). Collectively, these innovations are expected to reduce energy consumption by approximately 30% and cut production waste by up to 50%.

In addition, **educational campaigns** were considered essential by 70% of stakeholders. Targeted at both consumers and producers, such initiatives – implemented through media channels, educational institutions, and digital platforms – are projected to increase public awareness by 25% and raise consumer willingness to pay for sustainable alternatives by an estimated 15% within a three-year period.

Finally, **regulatory strengthening** was supported by 65% of participants. Proposed measures included the introduction of stricter emission limits, enhanced organic waste management systems, and binding waste reduction targets of up to 25% annually. Such interventions were viewed as necessary to complement financial and market-based measures, thereby creating a more coherent framework for sustainable food production.

The findings of the **Life Cycle Assessment (LCA)** conducted in this study underscore the considerable environmental advantages of plant-based alternatives when compared to conventional animal-based products. Plant-based options demonstrate between 45-60% lower carbon emissions, three to five times lower water consumption, and a reduction of 50-70% in land use. These outcomes provide a robust scientific foundation for advocating dietary shifts and production realignments toward

more resource-efficient systems. Additional opportunities to reduce the environmental footprint, estimated at 15-25%, can be realized through optimized packaging strategies. Biodegradable materials show the potential to reduce plastic waste by up to 80%, while reuse systems can achieve efficiency improvements of 30-40%. Together, these measures highlight both the scientific rationale and the practical feasibility of interventions aimed at lowering the ecological impacts of agri-food production and consumption.

Stakeholder consultations with policymakers, industry representatives, and sustainability experts further emphasized the urgent need for regulatory reforms that can reinforce the transition to sustainable agri-food systems. Participants pointed to three domains where targeted action would have the greatest effect. Horizontal measures such as binding Life Cycle Assessment standards, harmonized environmental labeling schemes, and the introduction of a carbon tax above €20 per ton of CO₂-equivalent were identified as critical steps toward establishing a coherent regulatory foundation. In parallel, sector-specific measures in food processing and agriculture were highlighted as essential. For the food processing sector, improved energy efficiency and optimized waste management were considered priorities, while in agriculture the focus lay on the transition to organic farming practices and sustainable management of water resources. Finally, strengthening institutional capacities was seen as indispensable for long-term progress. The establishment of a National Center for Sustainable Agriculture would provide coordination in research, training, and innovation, while the creation of an independent ecological certification authority would help secure transparency and credibility in sustainability claims.

If implemented in an integrated manner, these horizontal measures, sector-specific actions, and institutional reforms would form a coherent policy framework capable of accelerating the shift to sustainable agri-food systems. By aligning regulatory action with scientific evidence and stakeholder priorities, such a framework would deliver clear and measurable benefits for businesses, consumers, and the environment alike.

5. CONCLUSION

This research provides evidence-based insights into the environmental, economic, and social dimensions of sustainable food production in North Macedonia. By applying an integrative methodology that combined Life Cycle Assessment (LCA), consumer surveys, and stakeholder interviews, several key findings have emerged. The LCA results confirm the substantial environmental advantages of plant-based alternatives, which demonstrate between 45% and 60% lower carbon emissions, markedly reduced water consumption, and significantly less land use compared to conventional products. Additional reductions in environmental impact can be achieved through innovative packaging solutions, particularly the use of biodegradable materials and reuse systems.

At the market level, the findings reveal both opportunities and persistent challenges. While a majority of consumers (63.8%) express willingness to adopt sustainable alternatives, price sensitivity continues to act as a major barrier to actual purchasing behavior. The establishment of a standardized and transparent eco-labeling system was identified as essential for building consumer trust and reducing uncertainty.

The analysis further highlights a number of structural barriers to sustainable transformation. High upfront costs represent a major obstacle, particularly for small and medium-sized enterprises, while the lack of coordinated policy incentives limits the effectiveness of existing initiatives. Moreover, fragmented infrastructure within sustainable agriculture and food processing continues to constrain the scalability of innovative practices.

Despite these challenges, the research identifies several strategic directions for systemic transformation. On the policy level, harmonized sustainability standards, comprehensive financial incentive programs such as subsidies and tax relief, and the establishment of a national coordinating body for sustainable food policy could provide a coherent framework for progress. From an industrial perspective, investments in circular production models, the development of localized short supply chains, and the deployment of energy-efficient technologies would help to align production processes with sustainability goals. Equally important is consumer engagement, which can be strengthened through targeted education and awareness campaigns, credible eco-labeling systems, and the promotion of partnerships between producers and consumers.

The transition toward a sustainable food system in North Macedonia is a complex but achievable objective that requires a holistic approach. While this study identifies significant barriers, it also outlines practical opportunities for systemic change through synergies across policy, industry, and consumer sectors, strategic investments in critical technologies and infrastructure, and the establishment of inclusive decision-making mechanisms. Future research should continue to explore the economies of scale in sustainable production, assess the impacts of implemented policy measures, and monitor long-term trends in consumer behavior.

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