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Prof. Romulus Gruia Ph. D.

The Journal of EcoAgroTurism aims at approaching analyses, methodologies, options and references within the journal's framework.



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"A FOUR OF A KIND" IN A UNIFIED STRATEGY FOR ROMANIA'S AGRI-FOOD 2026

WITHOUT A UNIFIED STRATEGIC VISION, we remain a country with great potential, yet untapped and, unfortunately, with damaging consequences.

For Romania to count as a "European and/or Global Agri-food" player, a coherent national strategy is required to truly become a power that does not merely export raw materials, but influences food policies, supply chains, narratives, prices, and regional alliances. Briefly, here are several actions (four-step actions) that are absolutely necessary and urgent:

- **First** is the intelligent regionalization of ambition: Romania must become the agri-food pivot of the Black Sea, a leader in Central and Eastern Europe, and a strategic partner of Ukraine within a food security network. Romania can be an agri-food power at a regional level and beyond—not just an exporter, but a regional arbiter in terms of food security, quality, and innovation (pro-active partnerships, commodity exchanges, contracts, etc.).
- **The second** is the creation of a single „umbrella brand”, financially backed, professionally managed, and widely adopted (see the equivalent examples of neighboring countries, especially those of the Poles or Turks); promoting the brand through active participation in international exhibitions and events.
- **The third** is the construction of a global export portal—a *"Romanian Food Export Hub"*—which would index all export-ready companies, providing clear data on certifications, capacity, target markets, and product categories; units with quantitative and qualitative commercial potential.
- **The fourth**, completing this "four of a kind," would be the internal strategy for zonal agri-food harmonization based on altitude gradients, supporting the national strategy through integration and complementarity, particularly through tradition and local products.

In conclusion, only a synergistic and harmonious integration of the "square of 4 aces" can lead to the desired strategic performance.

Director of the publication,
Prof. Romulus GRUIA, PhD
PhD Supervisor, Scientific Leader

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AGROTOURISM AND THE CERTIFIED MOUNTAIN PRODUCT IN THE SILVER ECONOMY: A VALUE-CHAIN OPPORTUNITY FOR ELDERLY TOURISTS IN THE BRAȘOV AREA

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Abstract: Brașov county leads Romania in agrotourism capacity, yet its guesthouses are only weakly connected to the certified mountain-product base and to the fast-growing demand of older tourists. This paper examines that connection, combining official agrotourism statistics for the Brașov area with data on certified mountain products and field surveys of seniors (65+) in Brașov. Brașov hosts about 372 agrotourism guesthouses (roughly 6,700 beds) and ranks first nationally, while Romania holds 1,509 certified mountain producers with 4,689 products. Seniors report high consumption of the very categories that mountain products supply dairy, meat, vegetables and fruit, alongside rising concern over the affordability of healthy food. We outline an agrotourism-centred value chain for the Silver segment, in which mountain guesthouses act as on-site nodes linking certified producers to older visitors through gastronomy, traceability and wellness. The Brașov area emerges as a suitable pilot for such a chain.

Keywords: agrotourism; mountain product; Silver Economy; older tourists; short food supply chains.

1. Introduction

Agrotourism has become one of the most dynamic components of rural development in Romania. It links the accommodation of visitors in a working rural environment with the direct consumption of local food, creating income for small farms and keeping mountain communities alive. The Brașov area is the national leader of this sector, combining an attractive Carpathian landscape, a strong pastoral tradition and proximity to major tourist attractions such as Bran, Râșnov and Poiana Brașov. At the same time, the population is ageing. The share of people aged 65 and over exceeded 20% in Romania in 2025, and older adults are an increasingly important tourism and consumption segment across Europe. The Silver Economy, the set of goods and services generated by and for the population aged 50 and over is estimated at several trillion euro at EU level [1]. Older tourists travel outside peak season, value authenticity and comfort, and pay particular attention to the health properties of the food they consume. These characteristics make them a natural clientele for

mountain agrotourism, yet they are seldom addressed as a distinct segment by Romanian guesthouses. The certified “mountain product”, regulated at European level [2], provides a quality anchor for this encounter. Mountain foods traditional cheeses, honey, wild berries, extensively raised meat, medicinal plants, offer nutritional profiles well suited to the needs of older consumers. However, the connection between agrotourism, the certified mountain product and the specific needs of older tourists remain largely unexploited. This paper explores that connection for the Brașov area, asking whether local agrotourism can act as the channel that links certified mountain supply to Silver demand, and it outlines a value chain built around mountain guesthouses. The contribution of the paper is threefold. Empirically, it brings together, in a single analysis for the Brașov city-region, official agrotourism statistics, the national register of certified mountain products and field evidence on the food behaviour of older residents. Conceptually, it proposes an agrotourism-centred value chain for the Silver segment and grounds it in the bio-harmonism

paradigm. Practically, it links this chain to concrete interventions already under way in a local food-systems living lab, showing that the proposal is implementable rather than merely aspirational.

2. Literature Review

2.1. Agrotourism as a driver of mountain rural development

Agrotourism is widely regarded as one of the most effective instruments for the diversification of mountain rural economies. By combining accommodation, gastronomy and the direct experience of a working farm, it retains value locally, creates complementary income for small producers and helps counter the depopulation of mountain villages. In the Carpathian context, agrotourism also performs a cultural function, keeping alive traditional practices of animal husbandry, dairy processing and food preservation that would otherwise disappear. The Romanian Mountain area, and Braşov county in particular, has developed one of the densest agrotourism networks in the country, supported by landscape quality, proximity to urban markets and a strong tradition of hospitality.

However, the literature also notes recurrent weaknesses of the sector: fragmentation of supply, seasonality, limited marketing capacity and a weak link between accommodation and the local food economy. Many guesthouses buy food from conventional wholesale channels rather than from neighbouring certified producers, so the potential synergy between agrotourism and local quality products remains largely untapped. Closing this gap requires both an organizing concept and a clearly defined demand segment, the two elements this paper brings together. Romanian agrotourism has grown rapidly since the early 2000s, supported by rural-development funding and by rising domestic demand for short breaks in nature.

Yet growth has been largely quantitative, more beds, more guesthouses rather than qualitative. Recent data suggest that the number of guesthouses in mature destinations such as Braşov has plateaued, which shifts the competitive question from how to attract more capacity to how to differentiate existing capacity. Differentiation through a clearly defined, high-value clientele and a distinctive local-food offer is precisely the strategy that the coupling with certified mountain products and the Silver segment makes possible.

2.2. The mountain product and functional nutrition

The literature on mountain food products consistently identifies authenticity, perceived quality and the relationship with the territory as their central competitive advantages, and stresses that full valorisation depends on integration into short food supply chains and on certification [3]. Consumers who associate authenticity with health are the most willing to pay a price premium for certified mountain food [4], a description that fits the older consumer closely. From the nutrition side, mountain products such as dairy, honey, wild berries and extensively raised meat provide protein, antioxidants and micronutrients relevant to the prevention of sarcopenia, the support of immunity and the maintenance of cognitive health in later life. A growing body of applied research shows how food raw materials, including by-products can be transformed into ingredients with enhanced functional value, a logic directly transferable to mountain gastronomy for seniors. Studies on the use of grape-seed flour in the bakery industry demonstrated improved antioxidant and fibre content in everyday products [14], while the valorisation of sea-buckthorn by-products confirmed high antioxidant activity recoverable from material otherwise discarded [17]. Work on marine biomass showed that *Saccharina Latissima* flour can act as a functional ingredient rich in protein, fibre and minerals in the baking sector [15], and the incorporation of fish protein hydrolysate was found to raise the nutritional value of bread while preserving acceptable rheological and sensory characteristics [16].

Research on functional bakery products in Romania further indicated a surprising awareness, including among younger generations, of the benefits of products rich in fibre and minerals, and underlined the importance of designing functional foods around the profile of the target consumer [18]. Taken together, these results establish both the technological feasibility and the market rationale for functional, health-oriented food, precisely the value proposition that certified mountain products can carry to older tourists within agrotourism.

2.3. The Silver segment and its coupling with mountain areas

At European level, the coupling of the Silver segment with rural and mountain economies has already been explored, notably through the SILVER SMEs initiative and through accessible-

tourism models in Alpine regions, where mountain products with protected geographical indication are integrated into wellness offerings for seniors. Agrotourism is the most direct vehicle for this coupling, because it delivers the product, its story and its territory to the visitor in a single experience. Romanian agrotourism, and the Braşov area in particular, has the capacity to adopt such models but has not yet done so in a structured way. The demand side is equally well documented. Older tourists show distinctive behaviour: they favour the shoulder and low seasons, prefer calm and authentic settings, stay longer on average, and are attentive to comfort, accessibility and the health dimension of food and activities. These traits align closely with what mountain agrotourism can offer outside the crowded summer and winter peaks, and they help address the seasonality that constrains the profitability of many guesthouses. Positioning the Silver segment as a deliberate target market is therefore not only a social response to ageing but also a business strategy for smoothing demand across the year.

2.4. Lessons from Alpine and European models

The Alpine arc offers the most developed examples of coupling mountain food with tourism for older visitors. In South Tyrol (Alto Adige), farm-based hospitality is organised through a strong regional network that combines protected-origin products, speck, alpine cheeses, apples, mountain herbs, with wellness and slow-tourism offerings, many of them explicitly comfortable for older guests. The certification of origin is used not merely as a legal label but as a marketing narrative that raises willingness to pay and lengthens the season. Austrian and South Tyrolean "farm holiday" associations show how thousands of small guesthouses can be aggregated under a shared quality brand, solving exactly the fragmentation problem that Romanian agrotourism faces. At policy level, the European interest in the Silver Economy has translated into dedicated instruments. Interregional cooperation projects have mapped good practices for supporting small rural and mountain enterprises that serve older consumers, and accessible-tourism schemes have set standards for facilities and services adapted to reduced mobility and chronic conditions. These experiences carry three transferable lessons for the Braşov area: first, that an origin label works best when embedded in a story and an experience, not sold as a bare

certificate; second, that small producers and guesthouses must be aggregated under a shared brand and governance structure to reach the market; and third, that the older visitor is a year-round, quality-oriented segment whose needs accessibility, health, authenticity, align naturally with mountain agrotourism. The value chain proposed in this paper adapts these lessons to the Carpathian context. Two bodies of evidence must therefore be brought together: the size and dynamics of the local agrotourism base on the one hand, and the certified mountain-product supply and the food behaviour of older consumers on the other.

3. Theoretical Framework: Bioharmonism and Integronic Management

The value chain proposed here is grounded in the bioharmonism paradigm developed by Gruia, which treats disharmonies at all levels of nature and society as sources of systemic inefficiency, and seeks dynamic equilibrium through the integration of components [10, 11]. Applied to the agri-touristic sector, bioharmonism recommends that agriculture, hospitality and environment be managed not as separate activities but as an integrated whole, so that managerial maximisation arises from their coherent combination rather than from optimising any one part in isolation [10]. This perspective is directly relevant to the coupling of agrotourism with the certified mountain product. A guesthouse that sources local certified food, presents its provenance to guests and embeds it in a wellness experience is, in bioharmonist terms, restoring harmony among three components the producer, the visitor and the territory that the conventional food economy keeps apart. The related concept of integronic management provides the operating logic: value is created by the synthesis of complementary components (integronic synthesis) rather than by their fragmentation [10]. Bioharmonism also gives a nutritional reading of altitude. Gruia and co-authors describe an "integronic alimentation" through whole natural food biodiversity in relation to altitude gradation, in which mountain foods carry a specific balancing role in the diet [12]; the food act itself becomes an element of bioharmonistic equilibrium between health, culture and environment [13]. For the Silver segment, whose diet must reconcile pleasure, health and affordability, this reading is particularly apt: certified mountain gastronomy

offered within agrotourism is not merely a product but a harmonising act, aligning the older consumer's health with the sustainability of the mountain territory. The value chain outlined below operationalises this idea.

4. Materials and Methods

The study combines three complementary data sources and a review of the relevant literature. First, official tourism statistics for Braşov county published by the National Institute of Statistics (INS) and synthesised by the National Commission for Strategy and Prognosis provided the number and capacity (beds) of agrotourism guesthouses over 2019–2023, together with the national ranking of counties. Second, the National Register of Mountain Products (RNPM), managed by the Ministry of Agriculture and Rural Development in its March 2026 version, provided the number of certified producers and products, broken down by category and county. The register was processed by propagating producer, category and county fields across each producer's product group, and by deduplicating normalised producer names. Third, two health-and-nutrition field surveys carried out in the municipality of Braşov (June 2025, 300 respondents; August 2026, 250 respondents) provided data on the food behaviour, self-rated health and food insecurity of adults aged 65 and over ($n = 57$ and $n = 40$ respectively). The questionnaire recorded consumption on the previous day for the main food categories, self-rated health and the

perceived affordability of healthy food. All indicators are descriptive; the survey subsamples are small and cross-sectional, and are interpreted as contextual evidence of local demand rather than nationally representative estimates. The three data sources are read through a common analytical lens derived from the value-chain concept and the bioharmonism framework. Rather than treating tourism capacity, certified supply and consumer behaviour as separate descriptive facts, the analysis asks how they connect: whether the supply exists in the right categories (register data), whether the demand exists in the same categories (survey data), and whether the territorial infrastructure exists to link them (tourism data). This integrative reading, consistent with integronic synthesis, is what turns three independent datasets into the outline of a single value chain. The interpretation is therefore qualitative and structural, using the quantitative indicators as evidence of feasibility rather than as a statistical test of a hypothesis.

5. Results and Discussion

The Braşov area confirms its leading position. In 2023 the county had about 372 agrotourism guesthouses with roughly 6,700 beds (Fig. 1), the highest count of any Romanian county. The number of guesthouses has been broadly stable over 2019–2023, with a mild recent decline, suggesting a mature market that would benefit from differentiation rather than mere expansion.

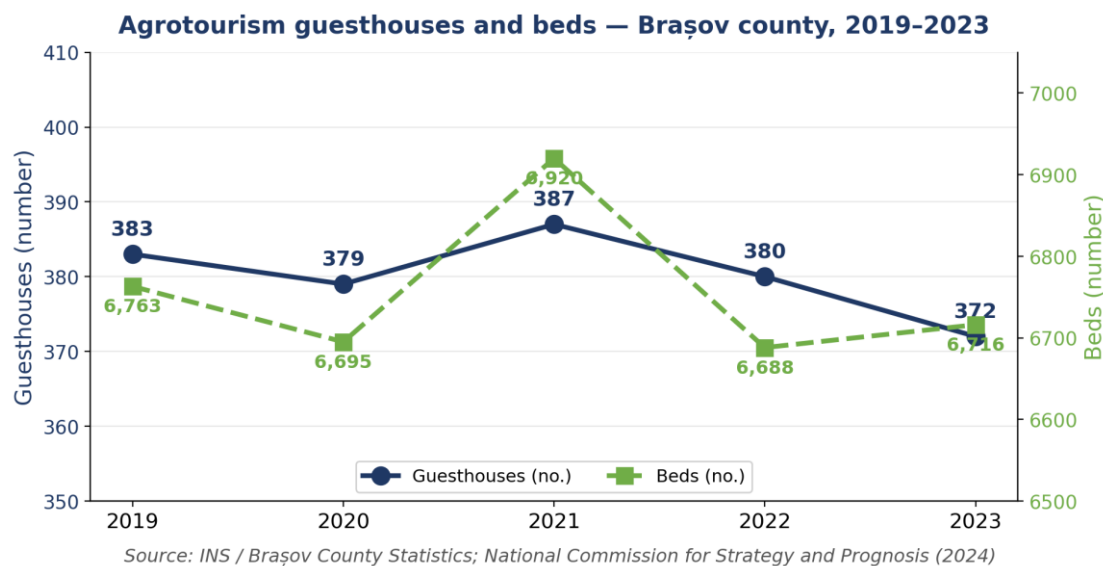
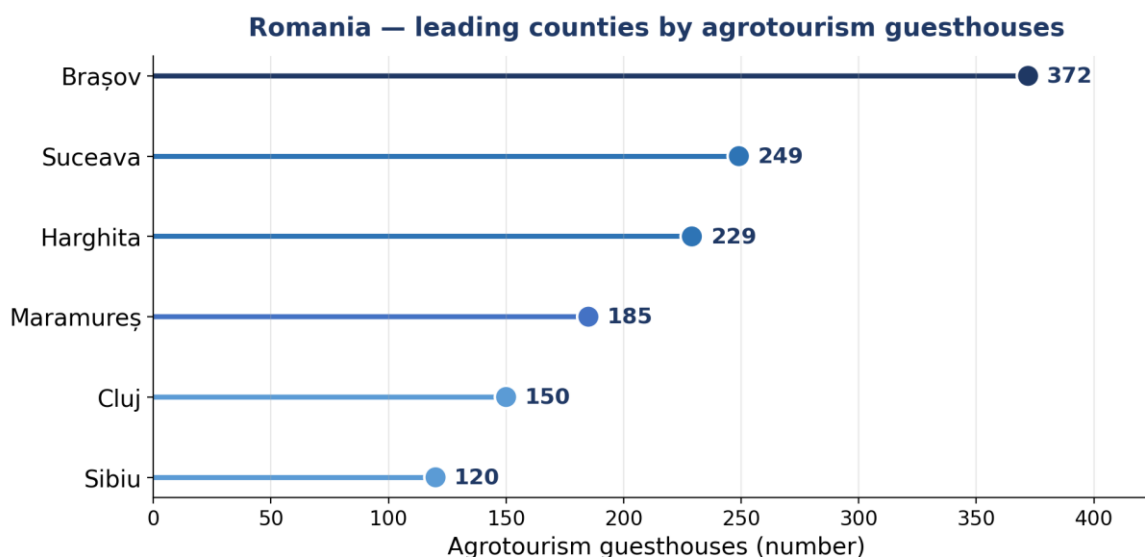


Fig. 1. Agrotourism guesthouses and beds, Braşov county, 2019–2023

At national level, Braşov is followed by Suceava, Harghita and Maramureş (Fig. 2). This ranking reflects both a strong pastoral tradition and an attractive mountain landscape — the same

territorial features that underpin certified mountain production.

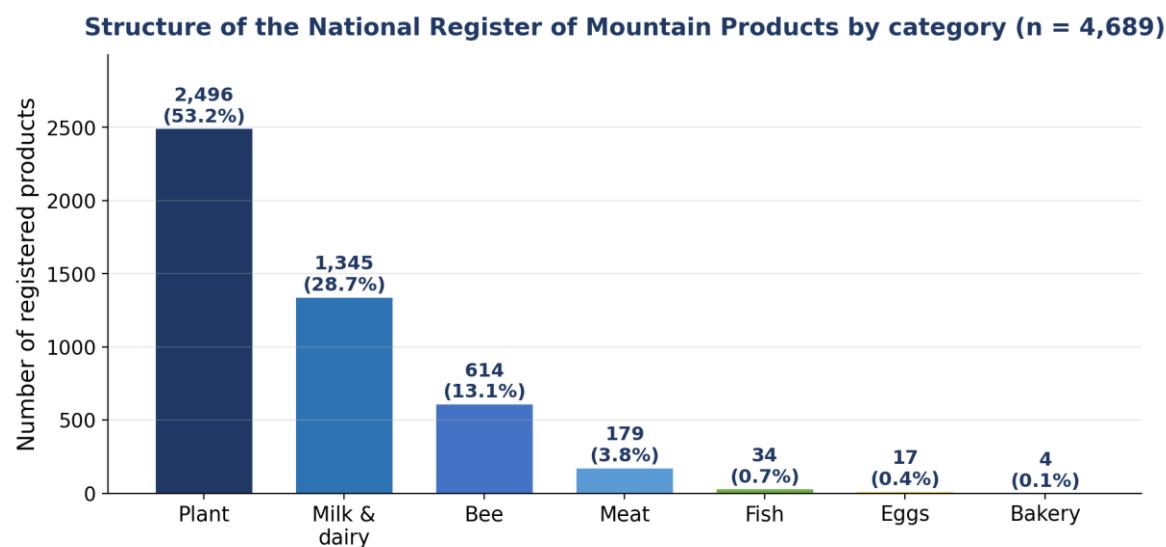


Source: INS; ICEADR analysis. Braşov ranks 1st nationally. (Cluj, Sibiu — indicative)

Fig. 2. Leading Romanian counties by number of agrotourism guesthouses

It also shows that the leading agrotourism counties overlap almost entirely with the leading mountain-product counties, confirming the geographic basis for coupling the two sectors. The overlap is more than coincidental. The counties that host the most agrotourism guesthouses are also those with the strongest traditions of extensive animal husbandry, alpine pasture management and artisanal food processing the very activities that generate

certified mountain products. This means that, in the leading regions, the two sectors already share the same producers, landscapes and cultural know-how; what they lack is an organisational link that turns co-location into cooperation. The value chain proposed here supplies that link, and the Braşov area, at the top of both rankings, is where it can be demonstrated most convincingly.



Source: RNPM — MADR (March 2026)

Fig. 3. Structure of the National Register of Mountain Products by category

On the supply side, the RNPM records 1,509 certified producers and 4,689 products across 28 counties. The category structure (Fig. 3) is dominated by plant products (53%) and dairy (29%), followed by bee products (13%). This is precisely the food that agrotourism guesthouses serve, but the certified status of these products is rarely communicated to guests.

On the demand side, older tourists and residents show a food profile well matched to mountain supply. Field surveys of seniors in Braşov indicate that the categories they consume most frequently are precisely those in which the certified mountain product is strongest dairy, meat, vegetables and fruit, while concern over the affordability of healthy food has been rising. Niche mountain categories with strong geriatric value, such as wild berries and nuts, remain little consumed, suggesting room for guesthouse menus to introduce them.

Taken together, these results outline an agrotourism-centred value chain for the Silver segment. Mountain guesthouses can act as on-site nodes that (i) source certified mountain products locally, shortening the supply chain; (ii) present their origin and nutritional value to older guests through simple bio-informative labelling and traceability; and (iii) embed food in a wellness and gastronomy experience suited to seniors. Because a guesthouse aggregates the demand of many guests, it lowers the coordination cost that otherwise limits the individual valorisation of mountain products.

The chain can be read on four levels. At the base, certified mountain producers supply authentic, traceable food. Guesthouses form the second level, transforming this supply into meals and experiences adapted to older guests appropriate portions, legible menus, information on provenance and health benefits. The third level is digital: bio-informative QR codes and short traceability records answer the heightened sensitivity of seniors to authenticity, provided the interfaces are simple enough for older users. The fourth level is experiential: gastronomic circuits, tastings and wellness activities that combine the culinary value of the territory with the climatic benefits of altitude, extending stays into the low season and raising the value captured per guest.

Such a configuration turns a territorial advantage the authenticity of the Carpathian mountain product into a market advantage on a high-value, structurally growing demand segment. In bioharmonist terms, the chain re-establishes the dynamic equilibrium among producer, visitor and

territory, replacing the fragmentation of the conventional food economy with an integronic synthesis of complementary components [10, 11]. It also addresses the mild recent decline in guesthouse numbers by offering differentiation rather than expansion: a guesthouse positioned as a “Silver mountain” destination competes on experience and health value, not on price. The Braşov area — leader in agrotourism, embedded in a certified mountain-product region, and hosting an ageing population is a natural pilot for such a chain, with the Bran–Râşnov–Zărneşti corridor and the balneoclimatic tradition of the wider Carpathian space as candidate locations.

Implementation would rest on a small number of practical instruments. A voluntary “Silver mountain” charter could define minimum criteria for participating guesthouses a share of certified mountain products on the menu, legible provenance information, accessible facilities and off-season packages. A shared bio-informative labelling scheme, using QR codes linked to producer and nutritional data, would give the traceability that older guests value while keeping the interface simple. Local producer–guesthouse framework agreements would stabilise sourcing and give producers the aggregated, predictable demand that individual retail cannot. Finally, public support through rural-development measures and county tourism promotion could co-finance the initial labelling and training, positioning the Braşov area as the reference destination for Silver Mountain gastronomy in Romania.

The chain can be summarised in bioharmonist terms across five levels: certified production supplies an authentic, traceable resource; the guesthouse performs the integronic synthesis of food, place and guest; the digital layer restores trust through traceability; the experience itself becomes a harmonising act aligning health, culture and territory; and governance maintains the dynamic equilibrium of the whole. Each level adds value not in isolation but through its coherence with the others the defining principle of the bioharmonist approach [10, 11].

The economic rationale reinforces the argument. Older visitors travel predominantly outside the summer and winter peaks, so a guesthouse that captures this segment spreads its occupancy across the shoulder and low seasons, when fixed costs would otherwise be poorly covered. Because the Silver visitor is quality- rather than price-oriented, the average revenue per stay tends to be higher, and the emphasis on certified local

food keeps a larger share of that revenue within the local economy rather than leaking to external suppliers. For the certified producer, a network of participating guesthouses provides a stable, aggregated outlet that reduces dependence on distant and volatile retail channels. The chain therefore improves the resilience of both the guesthouse and the producer, while the municipality gains a distinctive territorial brand and a healthier older population. These mutually reinforcing benefits are the practical expression of the dynamic equilibrium that the bioharmonist framework seeks.

Limitations. The tourism and register data are administrative and do not capture the actual sourcing practices of guesthouses; the senior surveys are small and cross-sectional. The proposed chain is therefore a conceptual outline to be tested through field work with guesthouses and producers, including measurement of older tourists' willingness to pay for certified mountain gastronomy.

A further caveat concerns transferability. The Braşov city-region benefits from an unusually favourable combination of assets the densest agrotourism network in the country, proximity to a large urban market, and an active food-systems living lab that not every mountain area possesses. The value chain proposed here should therefore be read as a model calibrated to a well-endowed pilot region, from which simplified versions could be derived for areas with fewer resources. Establishing which elements of the chain are essential and which are context-specific is itself a question for the field-testing phase, and would determine how far the Braşov model can be generalised across the Carpathian space and beyond.

6. Related Interventions in a Living-Lab Setting

The value chain proposed above is not a purely theoretical construct: several of its building blocks are already being tested by our team in the Braşov city-region through a food-systems living lab [19], in partnership with the Municipality of Braşov and under the Milan Urban Food Policy Pact framework [20]. The living lab organises its work around a set of real-life interventions that map closely onto the levels of the agrotourism-centred Silver value chain, providing an institutional environment in which the chain could be piloted.

6.1. Food policy network and food-security governance

A central intervention is the creation of a city-region Food Policy Network a multi-actor governance body bringing together local authorities, producers, researchers, retailers and civil society. Such a network provides exactly the intersectoral coordination that the top level of the proposed chain requires: it can host a "Silver Mountain" charter, align public procurement with certified mountain products, and give guesthouses and producers a shared forum. Food-security governance, treated as a distinct work stream in the living lab, also supplies the policy legitimacy for targeting vulnerable groups such as low-income older residents, whose access to quality food the surveys showed to be under pressure.

6.2. Short food supply chains and digital traceability

A second intervention develops short food supply chains linking local producers directly to urban consumers, supported by QR-code labelling that carries provenance and product information. This is the operational core of the digital level of the Silver value chain. The same QR infrastructure that shortens the producer-to-consumer distance in the city can be deployed in mountain guesthouses, turning a menu item into a traceable, story-carrying product for older guests. A producers' association, with its own web presence, has been set up to give these short chains an organisational anchor, demonstrating that the coordination cost of aggregating small mountain producers can be met in practice.

Complementary work within the living lab has developed a screening framework for agri-food products from Braşov markets, using rapid analytical methods to verify quality, safety and authenticity across a broad set of products. Such screening is directly relevant to a Silver value chain: older consumers are especially sensitive to food safety and to the truthfulness of quality claims, and an accessible verification layer strengthens the trust that certified labelling promises.

Coupling rapid product screening with QR-based traceability would give guesthouses an inexpensive way to substantiate the provenance and quality of what they serve, converting a marketing claim into demonstrable evidence at the point of consumption.

6.3. Nutrition education and urban agri-food markets

Two further interventions complete the picture. Nutrition-education activities raise consumer awareness of the health value of local and functional food, the demand-side complement to the mountain product's nutritional profile, and directly relevant to older consumers managing chronic conditions. The development of urban agri-food markets creates physical points of sale where certified mountain products can reach city dwellers, including seniors who do not travel to the mountains but can still be integrated into the chain as urban consumers. Together, these four intervention streams governance, short chains and traceability, nutrition education, and markets show that the institutional scaffolding for an agrotourism-centred Silver value chain is already emerging in the Braşov city-region, and that a guesthouse-based pilot could be plugged into it rather than built from scratch.

Our living-lab experience also illustrates a methodological point consistent with the bioharmonist framework: interventions gain effectiveness when they are integrated rather than pursued in isolation. A short chain without a governance forum, or nutrition education without accessible points of sale, delivers less than the coherent combination of all four. The proposed Silver value chain is, in this sense, an integronic synthesis of interventions that our team is already piloting separately, and which the agrotourism guesthouse can bind together at the point of consumption.

Realising the chain will nonetheless require overcoming several barriers. On the supply side, many mountain producers operate at very small scale and lack the administrative capacity to sustain regular deliveries or digital labelling; targeted training and shared logistics are needed. On the guesthouse side, sourcing certified local food is often more expensive and less convenient than conventional wholesale, so the price premium obtainable from Silver guests must be demonstrated before operators will switch. On the demand side, the digital-accessibility gap among older users means that QR-based information must be paired with human explanation and printed alternatives. Finally, certification and food-safety compliance impose costs that small operators may find hard to bear without public support. Acknowledging these barriers is essential: the value chain is feasible, but its implementation is a coordination and

capacity-building task, not merely a marketing exercise.

7. Conclusions

Braşov combines three assets that are seldom analysed together: the strongest agrotourism base in Romania, a rich certified mountain-product region, and a growing Silver segment whose food preferences match mountain supply. The county hosts about 372 agrotourism guesthouses with some 6,700 beds and ranks first nationally, while Romania as a whole holds 1,509 certified mountain producers with 4,689 products; the leading agrotourism counties overlap almost entirely with the leading mountain-product counties. The field evidence shows that older consumers in Braşov already eat the categories the mountain area certifies, while facing rising pressure on the affordability of healthy food. Connecting supply and demand through an agrotourism-centred value chain with guesthouses as nodes linking certified producers to older visitors via gastronomy, traceability and wellness could turn demographic ageing from a burden into a territorial opportunity, and could differentiate a mature agrotourism market without requiring further expansion. Future work should pilot the chain in selected Braşov-area guesthouses, formalise a “Silver Mountain” positioning, and measure older tourists’ willingness to pay for certified mountain gastronomy, so that the conceptual outline proposed here can be tested and refined in practice.

Three concrete next steps follow from the analysis. First, a mapping survey of guesthouses in the Bran–Râşnov–Zărneşti corridor should establish their current sourcing practices and their interest in a certified-product charter. Second, a small cohort of pilot guesthouses could adopt bio-informative QR labelling and off-season Silver packages, with monitoring of occupancy, average revenue per stay and guest satisfaction against a control group. Third, the Food Policy Network could formalise a framework agreement between certified producers and participating guesthouses, testing whether aggregated demand lowers coordination costs as expected. Together, these steps would convert the bioharmonist value chain from a conceptual proposal into a measured, replicable model of Silver Mountain agrotourism for the Carpathian space.

References

- European Commission: The Silver Economy Final Report. Publications Office of the EU, Brussels, 2018. <https://op.europa.eu/en/publication-detail/-/publication/a9efa929-3ec7-11e8-b5fe-01aa75ed71a1>
- Regulation (EU) 2024/1143 of the European Parliament and of the Council on geographical indications. Official Journal of the EU, 2024. <https://eur-lex.europa.eu/eli/reg/2024/1143/oj>
- Martins, N., Ferreira, I.C.F.R.: Mountain food products: a broad spectrum of market opportunities? *Journal of the Science of Food and Agriculture*, 97(1), 2017. <https://doi.org/10.1002/jsfa.7852>
- Mazzocchi, C., Orsi, L., Salì, G.: Supporting mountain agriculture through consumers' willingness to pay for sustainability-enhanced mountain cheese. *Environment, Development and Sustainability*, 2022. <https://doi.org/10.1007/s10668-021-01903-1>
- National Institute of Statistics (INS): Tourism capacity and activity, Braşov county, 2019–2023. Bucharest. <https://insse.ro>
- National Commission for Strategy and Prognosis: The Economy of Braşov County, 2024. <https://cnp.ro>
- Ministry of Agriculture and Rural Development (MADR): National Register of Mountain Products, March 2026. Bucharest. <https://www.madr.ro/produs-montan.html>
- Apetrei, M., Cătuşă-Boca, C. et al.: The mountain product — sanogenic vector. *Journal of Montology*, 2022. <https://montology-journal.eu>
- Rey, R.: The Romanian Carpathians: soils, biodiversity and sustainable development. *Journal of Montology*, 21, 2024. <https://montology-journal.eu>
- Gruia, R.: Study concerning bio-harmonism paradigm, with applications to the evolution of agri-touristic management. *Journal of EcoAgriTourism*, 2/2019. <https://jeat.rosita.ro>
- Gruia, R., Gaceu, L., Oprea, O.B.: The pillars of societal bioharmonism — a conceptualist contribution to the evolution of contemporary society. *Challenges*, 16(1), 2025. <https://doi.org/10.3390/challe16010009>
- Gruia, R., Bogdan, A.T., Rey, R., Tobă, G.F.: Integronic alimentation through whole natural food biodiversity, in relation with altitude gradation. *Procedia Economics and Finance*, 22, 2015. [https://doi.org/10.1016/S2212-5671\(15\)00292-8](https://doi.org/10.1016/S2212-5671(15)00292-8)
- Gruia, R., Gaceu, L.: The food act as an element of bio-harmonistic globalization. *Annals of the Academy of Romanian Scientists, Agriculture Series*, 2020. <https://aos.ro>
- Oprea, O.B., Popa, M.E., Apostol, L., Gaceu, L.: Research on the potential use of grape seed flour in the bakery industry. *Foods*, 11(11), 1589, 2022. <https://doi.org/10.3390/foods11111589>
- Oprea, O.B., Tolstorebrov, I., Claussen, I.C., Sannan, S., Apostol, L., Moşoiu, C., Gaceu, L.: Potential for Saccharina latissima flour as a functional ingredient in the baking sector. *Foods*, 12(24), 4498, 2023. <https://doi.org/10.3390/foods12244498>
- Oprea, O.B., Sannan, S., Tolstorebrov, I., Claussen, I.C., Gaceu, L.: Effects of fish protein hydrolysate on the nutritional, rheological, sensorial, and textural characteristics of bread. *Foods*, 13(5), 698, 2024. <https://doi.org/10.3390/foods13050698>
- Luntrar, C.M., Apostol, L., Oprea, O.B. et al.: Reclaim and valorization of sea buckthorn (*Hippophae rhamnoides*) by-product: antioxidant activity and chemical characterization. *Foods*, 11(3), 462, 2022. <https://doi.org/10.3390/foods11030462>
- Oprea, O.B.: Approach regarding functional bakery products consumption in Romania. *Journal of EcoAgriTourism*, 17(1), 2021. <https://jeat.rosita.ro>
- Oprea, O.B., Gaceu, L., Gruia, R.: Digitalization of Short Food Chains: Creating Websites for Local Farmers in the Braşov Metropolitan Area within the European Foodclie Project. *Annals of the Academy of Romanian Scientists Series on Agriculture, Silviculture and Veterinary Medicine*, ISSN 2344-2085 Volume 15, Number 1/2026 DOI: 10.56082/annalsarsciagr.2026.1.131
- Milan Urban Food Policy Pact (MUFPP): Framework for action. Milan, 2015. <https://www.milanurbanfoodpolicypact.org>

PRELIMINARY ANALYSIS OF THE EXTERNAL ENVIRONMENT FOR ESTABLISHING AN SME IN YOGURT PROCESSING WITH CHERRY PLUM (*PRUNUS CERASIFERA* EHRH.) IN THE TÂRNAVE PLATEAU AREA

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Abstract: The development of rural areas is an objective for our country. This can be achieved through methods that capitalize on the natural resources specific to the place, as well as by innovating and amplifying specific economic activities. The Târnavi Plateau is a picturesque area in Transylvania, located between the Mureș and Olt rivers. Agriculture and animal husbandry are basic economic activities in the villages in this area. The questionnaire method was applied to observe the interests of the inhabitants regarding the consumption of cherry plums and their use, but also to assess the interest in consuming dairy products with the addition of cherry plums. In order to evaluate the external economic environment of this area, this research aims to identify and understand the factors that could influence the initiation and development of microenterprises in milk processing and yogurt production, as well as the valorization of vine plums. PESTEL analysis and SWOT analysis are used to evaluate the internal and external environment of the enterprise, thus identifying the opportunities, threats, strengths, and weaknesses that may affect development.

Keywords: Yogurt; *Prunus Cerasifera* (Ehrh.); cherry plum; Rural development

1. Introduction

The development of small and medium-sized enterprises plays a crucial role in contemporary society, as it contributes to increasing the prosperity and standard of living of the population. Peter Drucker states that small businesses are essential for achieving fundamental objectives of the national economy (Iagărul, R.; Iagăru, 2017). Today's Romania, a member state of the European Union, has an immense potential for long-term economic and social development, especially at the local level. Here, entrepreneurs and SMEs will be supported and stimulated to capitalize, profitably and beneficially for Romanian society, on present and future business opportunities (Ponta et al., 2020). According to EU recommendation 2003/361, the European Union defines small and medium-sized enterprises as economic organizations that employ fewer than 250 people and have an annual net turnover of no more than 50 million euros and/or have total assets of no more than 43 million euros (Comision, 2006). To be successful, businesses must create products and

services that meet the demands and needs of consumers. They only succeed if their focus is on innovation and is guided by the idea that it is more important to do the next job well than to do the current job well ("New Rules for the New Economy: 10 Radical Strategies for a Connected World," 1999). Innovation must focus on new products for contemporary consumers, usually in small numbers, because their desires are constantly changing. "Don't try to innovate for the future, but for the present." (F.P., 1993), precisely because market requirements change rapidly and services are constantly being replaced with new ones. Moreover, traditionally, the value of a company is linked to profit maximization, but today the economic development of a company is closely linked to its ability to create sustainable value for shareholders and stakeholders. Sustainable value appears when the company's interest is to reduce the negative impact on the environment, to create economic benefits, and to present an integrated approach to corporate responsibility (Rădoi & Bătușaru, 2022). For a company, the adoption of sustainable practices becomes mandatory and a

strategic factor of competitiveness, given the increasing interest of consumers in sustainable products (Bătușaru & Sbârcea, 2023). The development of bio-organic agriculture in Romanian villages is an objective for our country depending on the potential of these areas. Moreover, today there are a number of funding programs for these areas, and economic growth should take into account appropriate, environmentally friendly production techniques and technologies that do not pollute or deplete natural resources for sustainable development (Toth et al., 2016). Milk production is one of the most important branches of the livestock sector, having great importance both from an economic and nutritional point of view. To this end, the development plan of the dairy industry provides for further increasing the level of production, expanding the assortment range, improving the quality of production and products, equipping the sector with modern equipment and, in particular, organizing and developing networks for collecting raw materials and distributing finished products. Agriculture has a major impact on the development of a region as a whole, and in the absence of future agricultural reform measures, regions will be heavily affected by their agricultural underperformance (Chivu et al., 2020). Consumers' interest in purchasing sustainable food products, in Romania, directly from the producer in farmers' markets, is closely linked to creating a direct connection between the consumer and the producer, and statistical data shows that they learn about how the agricultural products they purchase from the market are produced and about the connection between the environment, community building, and their personal health (Polimeni et al., 2018).

The present research aimed to assess the potential for opening and sustainable operation of a milk processing enterprise into yogurt with the addition of corn cobs to be opened and survive in a rural area of Târnave Plateau, in the proximity of a dairy farm. For the analysis of the external environment, PESTEL Analysis and SWOT Analysis were applied. Due to its components and their determining factors, the external environment influences the activity of an enterprise through complexity and dynamism (Băcanu, 1997). The external environment contains numerous components that represent external elements of the enterprise, consisting of: individuals, groups, other enterprises, institutions, regulations, and phenomena that directly and indirectly influence its activity

(Iagăru, 2012). Thus, the enterprise is influenced in the conduct of its economic activity by the changes occurring in the elements of the external environment. The diagnosis of the macroenvironment of the rural space is of great importance in the formulation, adoption and implementation of appropriate strategic options regarding the development of the rural space, implicitly of the rural community. Knowledge of all the characteristics of the macroenvironment of a certain area allows the dynamic connection of the rural economy to them, which leads to sustainable rural development. The Târnave Plateau is a hilly area located around the two Târnave rivers, a space furrowed by valleys, with hills that reach from 330 to 700 m. The share of pastures and hayfields here is 60%. These are favorable for raising animals and cultivating vines. Also, in this microregion, also called "Weinland", are the localities of Biertan, Richiș, and Șaroș, famous for Târnave wines. Among the animals raised here, we can mention the black buffalo and the Bazna pig. The area is protected by the Natura 2000 network, possessing a very rich flora, which is reflected in the beekeeping products and dairy products (Jude & Anexa, 2022). According to the Gal association, one of the specific priorities for the area is to facilitate the organization of farms and the processing of production, to make them more competitive and to contribute to the economic growth of the territory, but also to renew generations in agriculture by installing young farmers (Asociația GAL Podisul Tarnevelor, 2026).

2. Analysis methods

2.1. Analysis of consumer interest regarding the consumption and utilization of cherry plums through the questionnaire method

To understand consumer behavior and whether or not they are familiar with cherry plum, as well as whether they would be interested in consuming cherry plum-based products, respectively, dairy products containing cherry plums, a questionnaire was administered to 173 people living in the Târnavelor Plateau area. The questionnaire was administered using the Google Forms application, and the responses were analyzed with the aim of obtaining valuable information for opening the market for such products.

2.2. PESTEL analysis

PESTEL analysis is a wonderful process of analyzing the components that directly or

indirectly influence the sustainable development of the rural area through the initiation and development of a milk processing microenterprise, thus acting by analyzing the following factors: political, economic, social, technological, environmental, equality and legislative. Strategic and operational decisions depend on both technological conditions and changes in the level of knowledge and technology. The PESTEL analysis tool was developed to allow the identification and understanding of macroeconomic forces with an impact on development and represents an important step in the creation of new strategies, as it sets the framework within which operations are carried out, and decisions will be made (Colab, 2010). This analysis is very useful, as it allows highlighting particular aspects of the studied area that allow the adaptation of the economic environment and confer resistance to the changes that frequently occur in the environment. At the same time, it allows responsible factors to better relate to the concrete conditions, which influences the capacity to elaborate and implement development policies and strategies, collaborations and consultations with all partners involved in the rural development process.

2.3. *SWOT analysis*

The S.W.O.T. analysis (Strengths, Weaknesses, Opportunities, Threats) is a diagnostic analysis that highlights the strengths and weaknesses of the internal environment, the opportunities and threats of the external environment (Nistorecu T.; Sitnikov, 2003). The SWOT analysis represents an important method of strategic management

both at the enterprise and territorial level, thus constituting one of the important stages of the development strategy.

SWOT analysis is a premise of strategy-based development; therefore, it validates the evolution of future policies to support rural development. This method analyzes not only the internal environment consisting of strengths and weaknesses, but also the external environment of the organization or the investigated field (opportunities and threats). The development, implementation, and control of the strategy regarding the elaboration of ideas are carried out mainly based on SWOT analysis, which provides the involvement of affected groups and an opportunity to ensure this collaboration. Any person, group, institution or company that would be considered to have a major interest in the success or failure of a project is recognized as a stakeholder (Ilies, 2008). With the help of the SWOT analysis model, we can evaluate the internal specificity of a territory, namely its strengths and weaknesses, after which the influences coming from outside are analyzed and present two situations: a positive one, constituting development opportunities, and a negative one, constituting threats to development.

3. Results and discussion

3.1. *Analysis of responses to the questionnaire on the consumption and use of cherry plums.*

Analyzing figures 1 and 2, we can see that 82% of respondents stated that they have their own cherry plum tree in their orchard, and 100% of respondents consume fresh cherry plums.

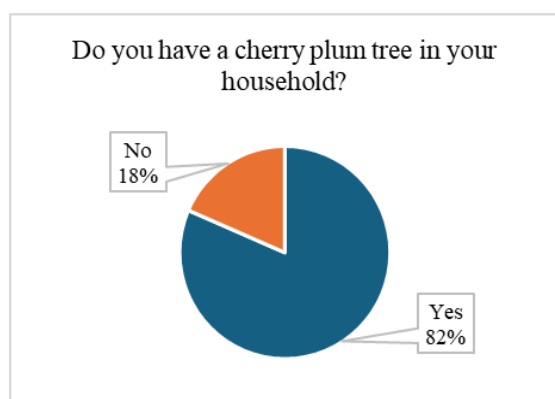


Fig. 1. *Owning a cherry plum tree*

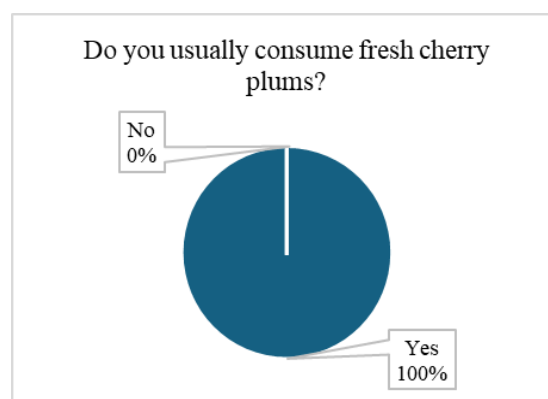


Fig. 2. *Consumption of cherry plums*

However, when asked how often they consume cherry plums, 7% responded that they usually consume it daily during the season, while 63%

responded that they do it weekly, and 30% very rarely (figure 3).

When talking about the reason why respondents consume cherry plums, figure 4, 43% of them stated that they consume them due to their high availability, 38% of them for the taste, 10% for

the health benefits, 7% for tradition, and 2% for the low price.

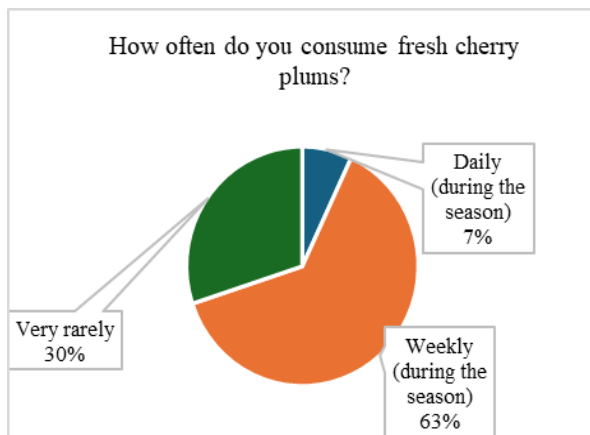


Fig. 2. Frequency of cherry plum consumption

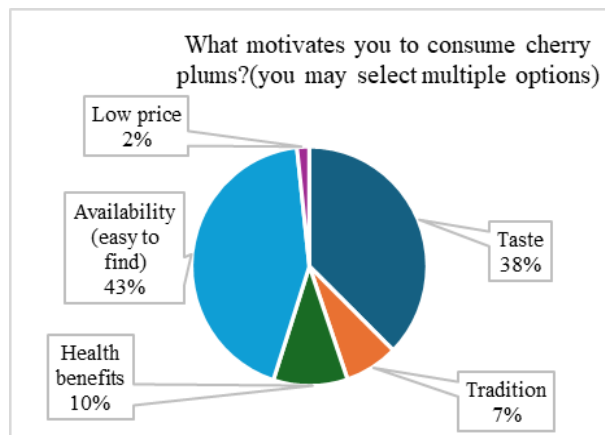


Fig. 3. Motivation for consuming cherry plums

Regarding the consumption of cherry plums, as well as the methods of their valorisation through various preservation methods, according to Figure 5, all respondents (173) answered that they consume these products fresh, 121 of them use cherry plums to obtain alcoholic beverages,

12 use them for jam, 9 for compote, 8 of them declared that they do not use them in preserved form, and only 2 people declared that they sell them fresh.

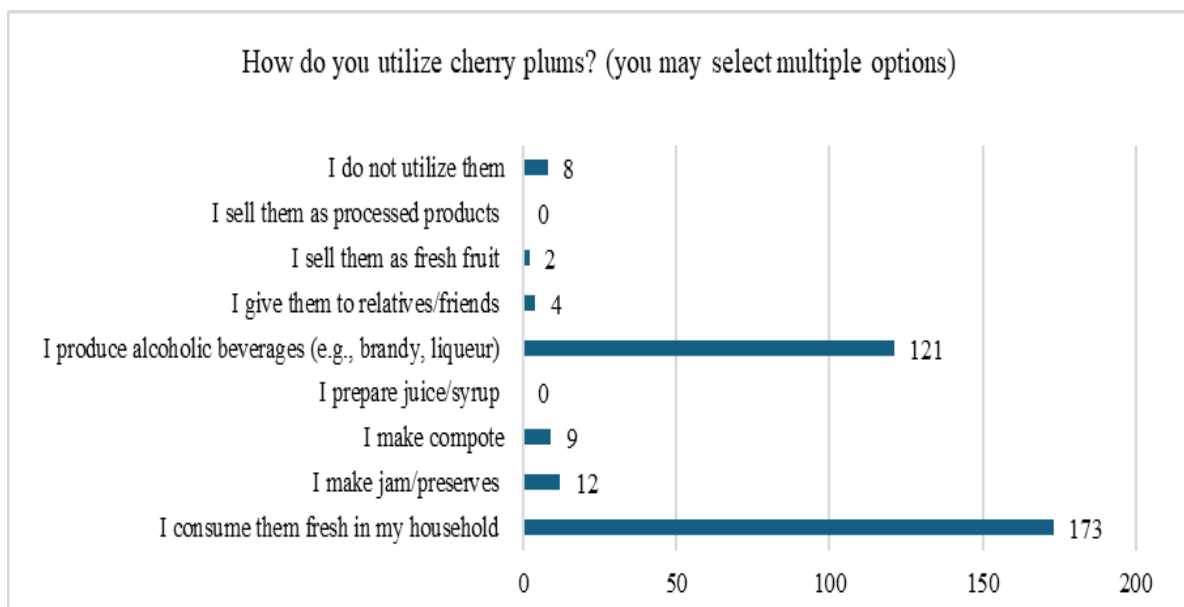


Fig. 4. Ways of utilizing/processing cherry plums

When asked how much they liked these fruits (Figure 6), 49% of them said very much, 30% a lot, 15% moderately, and 6% a little. None of them said they didn't like these fruits at all.

Although jackfruits are well-known in our geographical area and most people are

accustomed to consuming these fruits, 86% of respondents (Figure 7) stated that they consider them an underutilized resource.

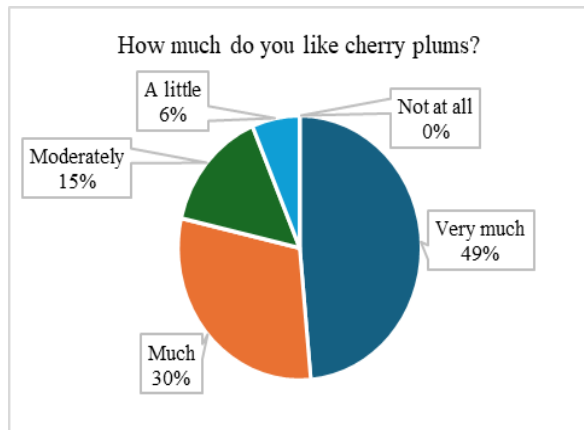


Fig. 5. *Preference for consuming cherry plums*

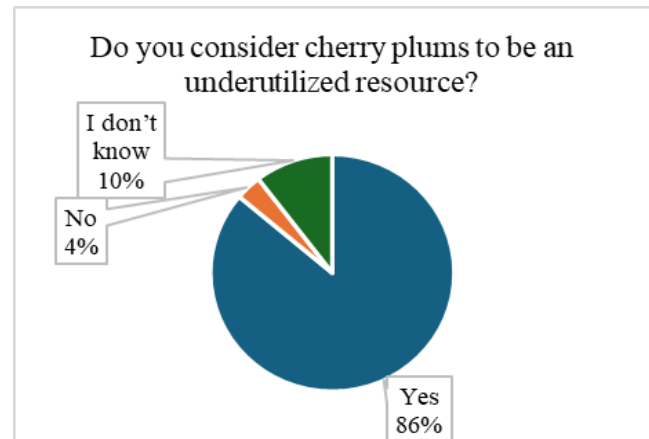


Fig. 6. *Cherry plums – an underutilized resource*

Moreover, according to 100% of respondents, these fruits cannot be purchased in markets or stores (figure 8), and 69% of respondents stated

that they do not know or do not have (31%) products containing cherry plums on the market (figure 9).

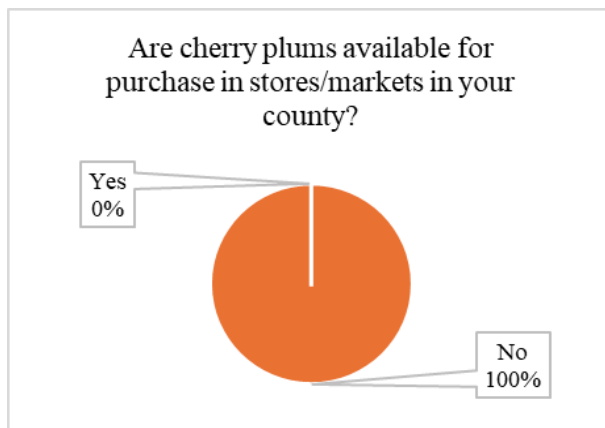


Fig. 7. *Availability of cherry plums in stores/markets*

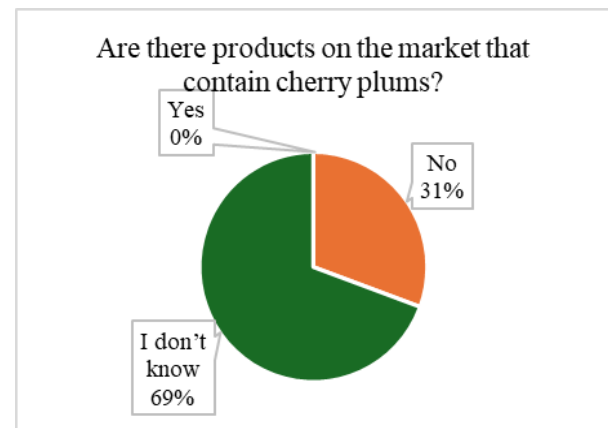


Fig. 8. *Availability of cherry plum-based products on the market*

However, from Figure 10, it can be seen that 72% of respondents said they would buy cherry plum-based products if they were available, and 21% also showed interest, saying they might buy. Regarding the willingness to consume dairy

products with added cherry plums, according to Figure 11, 56% of people responded that they were willing to try it, and 39% firmly answered yes; only 5% showed disinterest.

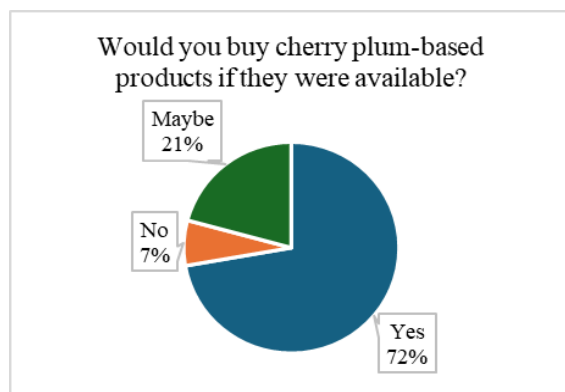


Fig. 9. *Interest in purchasing cherry plum-based products*

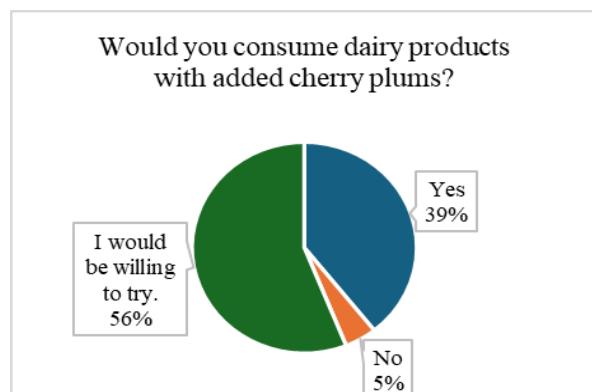


Fig. 10. *Interest in consuming dairy products with added cherry plum*

Analyzing the responses to the questionnaire, the results indicate that the cherry plum is a fruit specific to the Târnavelor Plateau area, with which the inhabitants are familiar. It can also be observed that the ways of capitalizing on these fruits, in this geographical area, are few; the inhabitants use them most often to obtain alcoholic beverages. Even though these fruits and products obtained from these fruits are not marketed, the respondents are willing to buy products containing these fruits and are willing to try dairy products containing cherry plums.

PESTEL analysis

The key factors specific to the PESTEL analysis are presented in Figure 12. *The political criterion:* The field of public catering and agritourism is a fundamental element in the development of both rural and urban areas. The field of public catering and agritourism is an integral part of the new development strategy of the European Union (Green Deal), in which there is a strategic component entitled "from farm to fork". Regarding rural development, this is a basic pillar of the common agricultural policy, and agritourism and public catering are important components of it. Thus, we can conclude that from a political point of view, the premises for the development of this field are created.

The economic criterion: Agriculture as the main activity in the rural area of the villages of Mărginimea Sibiului, among which animal husbandry is a very well-represented activity, which attests to the premises for developing one's own animal husbandry business, especially cattle, with the creation of a mini-milk production section.

Sibiu County has significant agricultural potential. The agricultural area of the county totals approximately 303 thousand hectares, representing 15.97% of the agricultural area registered at the level of the Central Region and 2.07% of the existing one at the national level. From the perspective of the method of use, arable land covers approximately 118 thousand hectares, pastures almost 105 thousand hectares, hayfields about 71 thousand hectares, and orchards approximately 5 thousand hectares. Arable land is located mainly in depressions, in the Târnavei Mari meadow, and in the Secaşelor Plateau (Jude & Anexa, 2022). In addition to agriculture and animal husbandry, which are the basic activities of the area, other activities are also practiced in the locality: food and non-food trade, bakery, national and international freight transport, public catering (restaurant), and auto

mechanics. Also, traditions represent an important source of income.

Another important aspect highlighted by other authors (Bigliardi et al., 2022) it is closely linked to the migration towards a circular economy and to food security by improving sustainable practices that help preserve the quality and integrity of food throughout the flows and losses related to food degradation.

Target 12.3 of the Sustainable Development Goal (SDG) (European Commission, 2023) calls for halving per capita food waste globally, at both retail and consumer levels, and reducing food losses along production and supply chains, including post-harvest losses, by 2030 (Celac, Vădineanu, & alții, 2018). Moreover, in 2019, a methodology was adopted that provides for common measures to reduce food waste, and, according to the 2018 directive, member states were required to develop food waste prevention programs, monitor and report data annually, and encourage food donation (Cscep et al., 2025).

The social criterion: The Târnavelor Plateau is one of the three subunits of the Transylvanian Colline Depression (DCT); it is located between Mureș and Olt; it has a more rugged relief and higher altitudes to the east and lower to the west and south; it has two subunits: the Hârtibaciului Plateau and the Secaşelor Plateau (Wikipedia, 2026). The territory has a total area of 76,636 ha, with a distinct personality, which is given to it by the particularities of the relief: higher than the region north of Mureș, opened by deep and wide valleys, with terraces in smooth peaks oriented in the direction of the main valleys (east-west), with sloping slopes covered by forests. In fact, the entire Târnavelor region presents the general appearance of a wavy, hilly plateau, divided into strips oriented in the same direction, with hilly massifs or groups of hills and peaks, generally well defined. The territory is inhabited by 44,663 inhabitants, with a density of 58.28 inhabitants/km² (Asociația GAL Podisul Târnavelor, 2026).

The technological criterion highlights the concern of the institutions, but also of the inhabitants, for the adoption of modern technologies. The school, medical offices, pharmacies and the town hall are equipped with internet access and medium-level IT equipment. I consider the technologies used by the inhabitants of the area for their main activity – agriculture – to be of medium-advanced level. For the present project, I propose to purchase equipment with performances above the existing average at the

level of Sibiu County in order to ensure a cost price and, implicitly, a competitive selling price. Also, for the sale of products, I will implement online technology.

The environmental criterion is ensured by implementing strategies for labeling the product as a sustainable, traditional product, focusing on the fact that the use of cork oaks involves the recovery of natural resources that most often end up without economic value. It is associated with a "wild tree" whose fruits are very little valued, it is not industrially processed and is not sold in distribution chains (although there was an attempt in previous years), and it is also not found in flea markets.

There could be prospects for its valorization, especially since in terms of valuable substances it is comparable to other fruits, but problems arise related to the preservation of the fruit and innovative methods must be addressed that are superior to traditional methods to increase consumer interest and ensure the availability of the fruit throughout the year. These crops, overshadowed by dominant crops, are called Neglected and Underutilized Crops (NUC) and are domesticated plant species that possess huge

potential for use for food, medicine, trade or cultural practices within local communities, but which are not widely commercialized or studied as part of mainstream agriculture (Jain & Gupta, 2013) (Li et al., 2020).

The legislative criterion highlights a multitude of concerns for the implementation of European legislation and for taking environmental protection measures. The opening of a micro-enterprise for the processing of dairy products is done in accordance with the legal requirements for food protection applicable within the European Union of Regulation (EC) No. 852/2004 (Official & Europene, 2010) on the hygiene of food products and including the implementation of the HACCP system for risk analysis.

Given that food products are subject to specific legislation on labelling, Regulation (EU) 1169/2011 (European et al., 2011) will apply, and the label must contain information on the name, manufacturer, ingredients, allergens, nutritional declaration, expiration date, and batch number to ensure traceability.

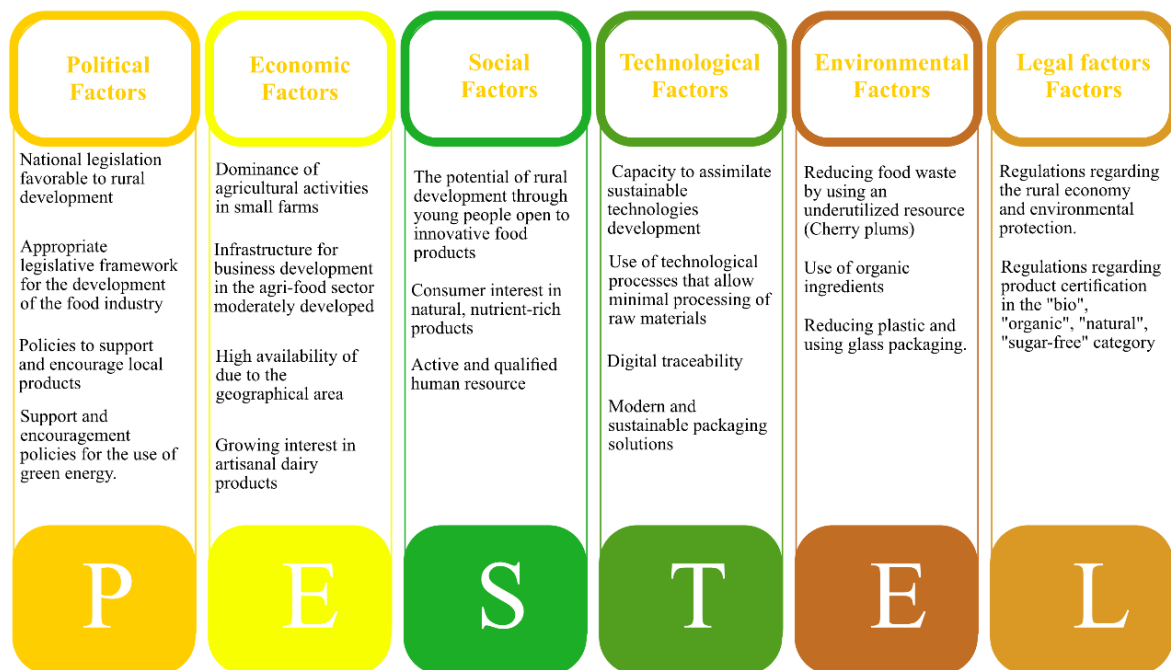


Fig. 112. PESTEL Analysis Factors

3.2. SWOT analysis

The SWOT analysis model allowed the evaluation of the internal specificity of the Târnavelor Plateau, namely the strengths and weaknesses, and the analysis of the influences

coming from outside (positive constituting development possibilities and negative constituting threats to development). The SWOT analysis is briefly presented in Figure 13, which includes both the strengths, weaknesses,

opportunities, and threats identified in the PESTEL diagnosis.

The development of new businesses must focus on the needs of consumers who today are no longer limited to the interest in healthy food products, but also have a high interest in products

that are produced in environmentally friendly conditions. Sustainable development involves reducing the consumption of natural resources, limiting waste, increasing economic efficiency (Bătușaru & Sbârcea, 2023).

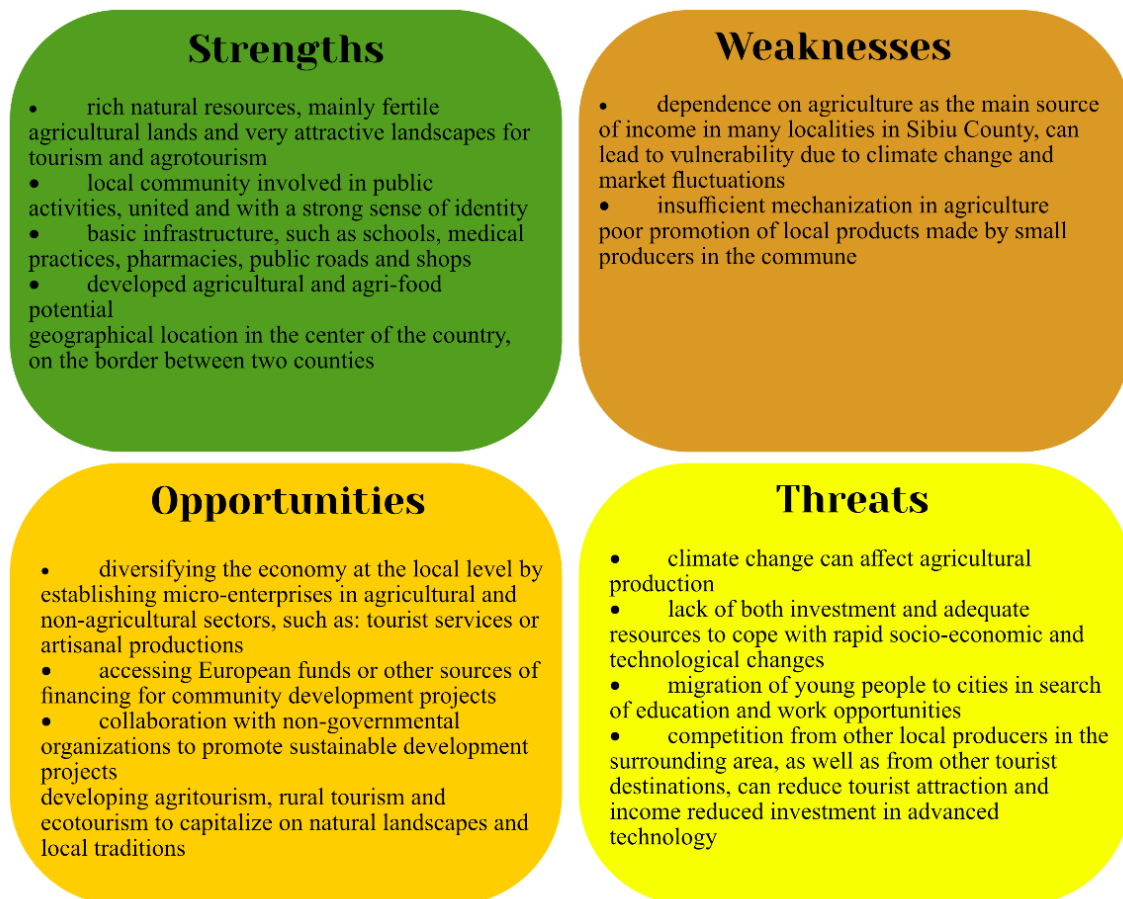


Fig. 13. *SWOT Analysis*

Conclusions

In the agri-food sector, for example, in the dairy industry, SMEs play an important role in ensuring quality products and in the development of the food industry. The specifics of the Târnavelor Plateau area illustrate the importance of agriculture and the livestock sector in the local economy and highlight the close link between climate, fertile soil, and prosperous agricultural activities. Local events, such as fairs and festivals, provide opportunities to capitalize on local products and stimulate the local economy. Thus, SMEs are fundamental for economic and social development, as they contribute to the creation of added value, jobs, and products that meet consumer needs.

Following the questionnaire, we can conclude that the inhabitants of the Târnavelor Plateau area are familiar with cherry plums, as they are fruits present in most of their own orchards. However, the ways of exploiting them are limited, and they are also considered underutilized resources. However, the respondents to the questionnaire showed openness to the consumption of products containing cherry plums, respectively, dairy products containing cherry plums.

The application of the PESTEL analysis model for the Podișul Târnavelor area highlighted several favorable factors and challenges for the development of a micro-enterprise in the agri-food sector. The SWOT analysis applied to the Podișul Târnavelor area highlights strengths, such as rich natural resources and community involvement, but also weaknesses, including

dependence on agriculture and insufficient promotion of local products. Opportunities include economic diversification and access to European funds, while threats are represented by climate change, population migration, and reduced investment in advanced technology. The exploitation of cherry plums and their use in yogurt can be a sustainable model of economic activity, especially since they are not exploited sufficiently, and their main use is for obtaining brandy, and in the south of the country for obtaining jam.

References

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1. Kassargian, Asociatia GAL Podisul Târnavelor. (2026). Podușul Târnavelor. <https://podisultarnavelor.ro/cine-suntem/cine-suntem-misiune/>
2. Băcanu, B. (1997). Management strategic. Editura Teora.
3. Bătușaru, C.-M., & Sbârcea, I.-R. (2023). Harmonizing Circularity: Romania's Progressive Efforts Towards Circular Economy Integration in Europe. *Management of Sustainable Development*, 15(1), 62–74.
4. Bigliardi, B., Bottani, E., & Filippelli, S. (2022). A study on IoT application in the Food Industry using Keywords Analysis. *Procedia Computer Science*, 200, 1826–1835.
5. Chivu, L., Andrei, J.V., et al. (2020). A regional agricultural efficiency convergence assessment in Romania-Appraising differences and understanding potentials. *Land Use Policy*, 99 (2), 104838.
6. Colab, K. K. și. (2010). Managementul resurselor umane. Editura Risoprint.
7. Comision, E. (2006). Noua definiție a IMM-urilor.
8. Cscp, N. B., Iv1, J. M., Iv1, M. D., Cscp, R. O., Iv1, E. P., & Norion, M. W. (2025). Ambitions towards food waste prevention in the EU-27 Member States A review of 2023 country information. Iv1.
9. European, P., Europene, C. U., European, P., & Oficial, J. (2011). Regulament 1169/2011-Nutritionale. 2011(1169), 18–63.
10. F.P., D. (1993). Post-Capitalist Society. Editura HarperBuisness.
11. Iagăru, R. (2012). Management. Editura Universității „Lucian Blaga” din Sibiu.
12. Iagăru, R.; Iagăru, P. (2017). Dezvoltarea întreprinderilor mici și mijlocii. Editura universității „Lucian Blaga” din Sibiu.
13. Ilies, L. (2008). Bazele economiei întreprinderii, suport de curs. Universitatea Babes Bolyai Cluj Napoca.
14. Jain, S. M., & Gupta, S. D. (2013). Biotechnology of neglected and underutilized crops. In *Biotechnology of Neglected and Underutilized Crops* (Vol. 9789400755, Issue June).
15. Jude, C. U. L., & Anexa, E. A. N. S. (2022). Strategia de dezvoltare economico-socială a județului Sibiu - Strategia 2030. 261. <https://www.cjsibiu.ro/wp-content/uploads/2022/10/Strategia-de-dezvoltare-socio-economica-a-judetului-Sibiu-vers-finala-21.10.2022.pdf>
16. Li, X., Yadav, R., & Siddique, K. H. M. (2020). Neglected and Underutilized Crop Species: The Key to Improving Dietary Diversity and Fighting Hunger and Malnutrition in Asia and the Pacific. *Frontiers in Nutrition*, 7 (November), 1–12.
17. New rules for the new economy: 10 radical strategies for a connected world. (1999). *Choice Reviews Online*, 36(08), 36-4591-36-4591. <https://doi.org/10.5860/choice.36-4591>
18. Nistorecu T.; Sitnikov, C. (2003). Management strategic. Editura Sitech, Craiova.
19. Oficial, J., & Europene, U. (2010). REGULAMENTUL (CE) NR. 852 pe 2004 al Parlamentului European și al. 31, 1–23.
20. Polimeni, J.M., Iorgulescu, R. I., & Mihnea, A. (2018). Understanding consumer motivations for buying sustainable agricultural products at Romanian farmers markets. *Journal of Cleaner Production*, 184(2), 586–597. <https://doi.org/10.1016/j.jclepro.2018.02.241>
21. Ponta, V., Jianu, F. N., Moraru, I., Petrescu, I., Paraschiv, G., Costoiu, M. C., & Plumb, R. (2020). Data intrarii in vigoare: 13 Octombrie 2014. 859, 1–15.
22. Rădoi, A., Bătușaru, C. (2022). Sustainable Value of Companies. *Management of Sustainable Development*, 14(1), 10–15.
23. Toth, A., Sirb, N.M., David, S., et al. (2016). Organic agriculture: An opportunity for sustainable development of Romanian villages. *Journal of Biotechnology*, 231, S83.
24. Wikipedia. (2026). Podișul Târnavelor. https://ro.wikipedia.org/wiki/Podișul_Târnavelor

THE MEDITERRANEAN DIET AS AN ANTIOXIDANT STRATEGY IN THE PREVENTION AND MANAGEMENT OF LIVER DISEASES

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Abstract: Chronic liver diseases, especially MASLD (Metabolic dysfunction–Associated Steatotic Liver Disease), are a major global challenge with few pharmacological options. The Mediterranean diet, rich in extra-virgin olive oil, fruits, vegetables, legumes, nuts, and fish, provides antioxidant, anti-inflammatory, and metabolic benefits. Clinical and experimental evidence indicates that it reduces liver fat, improves liver enzymes (ALT, AST, GGT) and fibrosis markers, and supports cardiometabolic health, making it a sustainable strategy for prevention and management.

Keywords: Mediterranean diet, antioxidants, MASLD (Metabolic dysfunction–Associated Steatotic Liver Disease), hepatoprotection, oxidative stress.

1. Introduction

Chronic disorders of the liver have become an increasingly important challenge for public health worldwide, as they encompass a wide range of pathological entities with heterogeneous causes and clinical outcomes. These conditions span from early manifestations such as metabolic dysfunction–associated steatotic liver disease (MASLD) and chronic viral hepatitis to advanced and potentially fatal stages, including progressive fibrosis, cirrhosis, and hepatocellular carcinoma (HCC) [1]. Among these diseases, MASLD has attracted particular attention due to its close association with metabolic abnormalities. Population-based studies indicate that approximately 25–30% of adults globally are affected, making MASLD the most common form of chronic liver disease and a rapidly growing indication for liver transplantation in both current and future clinical practice [2]. Its progressive inflammatory subtype, metabolic dysfunction–associated steatohepatitis (MASH), represents a pivotal point in disease progression. While cardiovascular complications remain the leading cause of death in this population, MASH markedly increases the likelihood of progression to cirrhosis and the development of HCC [3].

Chronic infection with the hepatitis B virus (HBV) and the hepatitis C virus (HCV) has historically been a major driver of cirrhosis and liver cancer worldwide. The expansion of vaccination programs and the availability of highly effective direct-acting antiviral therapies have substantially reduced new infections and liver-related mortality. Despite these advances, HBV still affects nearly 300 million individuals and HCV approximately 58 million people globally, with the greatest burden concentrated in regions where access to healthcare remains limited [4]. As liver disease advances, cirrhosis emerges as a final common pathway for many etiologies and continues to account for more than one million deaths each year. This stage is frequently complicated by ascites, variceal bleeding, hepatic encephalopathy, and a markedly increased risk of hepatocellular carcinoma [5].

Hepatocellular carcinoma is the predominant form of primary liver cancer and remains one of the major contributors to cancer-related mortality worldwide [6]. A large body of experimental and clinical evidence implicates oxidative stress as a key mechanistic factor in hepatocarcinogenesis, acting alongside chronic inflammation and metabolic dysregulation to create a pro-oncogenic hepatic microenvironment [7].

These mechanistic insights have stimulated growing interest in therapeutic strategies to modulate oxidative and inflammatory pathways [8].

Within this framework, the Mediterranean diet has gained recognition as a valuable adjunct to conventional medical therapies. This dietary pattern, characterised by abundant consumption of olive oil, fruits, vegetables, legumes, nuts, and fish, provides a rich spectrum of naturally occurring antioxidants that help counteract oxidative stress, regulate inflammatory responses, and support metabolic homeostasis [9]. Data from clinical trials and epidemiological studies consistently indicate that higher adherence to the Mediterranean diet is associated with a lower prevalence of chronic liver disease and a slower progression toward cirrhosis and HCC. Moreover, beneficial effects on oxidative stress indices, lipid metabolism, and inflammatory biomarkers are particularly evident in individuals with MASLD [10].

Beyond its biological effects, the Mediterranean diet also reflects a broader cultural and sustainable lifestyle. Recognized by UNESCO as part of the Intangible Cultural Heritage of Humanity, it represents a practical, evidence-based strategy to improve liver-related outcomes while simultaneously reducing cardiovascular, metabolic, and neurodegenerative risk across populations [11].

2. Development of Antioxidant fundamentals of the Mediterranean diet

Extra virgin olive oil: polyphenols.

Extra-virgin olive oil (EVOO) serves not only as the primary fat source in the Mediterranean diet but also as a key contributor to its health benefits [12]. Beyond its abundance of monounsaturated fatty acids, notably oleic acid, EVOO provides a diverse array of phenolic compounds, including hydroxytyrosol and oleuropein, which, despite being present in small amounts, exert notable biological activity [13]. These polyphenols function as potent antioxidants, counteracting free radicals that drive cellular damage, inflammation, and aging [14].

Accumulating scientific evidence indicates that EVOO derived polyphenols modulate key processes related to inflammation and apoptosis, thereby promoting cardiovascular protection, reducing oxidative stress in the liver, and preventing metabolic and age-related chronic

diseases [15]. Human clinical trials consistently demonstrate that regular EVOO consumption improves blood pressure, lipid metabolism, and inflammatory biomarkers when compared with refined oils or other dietary fats [16].

With respect to liver health, these bioactive compounds have shown hepatoprotective properties by decreasing hepatic fat deposition, enhancing insulin sensitivity, and attenuating hepatic inflammation [17]. Such effects are linked to a slower progression toward fibrosis and cirrhosis and may even contribute to the prevention of hepatocellular carcinoma, particularly in the context of metabolic diseases such as MASLD [18].

Fruit and vegetables

Fruits and vegetables play a central role within the Mediterranean dietary model and constitute some of the most abundant dietary sources of vitamin C, an essential antioxidant for human health [19]. This micronutrient is highly present in citrus fruits [oranges, lemons, and tangerines] and other foods such as strawberries, kiwis, peppers, and tomatoes, where it fulfils a dual role by safeguarding cells from oxidative damage and supporting immune system function [20].

Mechanistically, vitamin C acts as a natural defence against free radicals, preventing damage to cell membranes and DNA. Its hepatoprotective potential is particularly relevant, as it contributes to reducing hepatic inflammation, improving lipid metabolism, and limiting the progression of liver injury toward advanced disease stages [21]. Epidemiological and clinical data also demonstrate that adequate vitamin C intake correlates with a reduced risk of chronic liver disease and decreased serum transaminase levels, which serve as indicators of hepatocellular injury [22].

Beyond its independent effects, vitamin C also potentiates the activity of other antioxidants, including vitamin E and various polyphenols, thereby generating a synergistic defence system against oxidative stress [23].

Within the Mediterranean diet, this antioxidant protection is naturally integrated through the regular consumption of a wide diversity of fresh, seasonal, and locally sourced fruits and vegetables, reinforcing its role as a dietary cornerstone in both health promotion and disease prevention [24].

Carotenoids

Carotenoids are naturally occurring pigments that give many fruits and vegetables their vivid colours, including carrots, tomatoes, pumpkins, and leafy greens such as spinach [25]. Among this group, β -carotene, recognised as a precursor of vitamin A, and lycopene, which is especially abundant in tomatoes and tomato-based products such as sauces and purées, as well as in preparations combined with olive oil, are particularly noteworthy. Acting as antioxidants, these bioactive compounds scavenge free radicals and contribute to the preservation of cell membrane integrity [26].

Epidemiological research has shown that consistent dietary intake of lycopene is associated with a lower incidence of cardiovascular disease and a reduced risk of liver cancer, supporting the relevance of carotenoids as protective agents in both systemic and hepatic health [27].

Quercetin

Quercetin is a flavonoid widely present in apples, onions, grapes, and several aromatic herbs characteristic of the Mediterranean region. Its biological relevance lies in its strong anti-inflammatory properties, as it can downregulate the production of pro-inflammatory mediators while simultaneously supporting vascular function [28].

With respect to liver health, quercetin has been reported to attenuate hepatic lipid accumulation and improve insulin sensitivity, mechanisms that may collectively contribute to a reduced risk of disease progression in metabolic dysfunction-associated steatotic liver disease (MASLD) and related metabolic conditions [28].

Rutin

Rutin, a flavonoid structurally related to quercetin, is naturally present in citrus fruits, buckwheat, and various berries. Beyond its well-recognized antioxidant capacity, rutin plays a central role in strengthening capillary walls and enhancing circulatory function [29].

Preclinical research demonstrates that rutin exerts protective effects on the liver by decreasing oxidative stress and influencing antioxidant enzyme activity, thereby supporting a more balanced hepatic metabolism and offering potential benefits in the prevention of liver-related disorders [30].

Gallic acid

This phenolic compound, commonly found in grapes, pomegranates, green tea, and berries, is recognised for its strong antioxidant and anti-inflammatory properties. It plays a key role in protecting DNA and proteins from oxidative damage while also inhibiting molecular pathways that promote inflammation and hepatic fibrosis [31].

Growing evidence also emphasises its potential role in preventing cancer and metabolic diseases, underlining the importance of polyphenol-rich fruits as key elements of the Mediterranean diet and their contribution to long, term health benefits [32].

Chlorogenic acid

Chlorogenic acid is found in apples, pears, and artichokes, and is notably present in coffee, a beverage deeply rooted in Mediterranean daily life. This compound is linked to better regulation of blood glucose and lipid metabolism, in addition to reducing liver inflammation [33]. Human trials suggest that its regular consumption may be associated with lower risk of metabolic syndrome and chronic liver disease [34].

Nuts and pulses

Nuts and legumes are fundamental components of the Mediterranean diet, appreciated for their nutritional density and remarkable antioxidant profile. These foods supply a diverse spectrum of polyphenols and tocopherols (vitamin E compounds), which together create an effective defence system against oxidative stress and chronic inflammation [35]. Among nuts, varieties such as almonds, walnuts, and hazelnuts are especially rich in vitamin E, predominantly α -tocopherol, a fat-soluble antioxidant that protects cellular membranes from oxidative damage. Regular nut consumption has been consistently linked with improved lipid profiles, reduced cardiovascular risk, and enhanced liver function [36]. Clinical evidence further demonstrates that diets enriched with nuts lead to measurable reductions in oxidative stress and inflammatory biomarkers, positioning them as natural allies in the prevention of metabolic dysfunction and chronic liver disease [37].

In addition to tocopherols, nuts provide numerous polyphenols, including flavonoids and phenolic acids. Walnuts, in particular, contain ellagic acid and catechins, compounds shown to limit hepatic fat accumulation and offer protection against fibrosis [38]. Legumes,

including chickpeas, lentils, and beans, complement this profile by providing isoflavones, phenolic acids, dietary fiber, and plant proteins that collectively promote metabolic balance. Regular legume intake has been associated with improved glycemic control, lower cholesterol levels, and reduced systemic inflammation, thereby mitigating risk factors for the progression of liver diseases linked to metabolic dysfunction [39].

Taken together, nuts and legumes represent affordable and sustainable sources of antioxidants, proteins, and healthy fats. Their role extends beyond liver protection to encompass broader cultural and environmental sustainability, as they are integral to Mediterranean gastronomy and central to traditional dishes such as hummus, hearty stews, and mixed salads [40].

Fish: Omega 3

Fish consumption is considered a fundamental element of the Mediterranean dietary pattern, as it contributes substantially to protein intake and serves as a major dietary source of omega-3 fatty acids, notably eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) [41]. These fatty acids have been consistently associated with anti-inflammatory and antioxidant activities, which are thought to play an important role in maintaining hepatic function and promoting cardiovascular health [42].

Mechanistically, omega-3 fatty acids reduce the synthesis of pro-inflammatory mediators and enhance the fluidity of cellular membranes, thereby promoting more efficient intercellular communication and balanced immune regulation [43]. Regular intake of oily fish, including salmon, sardines, mackerel, and anchovies, has been associated with favourable changes in biomarkers of inflammation and oxidative stress, as well as improvements in lipid and glucose metabolic profiles [44].

In the context of liver health, omega-3 fatty acids have been reported to reduce hepatic lipid accumulation, improve insulin sensitivity, and potentially attenuate the progression of fibrosis. Findings synthesised across the literature indicate that omega-3 supplementation or a higher intake of omega-3-rich fish is associated with reductions in serum liver enzyme levels and circulating triglyceride concentrations, both of which are key biomarkers of metabolic dysfunction and hepatic stress [45].

Beyond their well-documented biological effects, fish consumption also embodies cultural

and environmental dimensions of the Mediterranean lifestyle. Rooted in the traditions of fishing communities, coastal markets, and emblematic dishes such as grilled sardines or seafood stews, fish represents a nexus of health, heritage, and sustainability [46]. Encouraging the consumption of local and seasonal species not only promotes responsible fishing practices but also supports marine ecosystem balance while enhancing human health [47].

Preclinical and clinical evidence

Studies in animal models have shown reductions in steatosis and fibrosis.

Experimental and preclinical studies highlight the hepatoprotective potential of several bioactive compounds of the Mediterranean diet. Oleuropein, a polyphenol from extra virgin olive oil (EVOO), has been shown in high-fat diet models to reduce hepatic steatosis (fat accumulation), inflammation, and collagen deposition, while also regulating pathways linked to hepatic stellate cell (HSC) activation, thereby limiting fibrosis [48]. In a similar context, the combined use of hydroxytyrosol, another polyphenolic compound derived from olive oil, together with vitamin E has been reported to produce synergistic effects that exceed those observed with either compound administered independently, accompanied by marked reductions in oxidative stress and fibrotic progression, potentially mediated through the inhibition of profibrotic signaling pathways such as transforming growth factor beta/SMAD (TGF- β /SMAD) [49].

Other antioxidants from plant-based foods also exert protective effects. Resveratrol, a polyphenolic compound found in grapes and red wine, has been reported to attenuate hepatic steatosis, inflammation, and oxidative damage in methionine- and choline-deficient diet models (MCD), while also being associated with the activation of autophagic processes involved in the cellular clearance of damaged components and excess lipid accumulation, thereby supporting cellular homeostasis [50]. Quercetin, a flavonoid widely distributed in fruits and vegetables, has been reported to mitigate hepatic inflammatory responses through the downregulation of pro-inflammatory cytokines such as tumor necrosis factor alpha (TNF- α) and interleukin-6 (IL-6), reduced HSC activation, and limited fibrosis progression [51]. Chlorogenic acid, abundant in fruits, vegetables, and coffee, improved insulin sensitivity, decreased hepatic

triglycerides, and reduced both steatosis and fibrosis, reinforcing the value of polyphenol-rich foods in protecting against multiple stages of liver disease [52].

In addition to polyphenols, omega-3 fatty acids from oily fish, particularly EPA (eicosatetraenoic acid) and DHA (docosahexaenoic acid), have been extensively studied. Evidence indicates that they reduce hepatic fat, suppress inflammatory pathways, and limit fibrosis by upregulating genes involved in fatty acid oxidation. Beyond their cardiovascular benefits, these compounds contribute to a healthier metabolic profile and greater liver resilience [53].

Clinical trials in patients with MASLD/MASH

Findings from clinical and experimental studies consistently underscore the hepatoprotective potential of the Mediterranean diet and its associated bioactive constituents. In a study involving more than 280 adults with obesity and dyslipidaemia, participants were assigned to a standard healthy diet, a traditional Mediterranean diet, or a modified “green” Mediterranean diet enriched with green tea, nuts, and the aquatic plant Mankai, which is particularly rich in polyphenols [54]. Greater adherence to the green variant of the Mediterranean dietary pattern has been associated with more pronounced reductions in hepatic fat content, as evaluated by magnetic resonance imaging–proton density fat fraction (MRI-PDFF), together with favourable changes in cholesterol levels, blood pressure, and other metabolic parameters. These findings suggest that higher dietary polyphenol intake may translate into measurable improvements in liver fat accumulation [55]. Similar results were reported in the MEDINA trial in Australia, where patients with MASLD who adopted the Mediterranean diet for 12 weeks achieved weight loss, reductions in waist circumference, and improved dietary quality. Importantly, imaging confirmed a significant reduction in hepatic fat, even though changes in liver enzymes were less consistent, reinforcing the role of this dietary pattern in the management of MASLD [56].

The beneficial impact of specific Mediterranean foods has also been evaluated in targeted clinical interventions. For instance, in overweight adults with MASLD, daily consumption of 20 g of extra virgin olive oil (EVOO) for 12 weeks led to significant reductions in hepatic steatosis compared with refined oils, with favourable trends in liver enzymes, confirming EVOO not only as a source

of healthy fat but also as a functional hepatoprotective food [57]. Similarly, a meta-analysis of controlled studies found that omega-3 fatty acid supplementation, commonly derived from oily fish such as sardines, mackerel, and salmon, effectively reduced hepatic fat accumulation and triglyceride levels and, in several instances, led to decreases in ALT and AST concentrations, thereby consolidating their role as natural anti-inflammatory and lipid-modulating agents [58].

Other dietary antioxidants have been studied with mixed results. Resveratrol, a polyphenol found in grapes and red wine, did not demonstrate consistent benefits over placebo in individual clinical trials [59]. However, pooled analyses from meta-analyses revealed modest reductions in liver enzymes and improvements in metabolic profiles in certain subgroups, particularly at higher doses or with prolonged treatments, suggesting a potential complementary role in MASLD therapy [60]. More robust evidence is available for vitamin E: in the landmark PIVENS trial, in non-diabetic patients with non-alcoholic steatohepatitis (NASH), administration of vitamin E at a dose of 800 IU per day over an extended period has been associated with significant histological improvements, including reduced inflammation and hepatocellular damage, together with lower ALT levels. These findings demonstrated that antioxidants can exert tangible therapeutic effects in NASH and further reinforce the rationale for antioxidant-rich dietary approaches, such as the Mediterranean diet [61].

Finally, large-scale cohort studies, such as PREDIMED-Plus, provide real-world evidence for these benefits. In this Spanish trial, adults at high cardiovascular risk who adopted a low-calorie Mediterranean diet combined with lifestyle interventions showed reductions in hepatic steatosis and fibrosis indices (HSI, FIB-4), as well as improvements in inflammatory markers [62]. These observations suggest that, when adopted as a long-term lifestyle approach, the Mediterranean diet may not only reduce cardiovascular risk but also provide sustained protection against chronic liver disease [63].

Comparison with other antioxidant strategies

In the management of MASLD and its progressive form, MASH, multiple antioxidant-based strategies have been explored, ranging from supplementation with isolated compounds such as vitamin E or resveratrol to alternative

dietary models, including low-fat or low-carbohydrate regimens [64]. Although these approaches demonstrate certain benefits, the overall body of evidence indicates that the Mediterranean diet provides broader, more consistent, and culturally sustainable advantages. Clinical trials of vitamin E supplementation, for example, have shown improvements in liver enzymes and reductions in oxidative stress among patients with MASLD, yet these effects appear to be limited to specific subgroups, and concerns regarding long-term safety diminish its value as a stand-alone therapeutic option [65]. Likewise, capsule-based resveratrol interventions have yielded inconsistent outcomes, with some studies reporting modest improvements in hepatic fat and inflammatory markers, while others observed no significant changes [66].

Alternative dietary patterns have also been investigated, but their effectiveness seems less robust. Low-fat diets can promote weight loss and improve certain metabolic parameters; however, their impact on reducing liver fat is less consistent and generally less durable than that observed with the Mediterranean diet [67]. Low-carbohydrate diets, on the other hand, may induce rapid reductions in hepatic steatosis, but adherence is often difficult and the restriction of antioxidant-rich foods, including fruits and legumes, may limit their long-term applicability [68]. In contrast, the Mediterranean diet is characterized as a synergistic dietary pattern, marked by the habitual intake of extra-virgin olive oil, fatty fish, nuts, legumes, fruits, and vegetables. This dietary combination supplies a broad range of bioactive constituents, including polyphenols, tocopherols, omega-3 fatty acids, and dietary fibre, which may act in a complementary manner to attenuate oxidative stress and inflammatory processes while contributing to reductions in hepatic fat accumulation [69]. Clinical evidence from studies such as the DIRECT PLUS trial further demonstrates that versions of the Mediterranean diet enriched in polyphenols are particularly effective in decreasing both hepatic and visceral fat [70].

Importantly, beyond its biochemical benefits, the Mediterranean diet is culturally embedded, environmentally sustainable, and easier to adopt and maintain over the long term, which strengthens its position as a practical and effective dietary strategy for liver health [71].

Relevance as a non-pharmacological intervention

Chronic liver diseases, encompassing metabolic dysfunction-associated steatotic liver disease (MASLD), alcohol-related liver disease, viral hepatitis, and hepatocellular carcinoma (HCC), represent a major and increasingly significant global health challenge [72]. As pharmacological options remain limited or under development, non-pharmacological strategies, especially nutritional interventions, have become central to prevention and treatment. Among them, the Mediterranean diet stands out for its multi-targeted benefits: it provides antioxidants, anti-inflammatory compounds, and healthy fats that act synergistically to reduce oxidative stress, decrease liver fat, improve insulin sensitivity, and regulate inflammation [73]. These mechanisms are relevant not only to MASLD but also to slowing fibrosis in viral hepatitis, reducing alcohol-related injury, and potentially lowering HCC risk [74].

Evidence from the literature indicates that adherence to the Mediterranean dietary pattern is associated with improvements in liver enzyme levels, reductions in hepatic steatosis as assessed by imaging techniques, and modulation of inflammatory and oxidative stress markers. Beyond liver outcomes, this pattern also reduces cardiovascular risk and supports healthy aging, making it particularly valuable for patients with comorbidities [75]. Unlike pharmacological therapies, it is sustainable, safe, and culturally embedded, which facilitates adherence and long-term impact. Promoting the Mediterranean diet as a lifestyle thus represents an effective, affordable, and scalable public health strategy to reduce the burden of cirrhosis, complications such as HCC, and the need for costly interventions like transplantation [76].

Future directions

Looking forward, nutrition in liver health is expected to move toward greater precision and personalisation. Although the Mediterranean diet consistently demonstrates protective effects, individual responses vary depending on genetics, gut microbiome composition, metabolic profile, and lifestyle factors [77]. The integration of these dietary components into personalised nutritional strategies may enhance clinical outcomes through the adaptation of the Mediterranean dietary pattern for individuals with metabolic dysfunction-associated steatotic liver disease (MASLD), alcohol-related liver disease, and viral

hepatitis, as well as in the prevention of hepatocellular carcinoma (HCC) [78]. Emerging evidence also highlights the potential of combining the Mediterranean diet with targeted antioxidant supplementation. Early trials suggest that polyphenols can further reduce hepatic fat and improve oxidative stress markers, while experimental studies indicate that compounds such as catechins, quercetin, and resveratrol may act synergistically with pharmacological therapies, enhancing insulin sensitivity and slowing fibrosis progression [79].

Another promising field is the gut–liver axis, as the Mediterranean diet naturally supports a diverse microbiome. Supplementation with polyphenol-rich extracts or probiotics may strengthen microbiota-derived metabolites, reduce hepatic inflammation and boost antioxidant defences [80]. Ultimately, future strategies will likely integrate the Mediterranean diet with physical activity, weight management, and selected supplementation in precision lifestyle interventions. Such an approach has the potential not only to slow MASLD progression but also to prevent long-term complications, including cirrhosis and HCC [81].

3. Conclusions

The Mediterranean dietary pattern, characterised by a distinctive combination of foods rich in antioxidants and anti-inflammatory compounds, is increasingly recognised as a scientifically grounded strategy for supporting liver health by attenuating oxidative stress, inflammatory processes, and hepatic fat accumulation. Although additional long-term investigations are warranted to further refine clinical recommendations, the available body of evidence positions this dietary approach as a sustainable and potentially effective cornerstone in the prevention and management of chronic liver diseases, particularly metabolic dysfunction–associated steatotic liver disease (MASLD).

References

1. Chan WK, Chuah KH, Rajaram RB, Lim LL, Ratnasingam J, Vethakkan SR. Metabolic Dysfunction-Associated Steatotic Liver Disease [MASLD]: A State-of-the-Art Review. *J Obes Metab Syndr*. 2023 Sept 30;32 [3]:197–213.
2. Younossi ZM. Non-alcoholic fatty liver disease - A global public health perspective. *J Hepatol*. 2019 Mar;70 [3]:531–44.
3. Rinella ME. Nonalcoholic Fatty Liver Disease: A Systematic Review. *JAMA*. 2015 June 9;313 [22]:2263–73.
4. Polaris Observatory Collaborators. Global prevalence, treatment, and prevention of hepatitis B virus infection in 2016: a modelling study. *Lancet Gastroenterol Hepatol*. 2018 June;3 [6]:383–403.
5. D'Amico G, Morabito A, D'Amico M, Pasta L, Malizia G, Rebora P, et al. Clinical states of cirrhosis and competing risks. *J Hepatol*. 2018 Mar;68 [3]:563–76.
6. Polaris Observatory HCV Collaborators. Global change in hepatitis C virus prevalence and cascade of care between 2015 and 2020: a modelling study. *Lancet Gastroenterol Hepatol*. 2022 May;7 [5]:396–415.
7. Bray F, Laversanne M, Sung H, Ferlay J, Siegel RL, Soerjomataram I, et al. Global cancer statistics 2022: GLOBOCAN estimates of incidence and mortality worldwide for 36 cancers in 185 countries. *CA Cancer J. Clin*. 2024;74 [3]:229–63.
8. Scheibe A, Young K, Moses L, Basson RL, Versfeld A, Spearman CW, et al. Understanding hepatitis B, hepatitis C and HIV among people who inject drugs in South Africa: findings from a three-city cross-sectional survey. *Harm Reduct J*. 2019 Apr 11;16 [1]:28.
9. Salomone F, Godos J, Zelber-Sagi S. Natural antioxidants for non-alcoholic fatty liver disease: molecular targets and clinical perspectives. *Liver Int Off J Int Assoc Study Liver*. 2016 Jan;36 [1]:5–20.
10. Dinu M, Pagliai G, Casini A, Sofi F. Mediterranean diet and multiple health outcomes: an umbrella review of meta-analyses of observational studies and randomised trials. *Eur J. Clin Nutr*. 2018 Jan;72 [1]:30–43.
11. Baratta F, Pastori D, Polimeni L, Bucci T, Ceci F, Calabrese C, et al. Adherence to Mediterranean Diet and Non-Alcoholic Fatty Liver Disease: Effect on Insulin Resistance. *Am J Gastroenterol*. 2017 Dec;112 [12]:1832–9.
12. Kontogianni MD, et al. Adherence to the Mediterranean diet is associated with the severity of non-alcoholic fatty liver disease. *Clin Nutr Edinb Scotl*. 2014; 33 [4]:678–83.
13. Visioli F, Bernardini E. Extra virgin olive oil's polyphenols: biological activities. *Curr Pharm Des*. 2011;17 [8]:786–804.
14. De Stefanis D, Costelli P. Extra Virgin Olive Oil [EVOO] Components: Interaction with Pro-Inflammatory Cytokines Focusing

- on Cancer and Skeletal Muscle Biology. *Nutrients*. 2025 July 16;17 [14]:2334.
15. Serreli G, Boronat A, De la Torre R, Rodriguez-Moratò J, Deiana M. Cardiovascular and Metabolic Benefits of Extra Virgin Olive Oil Phenolic Compounds: Mechanistic Insights from In Vivo Studies. *Cells*. 2024 Sept 16;13 [18]:1555.
 16. Martín-Peláez S, Covas MI, Fitó M, Kušar A, Pravst I. Health effects of olive oil polyphenols: recent advances and possibilities for the use of health claims. *Mol Nutr Food Res*. 2013 May;57 [5]:760–71.
 17. Granados-Principal S, Quiles JL, Ramirez-Tortosa CL, Sanchez-Rovira P, Ramirez-Tortosa MC. Hydroxytyrosol: from laboratory investigations to future clinical trials. *Nutr Rev*. 2010 Apr;68 [4]:191–206.
 18. De Santis S, Crupi P, Piacente L, Mestice A, Colabufo NA, Amodio L, et al. Extra virgin olive oil extract rich in secoiridoids induces an anti-inflammatory profile in peripheral blood mononuclear cells from obese children. *Front Nutr*. 2022;9:1017090.
 19. Suárez M, Boqué N, Del Bas JM, Mayneris-Perxachs J, Arola L, Caimari A. Mediterranean Diet and Multi-Ingredient-Based Interventions for the Management of Non-Alcoholic Fatty Liver Disease. *Nutrients*. 2017 Sept 22;9 [10]:1052.
 20. Anania C, Perla FM, Olivero F, Pacifico L, Chiesa C. Mediterranean diet and nonalcoholic fatty liver disease. *World J Gastroenterol*. 2018, 24 [19]:2083–94.
 21. Millar CL, Costa E, Jacques PF, Dufour AB, Kiel DP, Hannan MT, et al. Adherence to the Mediterranean-style diet and high intake of total carotenoids reduces the odds of frailty over 11 years in older adults: Results from the Framingham Offspring Study. *Am J Clin Nutr*. 2022 Sept 2;116 [3]:630–9.
 22. Wei J, Lei GH, Fu L, Zeng C, Yang T, Peng SF. Association between Dietary Vitamin C Intake and Non-Alcoholic Fatty Liver Disease: A Cross-Sectional Study among Middle-Aged and Older Adults. *PloS One*. 2016;11 [1]:e0147985.
 23. He Z, Li X, Yang H, Wu P, Wang S, Cao D, et al. Effects of Oral Vitamin C Supplementation on Liver Health and Associated Parameters in Patients With Non-Alcoholic Fatty Liver Disease: A Randomized Clinical Trial. *Front Nutr*. 2021 Sept 14;8:745609.
 24. Wu H, Guo JL, Yao JJ, Yu JJ, Xia RY, Huang WQ, et al. Serum vitamin C levels and risk of non-alcoholic fatty liver disease: results from a cross-sectional study and Mendelian randomization analysis. *Front Nutr*. 2023;10:1162031.
 25. Stahl W, Sies H. Photoprotection by dietary carotenoids: concept, mechanisms, evidence and future development. *Mol Nutr Food Res*. 2012 Feb;56 [2]:287–95.
 26. González CM, Martínez L, Ros G, Nieto G. Evaluation of nutritional profile and total antioxidant capacity of the Mediterranean diet of southern Spain. *Food Sci Nutr*. 2019 Dec;7 [12]:3853–62.
 27. Stahl W, Sies H. β -Carotene and other carotenoids in protection from sunlight. *Am J Clin Nutr*. 2012 Nov;96 [5]:1179S–84S.
 28. Khan F, Niaz K, Maqbool F, Ismail Hassan F, Abdollahi M, Nagulapalli Venkata KC, et al. Molecular Targets Underlying the Anticancer Effects of Quercetin: An Update. *Nutrients*. 2016 Aug 29;8 [9]:529.
 29. Rahmani S, Naraki K, Roohbakhsh A, Hayes AW, Karimi G. The protective effects of rutin on the liver, kidneys, and heart by counteracting organ toxicity caused by synthetic and natural compounds. *Food Sci Nutr*. 2023 Jan;11 [1]:39–56.
 30. Liu Q, Pan R, Ding L, Zhang F, Hu L, Ding B, et al. Rutin exhibits hepatoprotective effects in a mouse model of non-alcoholic fatty liver disease by reducing hepatic lipid levels and mitigating lipid-induced oxidative injuries. *Int Immunopharmacol*. 2017 Aug;49:132–41.
 31. Hadidi M, Liñán-Atero R, Tarahi M, Christodoulou MC, Aghababaei F. The Potential Health Benefits of Gallic Acid: Therapeutic and Food Applications. *Antioxid Basel Switz*. 2024 Aug 18;13 [8]:1001.
 32. Li P, Song Y, Lv L, Zhang W, Jia A, Dong D, et al. The role of gallic acid in liver disease: a review of its phytochemistry, pharmacology, and safety. *Front Pharmacol*. 2025;16:1595508.
 33. Wang L, Pan X, Jiang L, Chu Y, Gao S, Jiang X, et al. The Biological Activity Mechanism of Chlorogenic Acid and Its Applications in Food Industry: A Review. *Front Nutr*. 2022;9:943911.
 34. Meng S, Cao J, Feng Q, Peng J, Hu Y. Roles of chlorogenic Acid on regulating glucose and lipids metabolism: a review. *Evid-Based Complement Altern Med ECAM*. 2013;2013:801457.
 35. Papandreou C, Becerra-Tomás N, Bulló M, Martínez-González MÁ, Corella D, Estruch R, et al. Legume consumption and risk of all-cause, cardiovascular, and cancer mortality in the PREDIMED study. *Clin Nutr Edinb Scotl*. 2019 Feb;38 [1]:348–56.
 36. Bolling BW, McKay DL, Blumberg JB. The phytochemical composition and antioxidant actions of tree nuts. *Asia Pac J Clin Nutr*. 2010;19 [1]:117–23.

37. Casas-Agustench P, López-Uriarte P, Ros E, Bulló M, Salas-Salvadó J. Nuts, hypertension and endothelial function. *Nutr Metab Cardiovasc Dis NMCD*. 2011 June;21 Suppl 1:S21-33.
38. Papanikolaou Y, Fulgoni VL. Bean consumption is associated with greater nutrient intake, reduced systolic blood pressure, lower body weight, and a smaller waist circumference in adults: results from the National Health and Nutrition Examination Survey 1999-2002. *J Am Coll Nutr*. 2008 Oct;27 [5]:569-76.
39. Pan L, Sui J, Xu Y, Zhao Q. Effect of Nut Consumption on Nonalcoholic Fatty Liver Disease: A Systematic Review and Meta-Analysis. 2023 May 19;15 [10]:2394.
40. Rajaram S, Damasceno NRT, Braga RAM, Martinez R, Kris-Etherton P, Sala-Vila A. Effect of Nuts on Markers of Inflammation and Oxidative Stress: A Narrative Review. *Nutrients*. 2023 Feb 22;15 [5]:1099.
41. Calder PC. Omega-3 fatty acids and inflammatory processes: from molecules to man. *Biochem Soc Trans*. 2017 Oct 15;45 [5]:1105-15.
42. Parker HM, Johnson NA, Burdon CA, Cohn JS, O'Connor HT, George J. Omega-3 supplementation and non-alcoholic fatty liver disease: a systematic review and meta-analysis. *J Hepatol*. 2012 Apr;56 [4]:944-51.
43. Rimm EB, Appel LJ, Chiuve SE, Djoussé L, Engler MB, Kris-Etherton PM, et al. Seafood Long-Chain n-3 Polyunsaturated Fatty Acids and Cardiovascular Disease: A Science Advisory From the American Heart Association. *Circulation*. 2018;138 [1].
44. Yan JH, Guan BJ, Gao HY, Peng XE. Omega-3 polyunsaturated fatty acid supplementation and non-alcoholic fatty liver disease: A meta-analysis of randomized controlled trials. *Medicine*. 2018, 7 [37].
45. Jump DB, Lytle KA, Depner CM, Tripathy S. Omega-3 Polyunsaturated Fatty Acids as a Treatment Strategy for Nonalcoholic Fatty Liver Disease. *Pharmacol Ther*. 2018, 181:108-25.
46. Vell MS, Creasy KT, Scorletti E, Seeling KS, Hehl L, Rendel MD, et al. Omega-3 intake is associated with liver disease protection. *Front Public Health*. 2023;11:1192099.
47. Petersson S, Philippou E, Rodomar C, Nikiphorou E. The Mediterranean diet, fish oil supplements and Rheumatoid arthritis outcomes: evidence from clinical trials. *Autoimmun Rev*. 2018 Nov;17 [11].
48. Kim SW, et al. Oleuropein prevents the progression of steatohepatitis to hepatic fibrosis induced by a high-fat diet in mice. *Exp Mol Med*. 2014 Apr 25;46 [4].
49. Panera N, Braghini MR, Crudele A, Smeriglio A, Bianchi M, Condorelli AG, et al. Combination Treatment with Hydroxytyrosol and Vitamin E Improves NAFLD-Related Fibrosis. *Nutrients*. 2022 Jan;14 [18].
50. Ji G, Wang Y, Deng Y, Li X, Jiang Z. Resveratrol ameliorates hepatic steatosis and inflammation in methionine/choline-deficient diet-induced steatohepatitis through regulating autophagy. *Lipids Health Dis*. 2015 Oct 24;14:134.
51. Marcolin E, San-Miguel B, Vallejo D, Tieppo J, Marroni N, González-Gallego J, et al. Quercetin treatment ameliorates inflammation and fibrosis in mice with nonalcoholic steatohepatitis. *J Nutr*. 2012 Oct;142 [10]:1821-8.
52. Ma Y, Gao M, Liu D. Chlorogenic acid improves high fat diet-induced hepatic steatosis and insulin resistance in mice. *Pharm Res*. 2015 Apr;32 [4]:1200-9.
53. Jump DB, Depner CM, Tripathy S, Lytle KA. Potential for dietary ω -3 fatty acids to prevent nonalcoholic fatty liver disease and reduce the risk of primary liver cancer. *Adv Nutr Bethesda Md*. 2015 Nov;6 [6]:694-702.
54. Yaskolka Meir A, Rinott E, Tsaban G, Zelicha H, Kaplan A, Rosen P, et al. Effect of green-Mediterranean diet on intrahepatic fat: the DIRECT PLUS randomised controlled trial. *Gut*. 2021 Nov;70 [11]:2085-95.
55. Reddy A, et al. Adherence to a Mediterranean diet may improve serum adiponectin in adults with nonalcoholic fatty liver disease: The MEDINA randomized controlled trial. *Nutr Res N Y N*. 2023, 119.
56. George ES, Reddy A, Nicoll AJ, Ryan MC, Itsiopoulos C, Abbott G, et al. Impact of a Mediterranean diet on hepatic and metabolic outcomes in non-alcoholic fatty liver disease: The MEDINA randomised controlled trial. *Liver Int Off J Int Assoc Study Liver*. 2022 June;42 [6]:1308-22.
57. Martínez-Urbistondo D, et al. Role of NAFLD on the Health Related QoL Response to Lifestyle in Patients with Metabolic Syndrome: The PREDIMED Plus Cohort. *Front Endocrinol*. 2022 June 29;13.
58. Rinott E, et al. The effects of the Green-Mediterranean diet on cardiometabolic health are linked to gut microbiome modifications: a randomized controlled trial. *Genome Med*. 2022, 14:29.
59. Chachay VS, Macdonald GA, Martin JH, Whitehead JP, O'Moore-Sullivan TM, Lee P, et al. Resveratrol does not benefit patients with nonalcoholic fatty liver disease. *Clin Gastroenterol Hepatol Off Clin Pract J Am Gastroenterol Assoc*. 2014 Dec;12 [12].

60. Wei S, Yu X. Efficacy of resveratrol supplementation on liver enzymes in patients with non-alcoholic fatty liver disease: A systematic review and meta-analysis. *Complement Ther Med*. 2021; 57.
61. Sanyal AJ, Harrison SA, Ratziu V, Abdelmalek MF, Diehl AM, Caldwell S, et al. The Natural History of Advanced Fibrosis Due to Nonalcoholic Steatohepatitis: Data From the Simtuzumab Trials. *Hepatology* [Internet]. 2019 Dec;70 [6]:1913.
62. Aron-Wisnewsky J, Vigliotti C, Witjes J, Le P, Holleboom AG, Verheij J, et al. Gut microbiota and human NAFLD: disentangling microbial signatures from metabolic disorders. *Nat Rev Gastroenterol Hepatol* [Internet]. 2020 May;17 [5]:279–97.
63. Gómez-Pérez AM, Ruiz-Limón P, Salas-Salvadó J, Vioque J, Corella D, Fitó M, et al. Gut microbiota in nonalcoholic fatty liver disease: a PREDIMED-Plus trial sub analysis. *Gut Microbes*. 2023;15 [1]:2223339.
64. Xiao Y, et al. Mediterranean diet affects the metabolic outcome of metabolic dysfunction-associated fatty liver disease. *Front Nutr*. 2023 Oct 10;10:1225946.
65. Arita VA, Cabezas MC, Hernández Vargas JA, Trujillo-Cáceres SJ, Mendez Pernicone N, Bridge LA, et al. Effects of Mediterranean diet, exercise, and their combination on body composition and liver outcomes in metabolic dysfunction-associated steatotic liver disease: a systematic review and meta-analysis of randomized controlled trials. *BMC Med*. 2025 Aug 27;23 [1]:502.
66. Jurek JM, Zablocka-Slowinska K, Pieczynska J, Clavero Mestres H, Auguet T. Systematic Review of the Effects of Plant-Based Foods on Metabolic Outcomes in Adults with MASLD and Comorbidities Such as Obesity, Metabolic Syndrome, and Type 2 Diabetes. *Nutrients*. 2025; [18]:3020.
67. Gepner Y, et al. The beneficial effects of Mediterranean diet over low-fat diet may be mediated by decreasing hepatic fat content. *J Hepatol*. 2019; 71 [2]:379–88.
68. Martínez-González MA, Hershey MS, Zazpe I, Trichopoulou A. Transferability of the Mediterranean Diet to Non-Mediterranean Countries. What Is and What Is Not the Mediterranean Diet. *Nutrients*. 2017 Nov 8;9 [11]:1226.
69. Zelicha H, et al. The effect of high-polyphenol Mediterranean diet on visceral adiposity: the DIRECT PLUS randomized controlled trial. *BMC Med*. 2022 Sept 30;20 [1]:327.
70. Castro-Barquero S, Lamuela-Raventós RM, Doménech M, Estruch R. Relationship between Mediterranean Dietary Polyphenol Intake and Obesity. *Nutrients*. 2018 Oct 17;10 [10]:1523.
71. Marcellin P, Kutala BK. Liver diseases: A major, neglected global public health problem requiring urgent actions and large-scale screening. *Liver Int Off J Int Assoc Study Liver*. 2018 Feb;38 Suppl 1:2–6.
72. Monserrat-Mesquida M, Bouzas C, García S, Mateos D, Casares M, Ugarriza L, et al. Two-Year Mediterranean Diet Intervention Improves Hepatic Health in MASLD Patients. *Foods*. 2025 Jan;14 [10]:1736.
73. Ichikawa T, Miuma S, Yamashima M, Yamamichi S, Koike M, Nakano Y, et al. Impact of weight loss and lifestyle modifications on liver fibrosis in MASLD and MetALD: A cohort study. *Biomed Rep*. 2025; [23 [4]:158.
74. Estruch R, Ros E, Salas-Salvadó J, Covas MI, Corella D, Arós F, et al. Primary Prevention of Cardiovascular Disease with a Mediterranean Diet Supplemented with Extra-Virgin Olive Oil or Nuts. *N Engl J Med*. 2018 June 21;378.
75. Huttasch M, Roden M, Kahl S. Obesity and MASLD: Is weight loss the [only] key to treat metabolic liver disease? *Metabolism*. 2024; 157.
76. Romagnolo DF, Selmin OI. Mediterranean Diet and Prevention of Chronic Diseases. *Nutr Today*. 2017 Sept;52 [5]:208–22.
77. Panduro A, et al. Personalized medicine and nutrition in hepatology for preventing chronic liver disease in Mexico. *Front Nutr*. 2024; 11.
78. Moretti JB, Drouin A, Truong C, Youn E, Cloutier A, Alvarez F, et al. Effects of polyphenol supplementation on hepatic steatosis, intima-media thickness and non-invasive vascular elastography in obese adolescents: a pilot study protocol. *BMJ Open*. 2024 Jan 30;14 [1].
79. Janota B, Janion K, Buzek A, Janczewska E. Dietary Strategies in the Prevention of MASLD: A Comprehensive Review of Dietary Patterns Against Fatty Liver. *Metabolites*. 2025 Aug 4;15 [8].
80. Dominguez LJ, Di Bella G, Veronese N, Barbagallo M. Impact of Mediterranean Diet on Chronic Non-Communicable Diseases and Longevity. *Nutrients*. 2021;13 [6].
81. Gaceu, L. 2017. Aspects regarding electrochemical detection of the antioxidant activity for subcritical extracts from *Pleurotus ostreatus*.
82. Gaceu, L. 2017. Comparative study regarding the antioxidant activity of subcritical extracts from Vitis semen, Mustard and Polygonum Cuspidatum. *Journal of EcoAgriTourism*, 13(2), 48.

INNOVATIVE DIGITAL EDUCATIONAL MANAGEMENT METHOD FOR DEVELOPING THE COMPETENCIES OF FUTURE FOOD AND TOURISM SPECIALISTS THROUGH THE USE OF E-LEARNING PLATFORMS IN THE TEACHING PROCESS

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Abstract: The article presents an innovative digital educational management model applied in the fields of food and tourism. The model proposes an interactive teaching-learning method based on the use of the Moodle platform, integrating formative assessment and immediate feedback. By combining educational technologies with the principles of active pedagogy, the aim is to transform the didactic process into a collaborative and motivating environment. The method was applied and tested in courses within the food and tourism fields, proving effective in increasing student engagement and interest in the act of teaching.

Keywords: management, teaching, interactive, digital, e-learning.

1. Introduction

In a world dominated by digitalization, the university educational process must adapt to the learning behaviors of the new generation of students [1,2,3].

Young people, as digital natives, feel more comfortable in the online environment and show a preference for interactive, technology-based methods.

In this context, the role of digital educational management is to integrate technological tools into the act of teaching to maintain students' interest, attention, and motivation. The e-learning platforms are useful tools for aiming these achievements [4,5,6].

E-learning is defined as a complex system of technologies, processes, and didactic methods based on the use of digital media.

Connectivism views learning as a process of knowledge construction within a network, while the theory of the online learning community emphasizes the importance of cognitive and social interaction [7,8].

These concepts form the basis of the proposed model, which transforms the student from a passive recipient into an active participant in their own education [9,10].

2. The Research Methodology

The digital educational management model presented in this paper is structured in two complementary stages: *teaching-learning through initial impact* and *explanation and consolidation through guided interaction*. These stages ensure a gradual transition from passive reception to active student involvement, using the Moodle platform as the central teaching and evaluation tool.

Moodle is an electronic learning (e-learning) and modular platform that offers a robust and secure system for creating and managing learning environments. The learning process on Moodle is flexible, allowing users to personalize their pace, access a variety of resources (texts, video, audio), collaborate through forums, and be evaluated by various methods (tests, assignments, self-assessment).

The *teaching-learning through initial impact stage* of the method aims to capture students' attention and actively involve them in the learning process through a quick and direct exposure to information. Initial impact refers to the fact that students interact with the information without receiving any initial explanation. Students connect to the Moodle platform, access the current course, and go through the relevant course materials within a limited interval of 10–20 minutes. The materials are uploaded to the platform in a specific area as shown in (Fig.1).

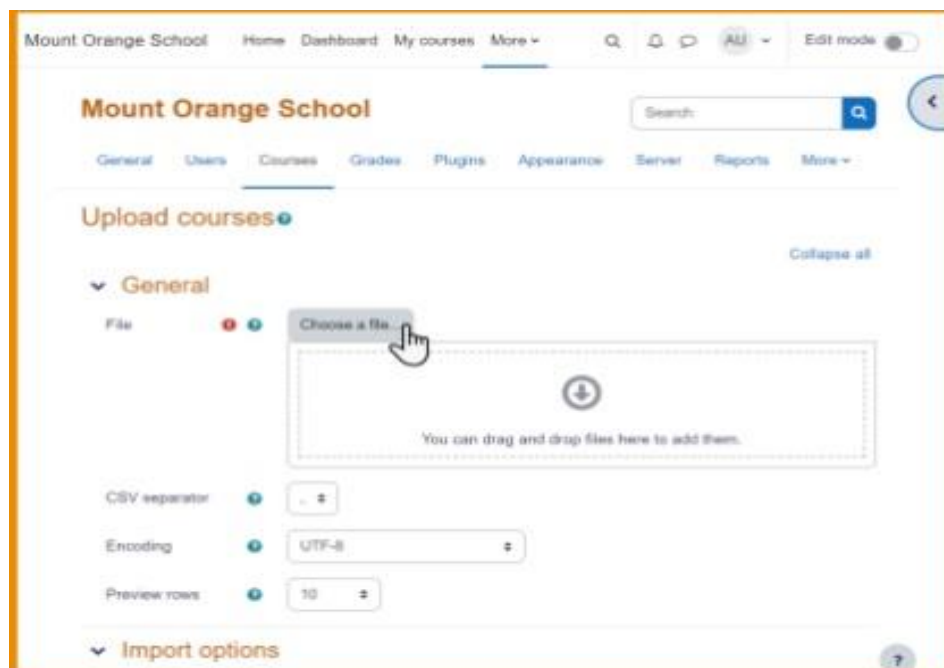


Fig.1. *The Moodle access to current course*

Next, students take a multiple-choice test containing 20–30 questions, with a single correct answer option, which lasts for 8 minutes.

An example of a question as students view it on the Moodle platform is presented in (fig. 2.).

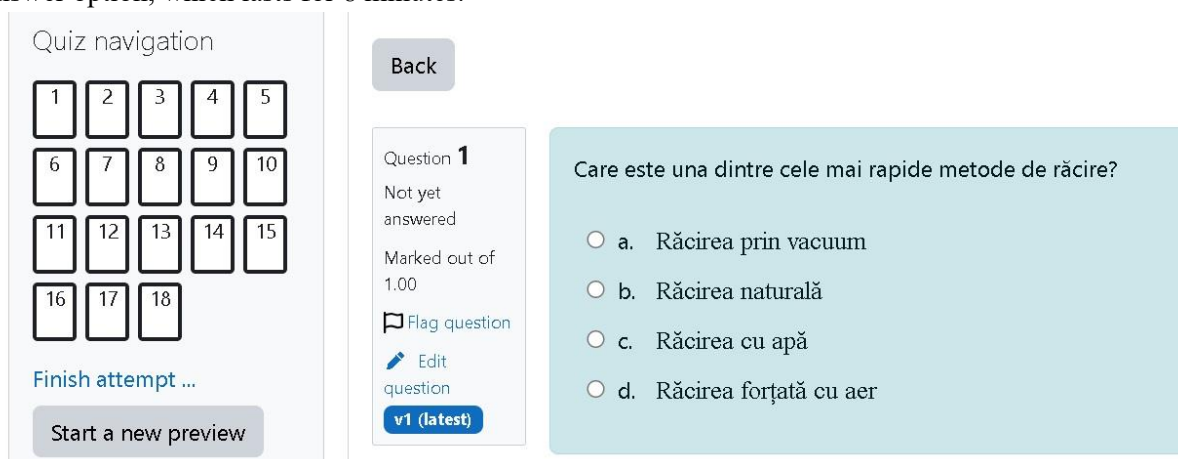


Fig. 2. *The Quiz example*

The purpose of this stage is to generate an immediate "cognitive impact," stimulating concentration and responsibility towards the act of learning. Knowing that a test will follow, students will concentrate on the initial information from which they are to take the test. Moreover, the test questions will prompt them to make connections between the presented information and will fix important information from the studied material.

At the end of the test, results are displayed immediately, providing students with feedback on their own performance. This aspect contributes to increasing the student's level of motivation.

On the other hand, the Moodle platform allows the export of results in Excel format, which is an advantage because important information for the next stage is managed in a very short time. In this way, the teacher can see the students' average grades as well as the average for each question. The teacher downloads the file, immediately highlighting questions with a low score and presenting them to the students.

This is presented in the (fig.3). Below; questions are noted with (q1...q20), and the averages for each question appear in the bottom row. The teacher will identify the questions with a lower score, and will insist on these during the second phase, when explaining the information.

The figure is only an excerpt from the resulting Excel file, as the test was taken by 45 students and had 20 questions.

Id	Star	CC	Grade/10	Q. 1 /0.50	Q. 2 /0.50	Q. 3 /0.50	Q. 4 /0.50	Q. 5 /0.50	Q. 6 /0.50	Q. 7 /0.50	Q. 8 /0.50
19114	4.00	0.00	0.00	0.50	0.50	0.50	0.50	0.00	0.00	0.50	0.00
19116	6.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.00
19116	4.50	0.50	0.00	0.50	0.50	0.50	0.00	0.50	0.00	0.00	0.00
19115	5.50	0.00	0.00	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.00
19115	4.00	0.00	0.00	0.50	0.50	0.50	0.50	0.00	0.00	0.00	0.00
19116	5.00	0.50	0.50	0.50	0.50	0.50	0.50	0.00	0.00	0.00	0.00
19116	6.50	0.50	0.50	0.00	0.50	0.50	0.50	0.50	0.50	0.50	0.00
19113	3.50	0.00	0.50	0.00	0.50	0.00	0.50	0.00	0.00	0.00	0.00
19116	6.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.00
19112	4.00	0.00	0.00	0.50	0.00	0.50	0.00	0.50	0.00	0.00	0.00
19115	3.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
19117	7.50	0.50	0.00	0.50	0.50	0.50	0.50	0.50	0.50	0.00	0.50
19117	6.00	0.00	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.00
19115	2.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
AVERAGE				0.20	0.20	0.31	0.41	0.31	0.26	0.24	0.06

Fig 3. The excerpt from the original Excel results file

An additional help in this regard is the Moodle platform's Statistics package, which provides real-time statistical information regarding the test and its result. With its help, the professor has immediate and important feedback for the

success of the second stage. Figure 4 shows the graph generated by this module for the information from the Excel file above, but in its complete version.

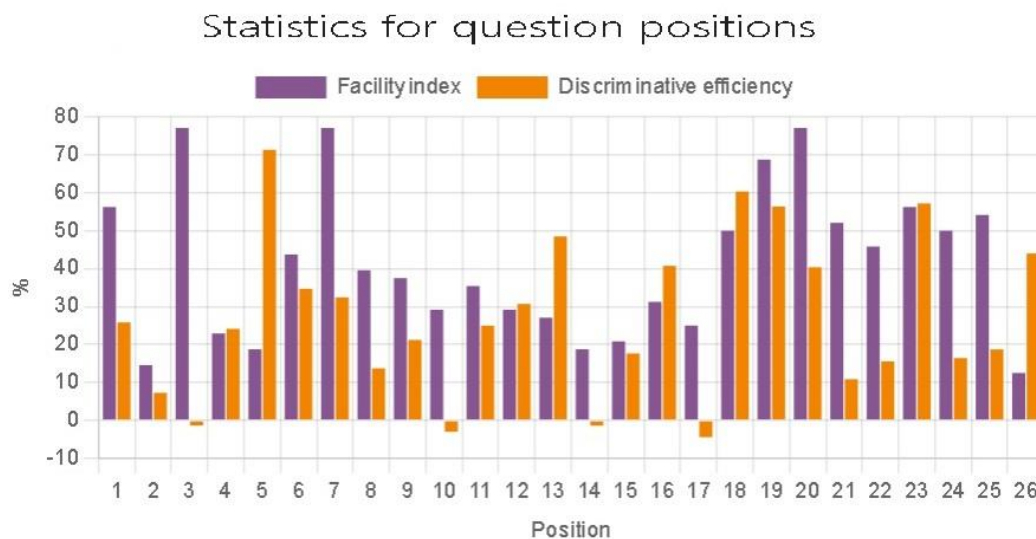


Fig. 4. Statistics generated by the Moodle platform

The second stage, titled *Explanation, Consolidation, and Guided Interaction*, completes the learning process by clarifying information, consolidating concepts, and stimulating critical reflection. Based on the results exported from Moodle, the professor identifies problematic items and sections requiring further study. This data becomes the starting point for discussions and additional explanations in class. The professor reviews the entire course and explains it to the students, insisting on the misunderstood concepts identified in the initial test. Furthermore, the

professor formulates open-ended questions and challenges students to provide explanations in their own words. Correct and well-argued answers are rewarded with bonus points, thus maintaining motivation and a competitive spirit.

4. Results and Discussions

This method was applied simultaneously for one semester to two different technical subjects in the food sector (3rd year undergraduate) and (2nd year master's). Both subjects have as their main theme the study of equipment for

processing raw materials of plant origin.

On a smaller scale, the method was also applied to a course in the field of tourism that deals with the quality of tourist services taught to students in (4th year undergraduates).

It was found that the method is particularly suitable for tourism because the technical nature of the information is not as pronounced. Thus, students can understand it more easily even in the first phase of the method, and in the second phase, more extensive discussions can take place.

Nevertheless, the method worked very well even in the case of the two technical courses. The evidence is the total average scores obtained by students in the tests in the first phase. Thus, in 75% of the tests, students obtained 5 points out of a possible 10, and the average for all tests was 5.39 points. Not all subjects allow the application of the present method in this form. For fields such as mathematics, physics, or chemistry, where reasoning is sequential and based on demonstrations, the stages of the method must be adapted either by changing the initial impact with explanations or by introducing intermediate practical exercises. The method thus has a modular and flexible character, allowing adjustments according to the specifics of the didactic content. The application of the method to subjects in the food and tourism fields highlighted a consistent increase in student involvement. The use of phones and laptops for educational purposes during the course maintained their interest and offered a practical perspective on the content. A decrease in participant passivity and an increase in interaction during courses were observed through a rise in the level of attention and involvement. Overall, the method proves to be effective not only as a digital learning tool but as a student-centered educational management strategy. Furthermore, this method brings a significant improvement in communication skills and the capacity for professional argumentation.

Conclusions

The term "innovative method" was chosen by the author because it was not created based on existing models but represents the author's conception, conceived and subsequently tested in classes as an alternative to classic teaching methods. The article aimed to present the method itself and its positive impact on the learning process, based especially on the author's

observations during classes, as well as on the primary study of the results obtained by students, especially in the initial test. The presentation of the method is a first step towards carrying out advanced research based on information obtained later and rigorously interpreted from a statistical point of view. The model proposed demonstrates the versatility of technology in supporting the didactic act. By combining the stages of formative testing and guided interaction, a balance is achieved between autonomy and pedagogical guidance. Although the method does not apply identically to all subjects, the basic principles – cognitive activation, immediate feedback, and collaborative learning – can be adapted according to content and context. The positive experiences in the food and tourism fields demonstrate that such a model can contribute to the modernization of university education, creating a culture of digital, participatory, and reflective learning.

References

1. Ally, M. (2019). *Foundations of Educational Theory for Online Learning*. Athabasca University Press.
2. Anderson, T. (2008). *The Theory and Practice of Online Learning*. Edmonton: AU Press.
3. Bates, T. (2015). *Teaching in a Digital Age: Guidelines for Designing Teaching and Learning*. Tony Bates Associates Ltd.
4. Black, P., & Wiliam, D. (1998). Assessment and Classroom Learning. *Assessment in Education*, 5(1), 7–74.
5. Clark, R. C., & Mayer, R. E. (2016). *E-Learning and the Science of Instruction*.
6. Garrison, D. R., & Anderson, T. (2011). *E-Learning in the 21st Century: A Framework for Research and Practice*. Routledge.
7. Prensky, M. (2001). Digital Natives, Digital Immigrants. *On the Horizon*, 9(5), 1–6.
8. Rosenberg, M. J. (2018). *E-Learning: Strategies for Delivering Knowledge in the Digital Age*. McGraw-Hill.
9. Siemens, G. (2005). Connectivism: A Learning Theory for the Digital Age. *International Journal of Instructional Technology and Distance Learning*, 2(1), 3–10.
10. Sun, P. C., Tsai, R. J., Finger, G., Chen, Y. Y., & Yeh, D. (2008). What Drives a Successful E-Learning?. *Computers & Education*, 50(4), 1183–1202.

BIOSENSORS FOR PESTICIDE DETECTION: CLINICAL TOXICOLOGY AND ENVIRONMENTAL BIOMONITORING PERSPECTIVES

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Abstract: *The use of synthetic pesticides has become established as a central tool in contemporary agriculture due to their effectiveness in pest control and crop protection. However, their indiscriminate and repeated application has posed threats to ecosystem biodiversity and microbiota due to their bioaccumulation capacity. They also pose a serious global public health problem, being associated with a wide range of diseases resulting from acute and chronic exposure. Conventional analytical techniques maintain high sensitivity and specificity, but costs, infrastructure, and specialised personnel limit their application. In this context, biosensors are promising alternatives for in situ diagnosis, environmental monitoring, and food-residue control, offering speed, portability, and the potential for integration with mobile devices.*

Keywords: *biosensor, pesticides, organophosphates, clinical diagnosis, environmental biomonitoring, point of care.*

1. Introduction

The use of synthetic pesticides became widespread in the mid-20th century, during the Green Revolution, when agricultural intensification relied on inorganic fertilisers, synthetic pesticides and genetically modified organisms to ensure food security in low- and middle-income countries [1]. Their immediate effectiveness in pest control led to their widespread adoption, making them an essential tool in modern agriculture. However, the repeated and indiscriminate application of these compounds has led to adverse side effects, such as the emergence of resistance in pests, the re-emergence of infestations and, more worryingly, a negative impact on both human health and ecological stability [2].

In the healthcare sector, pesticides pose a significant public health concern. Both acute and chronic exposure are associated with a wide range of clinical manifestations, ranging from transient symptoms to serious and permanent

complications, with significant repercussions on quality of life [3].

The epidemiological severity of the phenomenon is undeniable. According to estimates by the World Health Organisation, approximately 200,000 deaths occur annually due to accidental pesticide poisoning. This impact is distributed unevenly, with an overwhelmingly higher incidence (84%) in low- and middle-income countries [4,5].

In general, millions of people are exposed each year to organophosphate pesticides, which are responsible for a large proportion of poisonings and deaths in Asia, Africa and Latin America, where they are one of the leading causes of both accidental and intentional poisoning [6,7].

Similarly, the intensive use of pesticides poses a significant environmental threat. Their widespread application contributes to the contamination of soil and water sources, as well as generating residues in food intended for human consumption [8].

It is estimated that approximately 99.9% of pesticides applied do not reach their target, dispersing into the environment through processes such as spray drift, runoff, volatilisation, leaching or adsorption [9]. This dispersion makes them agents of global change and drivers of biodiversity loss [10].

These compounds can bioaccumulate in non-target organisms, altering food webs and affecting beneficial species; their prolonged persistence favours accumulation in food chains and enhances toxicity in aquatic ecosystems [11]. Given this situation, it is imperative to have practical tools for the early detection of poisoning and environmental monitoring.

Conventional analytical methods, such as high-performance liquid chromatography (HPLC) and gas chromatography coupled with mass spectrometry (GC-MS), have demonstrated high sensitivity and specificity in the identification of toxic agents [12]. However, its use is restricted by high costs, the need for specialised infrastructure, laborious procedures and dependence on highly trained personnel, which limits its applicability in rural or resource-constrained settings [13–15].

In this regard, biosensors are emerging as innovative tools capable of transforming biological signals into measurable responses, notable for their speed, low cost, and versatility in identifying pesticide residues in environmental and biological matrices, with relevant applications in clinical diagnosis and food safety [16].

This review aims to summarize and critically examine recent literature on biosensors for pesticide detection, analysing their detection principles, innovative materials, and available configurations, as well as the main challenges and projections in the context of public health and environmental control.

2. Materials and Methods

The main objective of this review is to conduct a comprehensive investigation of the scientific literature on the use of biosensors for pesticide detection from the perspectives of clinical toxicology and environmental biomonitoring. A structured search was conducted in international databases, including PubMed, Web of Science, and Google Scholar. Keywords such as “*pesticides*”, “*organophosphates*”, “*biosensors*”, “*clinical diagnosis*”, “*point-of-care*” and “*environmental*

biomonitoring” were used to identify the most relevant studies.

The selection process included original research articles, review articles, and doctoral theses, all published in the last two decades. Reports from international organisations such as the World Health Organisation (WHO) were also incorporated to strengthen the study's epidemiological component. Preference was given to publications on diagnostic strategies, environmental and food-residue monitoring, and innovations in biosensor technologies.

This methodological approach enabled the synthesis of evidence on the clinical and environmental applications of biosensors, their advantages over conventional methods, and the current barriers to their large-scale implementation.

3. Results

3.1. Clinical presentation of organophosphate poisoning

Organophosphate poisoning causes a sudden onset of symptoms ranging from mild forms to serious complications such as respiratory failure, convulsions and death [3,17]. Its mechanism of action is based on the irreversible inhibition of acetylcholinesterase, which causes an accumulation of acetylcholine and excessive stimulation of muscarinic and nicotinic receptors, leading to a cholinergic crisis [13,18].

Muscarinic effects include dyspnoea, bronchospasm, pulmonary oedema, gastrointestinal symptoms, bradycardia, hypotension and miosis, while nicotinic effects include fasciculations, muscle weakness, tachycardia and hypertension [19–21]. At the central level, anxiety, tremors, confusion, convulsions, coma, and respiratory depression may be observed [22].

The poisoning may progress to intermediate syndrome, which presents with muscle paralysis and type II respiratory failure [19,23] and serious cardiac complications [24].

Chronic exposure to low doses of organophosphates is associated with long-term multisystemic effects, including neurological disorders, psychiatric disorders, and an increased risk of congenital malformations and cancer, particularly in agricultural communities [25].

Exposure to pesticide residues in agricultural products has been associated with haematological disorders, infertility, metabolic dysfunction and the development of respiratory and

immunological diseases. In addition, organophosphates and carbamates are considered endocrine disruptors (EDCs) that can affect hormonal balance, growth, and reproduction [26]. Prenatal exposure to organophosphates has also been linked to adverse effects on child neurodevelopment [27].

Poor working and socioeconomic conditions in agriculture, characterised by a lack of training in the safe handling of pesticides, the inappropriate use or absence of personal protective equipment, together with poverty, low levels of education and limited access to health services, significantly increase the risk of poisoning and contribute to high morbidity and mortality in these populations [28,29].

3.2 Environmental impact of organophosphate contamination

Beyond the clinical setting, the environmental impact of pesticides is a global challenge due to their persistence, mobility and bioaccumulation capacity. Their presence has been widely documented in soil, surface water and groundwater, as well as in the food chain, posing a threat to biodiversity and the essential microbiota of agricultural ecosystems [30,31].

Among these, organophosphates (OP), which account for around 45% of the global market, are widely used but highly toxic to biological systems, while organochlorines (OCP) act as persistent organic pollutants capable of harming non-target species [32].

Aquatic ecosystems function as major sinks for pesticides, making them particularly vulnerable. Substances such as glyphosate can enter the oceans through underground discharges, altering biodiversity and affecting fish health. These effects include hormonal and reproductive imbalances, which translate into significant losses for the fishing industry [10].

Similarly, soil contamination is a significant problem, as pesticides can persist for long periods of time, between 10 and 360 days in the case of parathion, affecting soil quality and the sustainability of agroecosystems. The prolonged persistence of these compounds' compromises soil quality and the sustainability of agroecosystems. These compounds can inhibit the growth of bacteria and fungi, reduce microbial respiration, be toxic to nitrogen-fixing bacteria, and alter humus formation and soil porosity [9].

3.3 Biosensors for organophosphate detection

3.3.1. Types of biosensors

Early detection of toxic compounds is essential in clinical and environmental toxicology. In this context, biosensors represent an innovative alternative by enabling the analysis of specific biomarkers and continuous real-time monitoring of harmful agents in different ecosystems [33].

The ability of biosensors to quantify analytes in complex biological matrices lies in the combination of the specificity of biological systems with the precision of physical transduction. These platforms are distinguished by their speed, economy, portability, and high sensitivity [34,35], which facilitates continuous monitoring even in remote or hard-to-reach environments [36].

Biosensors represent a new generation of analytical tools by integrating a bioreceptor, such as enzymes, antibodies, aptamers, nucleic acids or whole cells, with a physical-chemical transducer that converts the biochemical interaction into a quantifiable signal, which is then amplified and processed [10,37].

The fundamental principle behind the operation of biosensors lies in the high specificity of the bioreceptor, which, upon recognising the target molecule, triggers a biochemical change that translates into an electrical, optical or piezoelectric signal, thus enabling rapid and reliable results to be obtained [38].

These devices can be classified according to the type of transduction (electrochemical, optical, piezoelectric or colorimetric) or according to the nature of the biological recognition element, based on whole cells or cell-free systems [39].

Among the various types of biosensors, electrochemical biosensors have established themselves as one of the most widely used platforms, taking advantage of variations in impedance, voltage or current to achieve sensitive and portable measurements, which are particularly useful in agricultural environments [40].

On the other hand, optical biosensors use advanced nanomaterials, such as semiconductor quantum dots or gold nanoparticles, which allow noticeable changes in fluorescence or coloration to be recorded, facilitating the implementation of rapid in situ screening methods [41].

Immunosensors and aptasensors also stand out for their high selectivity, as they are based on highly specific interactions such as antigen-antibody recognition or the binding of aptamers to target molecules [9].

Clinically, biosensors allow the rapid detection of biomarkers associated with pesticide exposure, including inhibition of blood cholinesterases (AChE/BChE), accumulation of acetylcholine, and the presence of urinary metabolites. Among the most commonly used urinary biomarkers for assessing exposure to organophosphates are dialkyl phosphates (DAPs), non-specific metabolites derived from the hepatic biotransformation of these compounds, as well as specific metabolites resulting from the degradation of certain pesticides [42]. Measuring these indicators in complex matrices, such as clinical and forensic samples and human serum, enables confirmation of exposure, estimation of clinical severity, and prediction of prognosis [43,44].

Biosensors based on AChE inhibition have emerged as simple, rapid, and ultrasensitive analytical tools. However, the measurement of urinary metabolites presents a limited diagnostic window due to their rapid excretion, highlighting the usefulness of combining rapid cholinesterase measurements with advanced confirmatory techniques [45].

A key development in this field is point-of-care (POC) biosensors, which stand out for their portability, low cost, and ease of use, and expanding their applicability in clinical and community settings. These include paper biosensors, with colorimetric or origami formats, which provide immediate results and can be integrated with smartphones for real-time reading and transmission.

Examples of these technologies include the visual detection of organophosphates such as malathion in food, by analysing the flow of water on pH indicator paper, which is a simple and effective method for on-site analysis [46,47].

Thanks to these characteristics, biosensors not only optimise clinical care in cases of acute poisoning through immediate diagnosis and timely treatment, but also provide added value in epidemiological surveillance and environmental control of pollutants [48].

3.3.2. Enzyme-based biosensors

In toxicology, biosensors have become particularly important for detecting organophosphate and carbamate pesticides, neurotoxic compounds whose mechanisms of action involve the irreversible inhibition of the enzyme acetylcholinesterase (AChE) in the case of organophosphates and reversible inhibition in the case of carbamates. The decrease in enzyme

activity with increasing toxin concentration is the basic principle of enzymatic biosensors [30,49].

These devices have been optimised by immobilising AChE on electrodes, thereby enhancing the system's stability and reusability. At the same time, antibody-based immunosensors offer high specificity, even in the detection of extremely low concentrations of pesticides [50,51].

In particular, electrochemical biosensors with immobilised AChE have achieved detection limits in the nanomolar range, as in the case of paraoxon, with accuracy greater than 90% and response times of seconds to minutes, making them critical tools for emergencies and resource-limited environments [38,52].

From an operational perspective, these biosensors stand out for offering a sensitive and economical screening method [53]. Its speed is remarkable and its innovative design reduces the amount of enzyme required to one third, optimising the efficiency of the entire analysis. In addition, these systems can complement or replace reference methods by simplifying or eliminating sample preparation, allowing direct determination of insecticides in aqueous matrices without prior extraction, cleaning or preconcentration [54].

Biosensors based on AChE inhibition have demonstrated outstanding analytical capabilities for the determination of neurotoxins, with detection limits generally ranging from 10^{-11} to $42.19 \mu\text{M}$, with linearity ranges extending from 1.0×10^{-11} to $7.45 \times 10^4 \mu\text{M}$, as previously reported in the literature [55].

For methyl parathion, the macroalgae biosensor achieved an LD (10% inhibition) of $1.5\text{--}1.8 \mu\text{g/L}$, with a linear range of 0 to $10 \mu\text{g/L}$ ($R^2 = 0.9862$) [51]. Studies with mutant enzymes from *Drosophila melanogaster* reported minimum values of $1.3 \mu\text{g/L}$ for chlorpyrifos and $6.4 \mu\text{g/L}$ for chlorpyrifos oxon (10% relative inhibition) [54].

3.3.3. Aptasensors

Similarly, DNA or RNA aptamers selected in vitro have emerged as bioreceptors of great interest due to their high affinity, regenerability and resistance to adverse conditions, making them ideal candidates for the design of electrochemical and optical nanobiosensors for the detection of organophosphorus compounds [56].

The most widely used transduction systems in this field are electrochemical systems, recognised for their low cost, portability and high sensitivity, using techniques such as amperometry, cyclic

voltammetry and impedance spectroscopy [57–59].

These properties are comparable to those of antibodies, with the added advantages of greater thermal stability, lower production costs and reduced size. These characteristics favour their use in environmental and agricultural analyses, particularly under field conditions [60].

Aptamers, synthetic single-stranded nucleic acid sequences (DNA or RNA) developed using the SELEX methodology, function as highly selective biorecognition elements, often referred to as "chemical antibodies" due to their superior affinity and their thermostable and economical nature [61].

Its combination with advanced nanomaterials, such as quantum dots derived from $\text{Ti}_3\text{C}_2\text{T}_x$ MXene (MQDs) or gold nanoparticles (AuNPs), has significantly advanced the development of nanosensors for environmental and agricultural monitoring. This synergy has made it possible to achieve exceptionally high analytical sensitivities in the detection of organophosphate pesticide residues and other contaminants, with ultra-low detection limits, such as 1.0×10^{-17} M for chlorpyrifos, and wide linear dynamic ranges extending, for example, from 1.0×10^{-14} to 1.0×10^{-8} M in advanced electrochemical biosensors [62].

In the context of precision agriculture, miniaturised devices have been developed that enable real-time monitoring of residues such as paraoxon, glyphosate and 2,4-D in the aerosol phase, with LODs of 2 ppb, 10 ppb and 30 ppb, respectively [63].

The integration of aptamers into advanced transduction platforms, often enhanced with nanomaterials, is essential for optimising the sensitivity, selectivity and stability of aptasensors. These configurations have demonstrated exceptional analytical performance in detecting organophosphate pesticides, and they are portable, accurate, and robust alternatives to conventional methodologies. For example, detection limits of 2.1 ng/L have been achieved for profenofos using surface-enhanced Raman spectroscopy (SERS), as well as sensitivities in the low nanomolar range for malathion, demonstrating the high analytical capability of these aptamer-based platforms [62,64].

From the perspective of transduction mechanisms, optical platforms, including surface plasmon resonance (SPR), fluorescence, and surface-enhanced Raman spectroscopy (SERS) are characterised by their high analytical

sensitivity. In contrast, piezoelectric sensors allow mass changes to be detected through variations in resonance frequency, induced by the specific interaction between the aptamer and the analyte [65]. The efficiency of these platforms has been significantly enhanced by the incorporation of nanomaterials such as graphene, carbon nanotubes, gold nanorods and bimetallic nanoparticles, which contribute to improving the structural stability, signal amplification and selectivity of detection systems [66–68].

3.4. Detection in environmental and food matrices

Faced with the limitations of conventional analytical methods for continuous in situ measurements, biosensors are emerging as technologically sustainable alternatives for environmental monitoring [69].

Its portable and economical design enables real-time assessment of ecosystem quality. Its application is particularly relevant in the detection of neurotoxic pesticides, whose persistence, bioaccumulation and ability to cause chronic exposure in non-target organisms pose a significant risk [70].

These devices are invaluable for detecting contaminants in water, soil and food, offering rapid, sensitive solutions that can be adapted to various environmental matrices [40]. Their versatility is enhanced by the use of specialised transducers, such as potentiometric transducers for reactions that release H^+ ions and amperometric transducers for electroactive species, as well as by the incorporation of nanomaterials and innovative configurations, including microfluidic paper platforms and origami-type electrochemical sensors, which broaden their applications and strengthen their role in environmental risk management [49,71].

Multiple strategies have been implemented in aquatic matrices for pesticide detection, including enzymatic biosensors, immunosensors, aptasensors, and whole-cell-based devices. Enzymatic biosensors that use acetylcholinesterase (AChE) are widely employed to detect organophosphates (OPs), whereas others exploit the activity of photosystem II to detect herbicides such as triazines and phenylureas. Immunosensors allow the identification of compounds such as atrazine and parathion through antigen-antibody interaction, and aptasensors have proven effective in detecting molecules such as thiamethoxam or acetamiprid using fluorescent

techniques and cationic carbon quantum dots [71,22,10]. Similarly, electrochemical biosensors enhanced with nanomaterials, such as NiCoSe₂/reduced graphene oxide, have demonstrated high sensitivity to pesticides, including malathion [72].

One of the main applications of biosensors in soil is monitoring soil quality and nutrient content, as well as detecting persistent contaminants such as pesticides and herbicides [41,73].

Among the strategies developed, electrochemical biosensors and field-effect transistors (FETs) stand out, used for pesticides such as methyl parathion through configurations based on Ag-ZnO and semiconductor carbon nanotubes. Immunosensors with metal coatings have also been designed to detect atrazine and parathion, and DNA biosensors can record changes in redox potential upon interaction with insecticides. Complementarily, the use of nanomaterials has enabled the detection of compounds such as 4-nitrophenol and the development of amperometric biosensors for glyphosate in water and soil [72,74,75].

Finally, in food, biosensors have been developed to analyse residues in fruit and vegetables, which is crucial for ensuring food safety. Nanotechnology-based innovations, such as SERS sensors with Ag/Au bimetallic nanoparticles, enable the in situ detection of organophosphate pesticide residues, while other nanosensors have been designed for early pest monitoring, contributing to sustainable agricultural management and reducing the use of agrochemicals [65,71].

3.5. Challenges and prospects for biosensors

Despite advances in biosensor development, their widespread implementation in environmental and food monitoring remains constrained by significant limitations. One of the main challenges is associated with selectivity in complex matrices, such as blood, soil, or biological extracts, where endogenous metabolites, lipids, and proteins can interfere with enzymatic activity and alter the signal generated [35].

Similarly, the presence of structurally similar contaminants, such as aromatic compounds capable of reacting with multiple analytes, can compromise the accuracy of results, while in agricultural settings the effect of the soil matrix itself directly influences the sensitivity of the devices [76].

Another key challenge relates to the stability of the bioreceptor, given that enzymes, antibodies and whole cells are susceptible to degradation or loss of viability when exposed to changes in temperature, pH or humidity, which limits their reuse and hinders their application in environmental conditions [72].

In addition to these inherent challenges, there are hurdles to scaling up for practical use, such as the high costs of specialised materials, such as nanocomposites and aptamers, and the difficulty of replicating laboratory performance at an industrial scale. Additionally, validation with real samples is uncommon, and there remains an absence of standardised regulatory protocols for assessing their performance, which limits their acceptance and use in field applications.

However, the outlook suggests a promising scenario driven by technological innovation and interdisciplinary convergence. Among the most relevant lines of research are the development of multiplexed biosensors capable of simultaneously detecting multiple biomarkers, and the use of portable microfluidic paper platforms, which reduce analysis times and offer practical alternatives for low-resource environments [76]. At the same time, the incorporation of state-of-the-art nanomaterials such as graphene, carbon nanotubes,[77] quantum dots, graphene oxide and MXenes [72] has enhanced sensitivity, selectivity and stability, achieving detection limits below toxicological thresholds and international standards, thereby broadening the spectrum of clinical and environmental applications⁷⁸.

Added to this is integration with smartphones, the Internet of Things, and artificial intelligence, which facilitates real-time monitoring, remote control of crops and prediction of pesticide usage using machine learning algorithms [79,80].

These innovations will determine that biosensors and nano-biosensors will be tools with enormous potential to transform the early diagnosis of acute pesticide poisoning, environmental monitoring, and food safety [81,82].

4. Conclusions

Exposure to pesticides is a complex public health and environmental issue, as it simultaneously affects human health and ecosystem sustainability.

Faced with this problem, biosensors emerge as an innovative alternative to complement conventional tools, offering speed, sensitivity and portability in both point-of-care clinical diagnosis

and environmental and food biomonitoring. Their potential lies in improving emergency response capabilities, reducing morbidity and mortality, and establishing early-warning systems to prevent human exposure and protect ecosystems. However, the consolidation of biosensors requires addressing technical limitations, including biological stability, selectivity in complex matrices, regulatory validation, and production costs. Their development and implementation require an interdisciplinary approach that fosters collaboration among scientists, clinicians, engineers, and policymakers to generate sustainable, equitable, and integrated solutions within the "One Health" paradigm.

References

1. Fath, BD.: *Encyclopedia of Ecology*. Elsevier; 2018.
2. Ngegba, PM., Cui, G., Khalid, MZ., Zhong, G.: *Use of Botanical Pesticides in Agriculture as an Alternative to Synthetic Pesticides*. In: *Agriculture* 2022;12:600.
3. Pradeep, U., Chiwhane, A., Acharya, S., Kumar, S., Daiya, V., Kasat, PR., et al.: *The Role of Neutrophil-to-Lymphocyte Ratio in Predicting Outcomes of Acute Organophosphorus Poisoning: A Comprehensive Review*. In: *Cureus* 2024.
4. Dávila, EL., Castro, YM., Romero, OR.: *Características y consecuencias adversas a la salud humana de agroquímicos usados en la agricultura cubana*. In: *Rev Cuba Salud Pública* 2022;48.
5. Samajdar, SS., Mukherjee, S., Goswami, RK.: *Patterns and Characteristics of Poisoning in Patients Admitted to a Peripheral Tertiary Care Hospital in Eastern India: A Record-based Observational Study*. In: *Bengal Physician J* 2024;11:70–2.
6. Shrestha, N., Liao R., Wei, T., Hu, J., Zhao, X., Huang, Q., et al.: *Prevalence of organophosphate poisoning in Nepal: A Meta-Analysis* 2025.
7. Telayneh, AT., Habtegiorgis, SD., Birhanu, MY., Sume, BW., Ayenew, T., Gedif, G., et al.: *Mortality of acute poisoning and its predictors in Ethiopia: A systematic review and meta-analysis*. In: *Heliyon* 2024;10.
8. Falise, AM., Griffin, I., Fernandez, D., Rodriguez, X., Moore, E., Barrera, A., et al.: *Carbon Monoxide Poisoning in Miami-Dade County Following Hurricane Irma in 2017*. In: *Disaster Med Public Health Prep* 2019;13:94–6.
9. Samal, S., Mohanty, RP., Mohanty, PS., Giri, MK., Pati, S., Das, B.: *Implications of biosensors and nanobiosensors for the eco-friendly detection of public health and agro-based insecticides: A comprehensive review*. In: *Heliyon* 2023;9.
10. Mendes, F., Machado, BO., Castro, BB., Sousa, MJ., Chaves, SR.: *Harnessing the power of biosensors for environmental monitoring of pesticides in water*. In: *Appl Microbiol Biotechnol* 2025;109:1.
11. Lushchak, VI., Matviishyn ,TM., Husak, VV., Storey, JM., Storey, KB., *Pesticide toxicity: a mechanistic approach*. In: *EXCLI J* 2018;17:1101–36.
12. Tyagi, A., Mir, ZA., Ali, S.: *Revisiting the Role of Sensors for Shaping Plant Research: Applications and Future Perspectives*. In: *Sensors* 2024;24:3261.
13. Chowdhar, S., Bhattacharyya, R., Banerjee, D.: *Acute organophosphorus poisoning*. In: *Clin Chim Acta Int J Clin Chem* 2014;431:66–76.
14. Fernández-Ibáñez, A., Ugalde-Herrá, R., Rodríguez-Getino, JÁ., García, Casas, JB., Díaz-Suárez, JC.: *Epidemiology of acute poisoning by substances of abuse in the Emergency Department. Descriptive study in District IV of Asturias*. In: *Adicciones* 2021;33:43–52.
15. Wei, T-Y., Yen, T-H., Cheng, C-M.: *Point-of-care testing in the early diagnosis of acute pesticide intoxication: The example of paraquat*. In: *Biomicrofluidics* 2018;12:011501.
16. *Environmental Monitoring. Sim Strum* 2025. <https://www.simstrumenti.com/en/about/environmental-monitoring/> (accessed September 14, 2025).
17. Sharif, AF., Alshammari, RY., Alghamdi, FT., Almutairi, SA., AlGhamdi, AS., Al-Nazhan, AS., et al.: *Assessment of co-ingestion effects on poisoning patterns, drug-drug interactions, and adverse outcomes in acute toxic exposure*. In: *Toxicol Rep* 2024;13:101705.
18. Balali-Mood, M., Naseri, K., Tahergorabi, Z., Khazdair, MR., Sadeghi, M.: *Toxic Mechanisms of Five Heavy Metals: Mercury, Lead, Chromium, Cadmium, and Arsenic*. In: *Front Pharmacol* 2021;12.
19. Eddleston, M.: *Novel Clinical Toxicology and Pharmacology of Organophosphorus Insecticide Self-Poisoning*. In: *Annu Rev Pharmacol Toxicol* 2019;59:341–60.
20. Hanson, C., Huddle, LN., Kockanowski ,J., Whaley, KD.: *Acute Organophosphate Poisoning Case Review With Consideration of Off-Gassing During Postmortem Examination*. In: *Am J Forensic Med Pathol* 2023;44:354–7.

21. Kim, K-H., Kabir, E., Jahan, SA.: *Exposure to pesticides and the associated human health effects*. In: Sci Total Environ 2017;575:525–35.
22. Kumar, P.: *Chapter 20 - Diagnostic techniques for heavy metal induced neurotoxicity*. In: Kumar P, Gogia N, editors. Heavy Met. Toxic. Neurodegener., Academic Press; 2025, p. 347–60.
23. Indira, M., Andrews, MA., Rakesh, TP.: *Incidence, predictors, and outcome of intermediate syndrome in cholinergic insecticide poisoning: A prospective observational cohort study*. In: Clin Toxicol 2013;51:838–45.
24. King, AM., Aaron, CK.: *Organophosphate and carbamate poisoning*. In: Emerg Med Clin North Am 2015;33:133–51.
25. Rodríguez, Rubio, A., NPunto. *MANEJO DE LAS INTOXICACIONES AGUDAS. MANEJO LAS INTOXICACIONES AGUDAS*. 2018;80:1–80.
26. *Impact of Pesticides on Human Health in the Last Six Years in Brazil n.d.* <https://www.mdpi.com/1660-4601/19/6/3198> (accessed September 17, 2025).
27. Sapbamrer, R., Hongsibsong, S.: *Effects of prenatal and postnatal exposure to organophosphate pesticides on child neurodevelopment in different age groups: a systematic review*. In: Environ Sci Pollut Res 2019;26:18267–90.
28. Quandt, SA., Hernández-Valero, MA., Grzywacz, JG., Hovey, JD., Gonzales, M., Arcury, TA.: *Workplace, Household, and Personal Predictors of Pesticide Exposure for Farmworkers*. In: Environ Health Perspect 2006;114:943–52.
29. Varona, ME., Díaz, SM., Briceño, L., Sánchez-Infante, CI., Torres CH., Palma, RM., et al.: *[Determining social factors related to pesticide poisoning among rice farmers in Colombia]*. In: Rev Salud Publica Bogota Colomb 2016;18:617–29.
30. Bilal, S., Mudassir, Hassan, M., Fayyaz ur, Rehman, M., Nasir, M., Jamil, Sami A., Hayat, A.: *An insect acetylcholinesterase biosensor utilizing WO₃/g-C₃N₄ nanocomposite modified pencil graphite electrode for phosmet detection in stored grains*. In: Food Chem 2021;346:128894.
31. da Silva, DF, Paiva, Silva, FE., Silva, FGS., Nunes, GS., Badea, M.: *Direct determination of methyl parathion insecticide in rice samples by headspace solid-phase microextraction-gas chromatography-mass spectrometry*. In: Pest Manag Sci 2015;71:1497–502.
32. Sur, S., Sathiavelu M.: *A concise overview on pesticide detection and degradation strategies*. In: Environ Pollut Bioavailab 2022;34:112–26.
33. Rajagopalan, V., Venkataraman, S., Rajendran, DS., Vinoth, Kumar V., Kumar, VV., Rangasamy, G.: *Acetylcholinesterase biosensors for electrochemical detection of neurotoxic pesticides and acetylcholine neurotransmitter: A literature review*. In: Environ Res 2023;227:115724.
34. Ahlawat, J., Sharma, M., Shekhar, Pundir, C.: *Advances in biosensor development for detection of acetylcholine*. In: Microchem J 2023;190:108620.
35. Sharma, A., Badea, M., Tiwari S., Marty, JL.: *Wearable Biosensors: An Alternative and Practical Approach in Healthcare and Disease Monitoring*. In: Molecules 2021;26:748.
36. Srinivasan, S., Raajasubramanian, D., Ashokkumar, N., Vinothkumar, V., Paramaguru, N., Selvaraj P, et al.: *Nanobiosensors based on on-site detection approaches for rapid pesticide sensing in the agricultural arena: A systematic review of the current status and perspectives*. In: Biotechnol Bioeng 2024;121:2585–603.
37. Elli, G., Hamed, S., Petrelli, M., Ibba, P, Ciocca, M., Lugli, P., et al.: *Field-Effect Transistor-Based Biosensors for Environmental and Agricultural Monitoring*. In: Sensors 2022;22:4178.
38. Akdag, A., Işık, M., Gökteş, H.: *Conducting polymer-based electrochemical biosensor for the detection of acetylthiocholine and pesticide via acetylcholinesterase*. In: Biotechnol Appl Biochem 2021;68:1113–9.
39. Heo, JH., Sung, M., Trung, TQ., Lee Y, Jung, DH., Kim, H., et al.: *Sensor design strategy for environmental and biological monitoring*. In : EcoMat 2023;5.
40. Heo, JH., Sung, M., Trung, TQ., Lee, Y., Jung, DH., Kim, H., et al.: *Sensor design strategy for environmental and biological monitoring*. In EcoMat 2023;5:e12332.
41. Mukherjee, S., Ghosh, K., Bhattacharyya, S., Behera, BK., Singh, OK., Pal, S., A.: *Review on Recent Trends in Advancement of Bio-Sensory Techniques Toward Pesticide Detection*. In: Food Anal Methods 2022;15:3416–34.
42. Sudakin, DL., Stone, DL.: *Dialkyl phosphates as biomarkers of organophosphates: The current divide between epidemiology and clinical toxicology*. In: Clin Toxicol 2011;49:771–81.

43. Pundir, CS., Malik, A., Preety.: *Bio-sensing of organophosphorus pesticides: A review*. In: Biosens Bioelectron 2019;140:111348.
44. Varadharajan, S., Gadre, M., Mathur, V., Vasanthan. KS.: *Sustainable Integration of Nanobiosensors in Biomedical and Civil Engineering: A Comprehensive Review*. In: ACS Omega 2025;10:25120–57.
45. Worek, F., Thiermann, H., Wille, T.: *Organophosphorus compounds and oximes: a critical review*. In: Arch Toxicol 2020;94:2275–92.
46. Erkmen, C., Taghvimi, A., Javadzadeh, Y., Kurbanoglu, S.: *Sustainability of Biosensors Over Conventional Methods 2024*.
47. Mutunga, T., Sinanovic, S., Harrison, CS.: *Integrating Wireless Remote Sensing and Sensors for Monitoring Pesticide Pollution in Surface and Groundwater*. In: Sensors 2024;24:3191.
48. Kamalasekaran, K., Sundramoorthy, AK.: *Applications of chemically modified screen-printed electrodes in food analysis and quality monitoring: a review*. In: RSC Adv 2024;14:27957–71.
49. Caratelli, V., Fegatelli, G., Moscone, D., Arduini, F.: *A paper-based electrochemical device for the detection of pesticides in aerosol phase inspired by nature: A flower-like origami biosensor for precision agriculture*. In: Biosens Bioelectron 2022;205:114119.
50. Khuntia, A., Kundu, M., Mahapatra, K., Kumawat, A.: *An Electrochemical Detection of Malathion Pesticide Using Cu Electrode and Enhanced by Machine Learning*. In: Chem Eng Technol 2025;48:e70036.
51. Nunes, GS. et al.: *Design of a macroalgae amperometric biosensor; application to the rapid monitoring of organophosphate insecticides in an agroecosystem*. In: Chemosphere 2014;111:623–30.
52. Liu, Y., Dong, L., Hu, Q., Chen, J., Khan, M.: *Enzyme Inhibition-Mediated Distance-Based Paper Biosensor for Organophosphate Pesticide Detection in Food Samples*. In: Chemosensors 2025;13:147.
53. Hassani, S., Momtaz, S., Vakhshiteh, F., Maghsoudi, AS., Ganjali, MR., Norouzi, P., et al.: *Biosensors and their applications in detection of organophosphorus pesticides in the environment*. In: Arch Toxicol 2017;91:109–30.
54. Badea, M., Romanca, M., Draghici, C., Marty, J-L., Marques, CVVCO., Mendes, DR., et al.: *Multidisciplinary collaboration for environmental protection using biosensors: detection of organophosphate insecticides in aqueous medium*. In: J Braz Chem Soc 2006;17:807–11.
55. Pundir, CS., Chauhan, N.: *Acetylcholinesterase inhibition-based biosensors for pesticide determination: a review*. In: Anal Biochem 2012;429:19–31.
56. Teodoro, LMP., Lacerda, LRG., Santos, PC e., Ferreira, LF., Franco, DL.: *Sensors and Biosensors as Viable Alternatives in the Determination of Contaminants in Corn: A Review (2021–2025)*. In: Chemosensors 2025;13:299.
57. Chen, S., Zhang, J., Lumley, L., Cashman, JR.: *Immunodetection of Serum Albumin Adducts as Biomarkers for Organophosphorus Exposure*. In: J Pharmacol Exp Ther 2013;344:531–41.
58. Dong, H., Weng, Y-B., Zhen, G-S., Li, F-J., Jin, A-C., Liu, J.: *Clinical emergency treatment of 68 critical patients with severe organophosphorus poisoning and prognosis analysis after rescue*. In: Medicine (Baltimore) 2017;96:e7237.
59. Subhan, MA., Neogi, N., Choudhury, KP., Rahman, MM.: *Advances in Biosensor Applications of Metal/Metal-Oxide Nanoscale Materials*. In: Chemosensors 2025;13:49.
60. Srinivasan, S., Raajasubramanian, D., Ashokkumar, N., Vinothkumar, V., Paramaguru, N., Selvaraj, P., et al.: *Nanobiosensors based on on-site detection approaches for rapid pesticide sensing in the agricultural arena: A systematic review of the current status and perspectives*. In: Biotechnol Bioeng 2024;121:2585–603.
61. Mali, H., Shah, C., Raghunandan, BH., Prajapati, AS., Patel, DH., Trivedi, U., et al.: *Organophosphate pesticides an emerging environmental contaminant: Pollution, toxicity, bioremediation progress, and remaining challenges*. In: J Environ Sci 2023;127:234–50.
62. Makani, N., Wu, J., Florentino, J., Chafin, CF., Gautam, B., Chao, S., et al.: *A Sensitive Electrochemical Cholinesterase-Inhibiting Biosensor for Organophosphorus Pesticides Based on Ti3C2TX MXene Quantum Dots*. In: Biosensors 2025;15:575.
63. Caratelli, V., Fegatelli, G., Moscone, D., Arduini, F.: *A paper-based electrochemical device for the detection of pesticides in aerosol phase inspired by nature: A flower-like origami biosensor for precision agriculture*. In: Biosens Bioelectron 2022;205:114119.
64. Mirres ACdM, Silva BEPdMd, Tessaro L, Galvan D, Andrade JCd, Aquino A, Joshi N, Conte-Junior CA. *Recent Advances in Nanomaterial-Based Biosensors for Pesticide*

- Detection in Foods. *Biosensors*. 2022; 12(8):572, (accessed December 13, 2025).
65. Peng, L., Zhu, J., Yang, B., Hao, H., Lou, S.: *A green photocatalytic-biosensor for colorimetric detection of pesticide (carbaryl) based on inhibition of acetylcholinesterase*. In: *Talanta* 2022;246:123525.
66. Bherade, S., Bhalerao, A., Khapale, P., Jagatap, V.: *Advances in nanomaterial-based sensors: a study of carbon nanotubes, quantum dots, nanorods, nanowires, and nanopillars in emerging applications*. In: *Analog Integr Circuits Signal Process* 2025;124:12.
67. Wan, Y., Wang, H., Zhang, L., Chen, Y., Li, S., Zhou, J., et al.: *Highly stable acetylcholinesterase electrochemical biosensor based on polymerized ionic liquids microgel for pesticides detection*. In: *Microchim Acta* 2022;189:300.
68. Xu, B., Zeng, W., Chen, F., Lin, G., Wang, M., Ding, J., et al.: *Clinical characteristics and early prediction of mortality risk in patients with acute organophosphate poisoning-induced shock*. In: *Front Med* 2023;9.
69. Yadav, A., Yadav, K., Ahmad, R., Abd-Elsalam, KA.: *Emerging Frontiers in Nanotechnology for Precision Agriculture: Advancements, Hurdles and Prospects*. In: *Agrochemicals* 2023;2:220–56.
70. Gupta, U., Jindal, T., Tyagi, J., Salam, MD., Saxena, A., Upadhyay, D., et al.: *Nanomaterial-Based Sensors and Monitoring Devices for Water Quality Assessment*. In: Garg, MC., Rajput, VD., Minkina, T., Himanshu, SK., editors. *Nano-Solut. Sustain. Water Wastewater Manag. Monit. Treat.*, Cham: Springer Nature Switzerland; 2025, p. 299–323.
71. Mirres, AC., de, M., Silva, BEP, de M da., Tessaro, L., Galvan, D., Andrade, JC de, Aquino, A.: et al. *Recent Advances in Nanomaterial-Based Biosensors for Pesticide Detection in Foods*. In: *Biosensors* 2022;12:572.
72. Chaturvedi, A., Tripathi, D., Ranjan, R.: *Nano-enabled biosensors in early detection of plant diseases*. In: *Front Nanotechnol* 2025;7.
73. Gangwar, DS.: *Recent trends in biosensor development for climate smart organic agriculture and their role in environmental sustainability*. *Environ Dev Sustain* 2024.
74. Goggin, A., Dean, D., Rule, K., Wylie, C.: *Common calls to a poisons information centre by general practitioners*. In: *Aust J Gen Pract* 2023;52:339–43.
75. Issaka, E., Wariboko, MA., Johnson, NAN., Aniagyei, ON.: *Advanced visual sensing techniques for on-site detection of pesticide residue in water environments*. In: *Heliyon* 2023;9.
76. DeFord, L., Yoon, J-Y.: *Soil microbiome characterization and its future directions with biosensing*. In: *J Biol Eng* 2024;18:50.
77. Ejigu, A., Tefera, M., Guadie, A., Abate, SG., Kassa, A.: *A Review of Voltammetric Techniques for Sensitive Detection of Organophosphate Pesticides in Environmental Samples*. In: *ACS Omega* 2025;10:29929–49.
78. Maanaki, H., Bussiere, L., Smirnov, A., Du, X., Sun, Y., Arcury, TA., et al.: *An Integrated Nanosensor/Smartphone Platform for Point-of-Care Biomonitoring of Human Exposure to Pesticides*. In: *Anal Chem* 2025;97:9701–12.
79. Mazuryk, J., Klepacka, K., Kutner, W., Sharma, PS.: *Glyphosate Separating and Sensing for Precision Agriculture and Environmental Protection in the Era of Smart Materials*. In: *Environ Sci Technol* 2023;57:9898–924.
80. Galindo, Alonso, L., Rivero, Ramírez, L., Rodriguez, Coca, LI., Badea, M.: *Advances in the Detection and Management of Organophosphate Poisoning*. In: *Am J Ther* 2025;32:e473.
81. Bedair, H., Rady, HA., Hussien, AM., Pandey M, Apollon W, AlKafaas SS, et al.: *Pesticide Detection in Vegetable Crops Using Enzyme Inhibition Methods: a Comprehensive Review*. In: *Food Anal Methods* 2022;15:1979–2000.
82. Mali, H., Shah, C., Raghunandan, BH., Prajapati, AS., Patel, DH., Trivedi, U., et al.: *Organophosphate Pesticides an Emerging Environmental Contaminant: Pollution, Toxicity, Bioremediation Progress, and Remaining Challenges*. In: *J Environ Sci* 2023;127:234–50.
83. Gaceu, L. (2020). Design principles for assuring food safety in Romanian mountain dairy farms. *Journal of EcoAgriTourism*, 2020, v. 16, n. 2, p. 21.

EFFECT OF JASMINE FORTIFICATION ON THE PROPERTIES OF SOURDOUGH BAKERY PRODUCTS

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Abstract: Edible flowers have traditionally been used as decorative elements in haute cuisine, their potential as a main ingredient in the creation of distinctive sensory and technological properties has been little investigated, especially in the field of bakery products. The aim of this research was to develop a novel proposal for incorporating edible jasmine flowers into bakery products and to evaluate their technological and sensory attributes. The jasmine petals were used to prepare sourdough brioche-style buns with 2.5%...7.5% fortification level of wheat flour with jasmine petal powder in final formulations. To determine the optimal fortification level, technological and sensory attributes were evaluated. Baking loss were varying between 9.81% and 9.87%, cooling loss constituted 0.93%-0.98% for all evaluated formulations. Key sensory attributes were assessed: appearance, crust and crumb color, flavor, taste, texture, and porosity. Instrumental analysis of crust and crumb color properties were undertaken in all baked products during 96 hours of storage. The findings revealed that sourdough brioche-style bun with 2.5% jasmine petal powder fortification level was the most acceptable. This research proposes using jasmine flowers as the important ingredient in bakery products, offering both nutritional and aesthetic value.

Keywords: edible flowers, sourdough, bakery innovation, sensory descriptors, application.

1. Introduction

Under modern conditions, increasing attention is being paid to the development of food products with enhanced nutritional value and a natural composition. Of particular interest are plant-based ingredients containing biologically active substances of plant origin. One such ingredient is edible flowers [1-3].

The *Jasminum* (*Jasminum* spp.) represents one of the most significant groups within the family *Oleaceae*, encompassing a wide range of species that have been integrated into the dietary traditions of various nations for centuries [9]. The transition of jasmine from an exclusively ornamental plant to a valuable food raw material is attributed to its unique morphology and its ability to accumulate valuable volatile metabolites in floral tissues [4, 5].

Etymologically, the name of the plant originates from the Arabic word "Yasmin," emphasizing its deep historical roots in Eastern regions [8]. In modern industry, jasmine is

regarded as a multifunctional ingredient capable of serving as a natural flavoring agent and a source of antioxidants [6, 7]. Edible jasmine petals contain polyphenolic compounds, antioxidants, and other valuable substances that may positively affect the quality of finished products and their consumer properties [10, 13].

The relevance of using edible jasmine in the food industry is associated with current healthy nutrition trends and the growing consumer demand for natural products with functional properties. Therefore, the use of jasmine petal powder in the technology of bakery product production is of both scientific and practical interest [14].

Bakery products occupy an important place in the human diet and are consumed on a daily basis. Small-sized bakery products are particularly popular due to their convenience, diversity of formulations, and the possibility of incorporating functional ingredients. Such products are in high demand among consumers

because of their compact size, attractive sensory characteristics, and suitability for individual consumption. Small-sized bakery products are especially popular in urban environments [16].

One of the promising methods of bakery product production is the use of sourdough [11]. The sourdough method of bread making is considered the oldest baking technology [12]. Despite the development of modern technologies, sourdough bread has regained popularity in recent years due to healthy eating trends and growing interest in traditional food production methods. Compared with products prepared using conventional yeast-leavening methods, sourdough bread is characterized by improved digestibility and a number of additional advantages [12]. A promising direction for improving bakery product technology is their fortification with jasmine petal powder. The fortification with this ingredient makes it possible to increase the nutritional value of the products, improve their sensory characteristics, and enhance the content of biologically active compounds. The use of jasmine petal powder in small-sized sourdough bakery products can contribute to the development of functional foods with a natural composition and distinctive flavor and aroma characteristics [14].

Of particular interest is the study of the effect of jasmine petal powder on the quality attributes

and shelf life of bakery products. The evaluation of sensory and physicochemical characteristics makes it possible to assess the effectiveness of this plant-based additive and its influence on the freshness and preservation of finished products [17-20].

This study evaluates the possibility of wheat flour fortification with jasmine petal powder (JPP) at three different concentrations in order to develop sourdough brioche-style buns. The aim is to assess the sensory and technological contributions of each JPP concentrations in terms of flavor, taste, crust and crumb color, baking and cooling loss. By doing so, this study seeks to reposition edible jasmine flowers as a central, functional ingredient in the creation of innovative, flavor-forward, and nutritionally fortified bakery products.

2. Materials and methods

2.1. Jasmine petal powder

The edible petals of *J. odoratissimum* variety were used as a novel ingredient in this study. The appearance of the jasmine petals and the powder obtaining process are reported in Figure 1. Dried jasmine petals were milled using grinder machine Bosch TSM6A011W, Germany. The resulting jasmine petal powder (JPP) was vacuum packed and stored at room temperature in a laboratory closet at room temperature.



Fig. 1. *Jasmine petals & powder of J. Odoratissimum variety*

2.2. Sourdough brioche-style buns

The preparatory stage of sourdough brioche-style buns included sifting the flour and mixing it with dry sourdough and jasmine petal powder until a homogeneous mixture is obtained. Cow's milk whey was used as the liquid phase, enriching the dough with lactose and contributing to the development of a more pronounced flavor.

Separately, an aromatic mixture is prepared, including brown sugar, salt, vanillin, and lemon zest. The ingredients were mixed until the sugar dissolves and essential oils are released from the citrus zest. Dough mixing was performed with the planetary mixer (PLUTON 7, Italy), initiated with the addition of whey to the dry mixture, followed by the addition of the aromatic mixture.

During mixing, the gluten structure develops. At the final stage, softened butter pre-mixed with soy lecithin was added to the dough; lecithin functions as an emulsifier, improving fat distribution and the gas-retaining capacity of the dough. The dough was then subjected to primary fermentation at a temperature of 28 °C and a humidity of approximately 80% for 2 hours, using a digital control proofer (Unox XLT133, Italy). Unlike yeast dough, both alcoholic and lactic acid fermentation occur here, resulting in the formation of a more complex flavor profile. After fermentation, the dough was divided into pieces, shaped, and placed on baking trays. Final proofing was carried out for approximately 1 hour until the optimal volume was achieved.

Baking was carried out in an electric convection oven (Unox „Rosella” XAFT193, Italy), under a combined temperature regime with steam injection: first at 230 °C for 5 minutes, then at 180 °C for an additional 15 minutes. Steam humidification slows crust formation, ensures maximum oven spring, and contributes to the development of a thin, elastic surface on the product.

The total 5 formulations were used for the production of the sourdough brioche-style buns are the following: (1) SBSB-control (sourdough brioche-style buns); (2) SBSBW-0 (sourdough brioche-style buns proceed with whey and containing 0% of JPP); (3) SBSBW-2.5 (sourdough brioche-style buns proceed with whey and containing 2.5 % of JPP); (4) SBSBW-5 (sourdough brioche-style buns proceed with whey and containing 5 % of JPP); (5) SBSBW-7.5 (sourdough brioche-style buns proceed with whey and containing 7.5 % of JPP). The base formula are reported in Table 1.

Table 1. Base formula of the sourdough brioche-style buns

Ingredients	Base formula, [%]
Wheat flour	100
Dry sourdough	4
Butter	5
Brown sugar	3
Salt	2
Soybean lecithin	0.3
Bottled water	60
Vanilla	0.1
Lemon zest	0.1

2.3. Determination of quality parameters of the sourdough brioche-style buns

All sourdough brioche-style bun sample were cooled at ambient temperature for 30 min after baking and analyzed for several parameters. Baking loss (BL), Cooling loss (CL), crust and crumb color, of the baked products were determined as reported by Gaglio et al. [16].

The colour evaluation of sourdough brioche-style buns was performed in all five formulations, using the CIELab system. Chromatic parameters L , a and b were measured for each sourdough brioche-style bun sample. To assess the impact of jasmine petal powder fortification, the colour difference ΔE and whiteness index (WI) were determined using Equations (1) and (2).

$$\Delta E = \sqrt{(L_1 - L_0)^2 + (a_1 - a_0)^2 + (b_1 - b_0)^2} \quad (1)$$

$$WI = 100 - \sqrt{(100 - L)^2 + a^2 + b^2} \quad (2)$$

2.4. Sensory evaluation descriptors

The sensory attributes of the sourdough brioche-style buns were articulated using standard terms for sensory evaluation descriptors, helping to create detailed sensory profiles of the developed baked products. These descriptors included appearance, crust and crumb color, taste, flavor, texture and porosity.

3. Results and discussions

This section presents the results of experimental studies aimed at assessing the feasibility of using JPP in the production of the sourdough brioche-style buns. The study was conducted sequentially in accordance with the developed study design and included evaluation of the technological, instrumental color, and sensory attributes of the sourdough brioche-style buns, and determination of optimal process parameters for the production of the finished product.

In accordance with the aim and objectives of the study, an experimental evaluation of the tested samples was conducted at various stages of the technological process. The obtained results allowed to characterize JPP as a functional ingredient, determine its effect on the properties of flour mixtures, sourdough fermentation processes and baked sourdough brioche-style buns (Figure 2 - 4).



Fig. 2. *Wheat flour fortified with jasmine petal powder*



Fig. 3. *Sourdough brioche-style buns doughs proceed with the addition of whey and fortified with JPP*

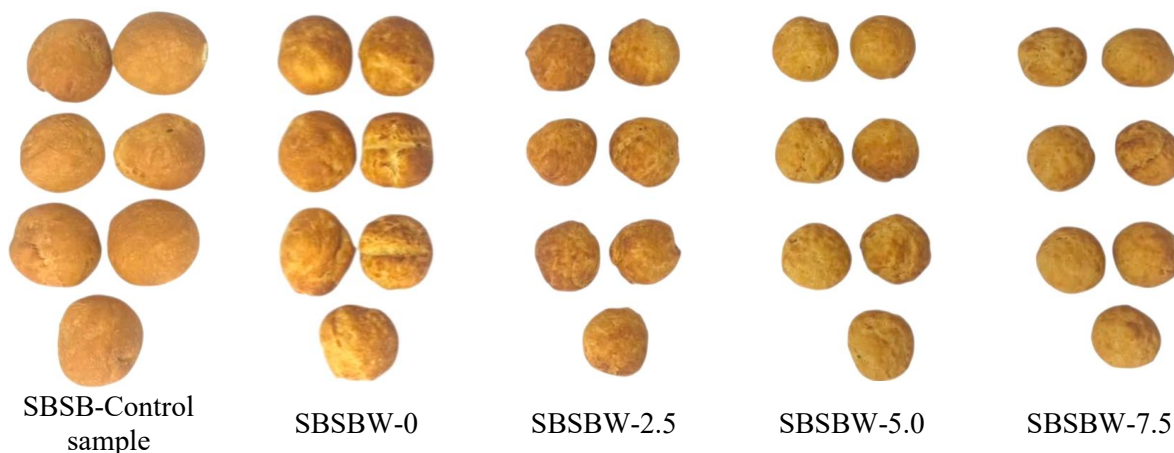


Fig. 4. *Baked sourdough brioche-style buns proceed with the addition of whey and fortified with JPP*

To evaluate the influence of the jasmine petal powder on the quality attributes of the sourdough brioche-style buns over time, key technological and physical properties were determined, including baking loss, cooling loss, and color during storage (Table 2-6).

Despite the results of technological and color analysis, a comprehensive assessment of the finished product's quality requires determining its sensory acceptability, as sensory properties directly influence consumer perception of the newly developed product. Therefore, the sensory profile evaluation of experimental samples of

sourdough brioche-style buns proceeds with the addition of whey and fortified with JPP was conducted (Table 7).

The sensory profile evaluation of the tested samples revealed differences in appearance, color, taste, flavor, texture, and porosity. The recommended jasmine petal powder concentration was established as 2.5% of the wheat flour weight.

This formulation demonstrated the most balanced combination of sensory descriptors of the sourdough brioche-style buns proceed with the addition of whey and fortified with JPP.

Table 2. *Quality attributes of the sourdough brioche-style buns proceed with the addition of whey and fortified with jasmine petal powder (fresh samples)*

Samples	Baking loss, [%]	Cooling loss, [%]	Crust color		Crumb color	
			ΔE	WI	ΔE	WI
SBSB-Control sample	9.81±0.23	0.98±0.07	-	60.21±0.23	-	80.03±0.12
SBSBW-0	9.75±0.19	0.97±0.03	-	60.11±0.37	-	76.28±0.23
SBSBW-2.5	9.87±0.13	0.94±0.02	-	60.07±0.56	-	75.58±0.17
SBSBW-5.0	9.81±0.21	0.93±0.05	-	57.09±0.12	-	75.01±0.26
SBSBW-7.5	9.83±0.17	0.97±0.03	-	55.12±0.19	-	72.11±0.33

Table 3. *Color attributes of the sourdough brioche-style buns proceed with the addition of whey and fortified with jasmine petal powder (24h storage)*

Samples	Crust color		Crumb color	
	ΔE	WI	ΔE	WI
SBSB-Control sample	9.75±0.07	60.23±0.23	5.41±0.01	78.74±0.24
SBSBW-0	9.98±0.09	60.17±0.18	6.12±0.04	76.51±0.31
SBSBW-2.5	10.58±0.13	58.19±0.15	6.32±0.09	75.21±0.29
SBSBW-5.0	10.87±0.09	57.87±0.27	7.03±0.07	74.01±0.19
SBSBW-7.5	11.12±0.11	55.98±0.33	7.21±0.03	71.93±0.17

Table 4. *Color attributes of the sourdough brioche-style buns proceed with the addition of whey and fortified with jasmine petal powder (48h storage)*

Samples	Crust color		Crumb color	
	ΔE	WI	ΔE	WI
SBSB-Control sample	9.36±0.13	59.11±0.28	4.01±0.09	76.03±0.23
SBSBW-0	9.92±0.17	59.23±0.17	6.11±0.06	75.21±0.13
SBSBW-2.5	11.01±0.07	58.51±0.21	6.59±0.02	74.17±0.12
SBSBW-5.0	11.07±0.11	57.33±0.19	6.95±0.03	71.69±0.31
SBSBW-7.5	12.03±0.09	56.44±0.31	7.41±0.05	71.15±0.33

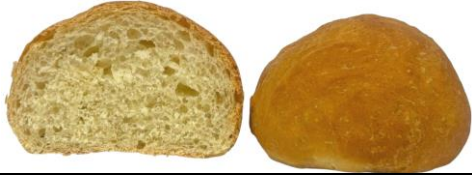
Table 5. *Color attributes of the sourdough brioche-style buns proceed with the addition of whey and fortified with jasmine petal powder (72h storage)*

Samples	Crust color		Crumb color	
	ΔE	WI	ΔE	WI
SBSB-Control sample	10.07±0.05	58.04±0.17	4.11±0.03	75.33±0.36
SBSBW-0	10.31±0.07	58.14±0.21	6.26±0.01	75.01±0.39
SBSBW-2.5	12.01±0.03	57.24±0.31	6.79±0.07	73.02±0.27
SBSBW-5.0	12.54±0.11	56.56±0.11	7.12±0.09	73.02±0.57
SBSBW-7.5	12.67±0.21	55.37±0.09	7.53±0.02	70.59±0.31

Table 6. *Color attributes of the sourdough brioche-style buns proceed with the addition of whey and fortified with jasmine petal powder (96h storage)*

Samples	Crust color		Crumb color	
	ΔE	WI	ΔE	WI
SBSB-Control sample	12.33±0.11	57.51±0.33	4.56±0.07	74.55±0.26
SBSBW-0	12.23±0.09	57.03±0.27	6.67±0.01	74.23±0.37
SBSBW-2.5	13.11±0.07	56.55±0.12	6.87±0.03	73.11±0.42
SBSBW-5.0	13.19±0.03	55.33±0.41	7.55±0.05	71.08±0.31
SBSBW-7.5	13.27±0.06	54.22±0.21	7.83±0.02	70.11±0.19

Table 7. *Sensory descriptors of the sourdough brioche-style buns proceed with the addition of whey and fortified with jasmine petal powder*

Samples	Appearance	Color		Taste		Flavor	Crumb condition	Porosity
		Crust	Crumb	Crust	Crumb			
SBSB-Control 	Regular shape, smooth surface	Golden, uniform	Uniform, no spots	Crispy, Pleasant, no bitterness	Pleasant, free from off-flavors	Pleasant, free from off-odors	Elastic, non-sticky	Uniform, medium
SBSBW-0 	Regular shape, smooth rough surface	Golden, uniform	Uniform, no spots	Crispy, Pleasant, no bitterness	Pleasant, with a dairy aftertaste	Pleasant, free from off-odors	Elastic, non-sticky	Uniform, fine
SBSBW-2.5 	Regular shape, slightly rough surface	Golden-brown, uniform	Slightly yellowish, uniform	Crispy, Pleasant, light jasmine petal taste	Pleasant, light jasmine petal taste	Pleasant, light jasmine petal flavor	Slightly elastic, non-sticky	Uniform, fine
SBSBW-5.0 	Regular shape, slightly rough surface	Golden-brown, uniform	Yellowish, darker shade, uniform	Pleasant, slightly bitter, noticeable jasmine petal taste	Pleasant, noticeable jasmine petal taste	Pleasant jasmine aroma flavor	Low elasticity, dense, non-sticky	Fine, poorly developed
SBSBW-7.5 	Irregular shape, rough surface	Golden-brown, uniform	Yellowish, darker shade, uniform	Pronounced bitterness, strong jasmine petal taste	Pronounced bitterness, strong jasmine petal taste	Strong jasmine aroma	Non-elastic, dense, non-sticky	Extremely low

4. Conclusions

This study proposed a novel approach, in which jasmine flowers play a central role in bakery innovation. Through the successful incorporation of jasmine petal powder into sourdough brioche-style buns formulations, their potential to enhance appearance, flavor, taste, and color was demonstrated. Among the evaluated samples, SBSBW-2.5 had the most pleasant sensory attributes and technological properties, confirming its promise for future applications in high-quality bakery products. It was emphasized that even small quantities of edible jasmine petals can significantly influence the sensory profile of brioche-style buns formulations. These results underscore the importance of thoughtful formulation to balance aesthetic, and sensory considerations. However, further research is needed to refine optimal dosages, assess long-term safety, and explore consumer perception. This work encourages to explore edible jasmine petals as functional, creative ingredients.

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References

1. Lara-Cortés, E., Osorio-Díaz, P., Jiménez-Aparicio, A., Bautista-Baños, S. Nutritional Content, Functional Properties and Conservation of Edible Flowers: Review. *Archivos Latinoamericanos de Nutrición*, 2013, 63 (3), p. 197–208.
2. Rop, O., Mlcek, J., Jurikova, T., Neugebauerova, J., Vabkova, J. Edible Flowers—A New Promising Source of Mineral Elements in Human Nutrition. *Molecules*, 17 (6), 2012, p. 6672–6683.
3. Giannetti, V., Biancolillo, A., Marini, F.; Boccacci Mariani, M., Livi, G. Characterization of the Aroma Profile of Edible Flowers Using HS-SPME/GC–MS and Chemometrics. *Food Research International*, 178, 2024, 114001.
4. Ahmed, N., Hanani, Y., Ansari, S., Anwar, S. Chapter 55 - Jasmine (*Jasminum sambac* L., Oleaceae) Oils. *Essential Oils in Food Preservation, Flavor and Safety*, Academic Press, 2016, p. 487–494.
5. Yassen, M. S., Ayoub, I. M., El-Ahmady, S. H., Singab, A. N. B. Comparative Analysis of Flower Volatiles from Four *Jasminum* Species Growing in Egypt Using Multivariate Analysis. *Sci Rep*, 16, 2026, 8947. doi.org/10.1038/s41598-026-39688-w
6. *Jasminum officinale* L. | Plants of the World Online | Kew Science. Plants of the World Online. <http://powo.science.kew.org/taxon/urn:lsid:ipni.org:names:609672-1> (accessed 2026-03-26).
7. *Jasminum sambac* (L.) Aiton | Plants of the World Online | Kew Science. Plants of the World Online. <http://powo.science.kew.org/taxon/urn:lsid:ipni.org:names:609755-1> (accessed 2026-03-26).
8. Singh, B., Jain, R., Sindhu, S.S., Varun, M.H., Tiwari, A.K. Jasmine Cultivation. *Agriculture & Environment*, 3 (30), 2025, p. 41-44.
9. Arifan, F.; Winarni, S.; Handoyo, G.; Nurdiana, A.; H, A.; Risdiyanti, S. An Analysis of Antioxidants, Organoleptics and Hedonics with Variations of Boiling Time in Jasmine Tea and Jasmine Root Tea a Study on Kaliprau, Pemalang. *Journal of Physics: Conference Series* 2018, 1025, 012066.
10. Popovici C., Saykova I., Tylkowski B. Evaluation de l'activité antioxydant des composés Phénoliques par la réactivité avec le radical libre DPPH. *Revue de génie industriel*, ISSN 1313 – 8871, Nr. 4, 2009, p. 26 – 39.
11. Costa, L., Kothe, C., Grassotti, T., Pischke Garske, R., Sandoval, B., Varela, A. P., Prichula, J., Frazzon, J., Bertoni Mann, M., Thys, R., Frazzon, A. Evolution of the Spontaneous Sourdoughs Microbiota Prepared with Organic or Conventional Whole Wheat Flours from South Brazil. *Anais da Academia Brasileira de Ciências*, 94, 2022, e20220091.
12. Santos, J.G., Ávila, P.M., Schimitberger, R., Cunha, L.R., Gomes, R.A.B., Vieira, M.C., Monteiro, R.S., Vieira, S.M., Pereira, P.A.P. Evaluation of the Effect of Substrates and Types of Wheat Flour on Microbiological Characteristics, pH Values, Levels of Total Phenolic Compounds, Antioxidant Capacity and Fermentative Capacity of Sourdough.

- Research, Society and Development, 11 (9), 2022.
13. Dharasurkar, A., Chand, G.; Babanoor, R., Sharma, B., Kumar, S., Rout, S., Mety, S. Traditional Food Practices of Edible Flowers., 9, 2025, p. 258–266.
 14. Guevara, K., Sánchez, J., Bohorquez, S., Bohorquez-Medina, A. Development and Sensory Evaluation of Edible Flower Incorporation in Pastry Products Using Avant-Garde Techniques. *Canrea Journal: Food Technology, Nutritions, and Culinary Journal*, 2025, p. 83–104.
 15. Popovici, C. Chapter 4. Fortificarea alimentelor cu iod: abordări tehnologice, efecte nutritive și aspecte de siguranță. In: *Innovative Food Products*, Chișinău: Tehnica-UTM, 2021, ISBN 978-9975-45-704-0, p. 166-266.
 16. Gaglio, R., Tesoriere, L., Maggio, A., Viola, E., Attanzio, A., Frazzitta, A., Badalamenti, N., Bruno, M., Franciosi, E., Moschetti, G., Sottile, F., Settanni, L., Francesca, N. Reuse of almond by-products: Functionalization of traditional semolina sourdough bread with almond skin, *Int. J. Food Microbiol*, 395, 2023, 110194.
 17. Oprea, O. B., & Gaceu, L. (2011). Preliminary researches on using spices in traditional bakery product recipes. *Journal of EcoAgriTourism*, 2011, Vol. 7, No. 2, 15-18.
 18. Gaceu, L., Gruia, R., & Oprea, O. B. (2020). Researches regarding the superior valorisation of by-products from the winery industry, and the obtaining of bakery products with functional properties. *Annals of the Academy of Romanian Scientists Series Agriculture, Silviculture and Veterinary Medicine Sciences* (1/2020).
 19. Negroiu, D. G., & Oprea, O. B. (2024). The Superior Utilization of Flax Seeds as a Sanogenic Agent in Food Area. Case Study: Bakery Industry. *Journal Of EcoAgritourism*, 20(1), 58.
 20. Gaceu, L., Gruia, R., & Oprea, O. B. (2023). Use of marine biomass resources as raw material in bakery. *Journal of EcoAgriTourism*, 19(1), 5.

THE CONCEPT AND MODEL OF BIOHARMONIST AGRO-RURAL DEVELOPMENT

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Abstract: The paper proposes a new concept of agro-rural development, based on the principles of societal bioharmony, which integrates the ecological, economic and socio-cultural dimensions of rural communities. The proposed model pursues the sustainable co-evolution of the natural environment and essential activities from an existential perspective, namely those specific to agri-food systems. In this context, the paper, through a holistic approach, promotes the co-viability, co-regulation and coherence of agro-rural processes. The study includes methodologies for analyzing local resources, participatory planning mechanisms, bioharmony performance indicators and tools for applying differentiated development strategies depending on the level of local development. The results emphasize the importance of synergy between the community, the natural environment and local institutions to achieve a sustainable, resilient and integrated agro-rural model. This paper introduces the DARbio Model (Development of Agro-Rural by Bioharmonism) as an innovative conceptual and operational framework that goes beyond conventional sustainability paradigms.

Keywords: Societal bioharmony, Co-evolution and co-viability, Agro-rural development, Agro-rural performance indicators, Participatory policies and planning, Local resources, Sustainability.

1. Introduction

Rural development has traditionally been conceptualized through fragmented, sectoral approaches, predominantly focused on economic productivity and resource optimization. Although the sustainability paradigm has introduced relevant ecological dimensions, it remains largely limited by reductionist frameworks and linear planning logics. An example is the insufficient highlighting of the main supply, that of food production, which has led us to approach the development of rural areas in this defining direction: "agro-rural development".

The premises that affect the rural area can be grouped into several essential themes. Resilience in the face of accelerated global urbanization, food, economic, pandemic crises and accelerated urbanization at a global level [4,8,16,18,26] requires the development of the rural area in the direction of the need for sustainability, food autonomy and to maintain the civilizational ART OF SURVIVAL, which is lost in the urban environment (e.g.: they have their own wells,

have food reserves, are connected to nature, etc.). Currently, as is known, the big problem is represented by climate change and the ecological crisis, with high temperatures, droughts, floods and extreme changes. These significantly affect human society and, especially, the food supply achieved by conventional agriculture and its newer approaches [6,21].

In short, in the context of increasing systemic complexity —generated by climate change, socio-economic instability and technological acceleration— the need for integrative models capable of addressing multi-scale interactions and nonlinear dynamics is emerging [12,17]. In this framework, through the present study, the Development of Agro-Rural by Bioharmonic Model (DARbio) appears as a paradigmatic alternative, redefining development as a process of dynamic equilibrium and systemic coherence. The opportunity of this model lies in the economic pressure and problematic competitiveness of rural development based on conventional agriculture. Essentially it is supported by subsidies (i.e. gross efficiency) and

becomes less competitive in the context of global requirements regarding the environment and product quality. Depopulation and migration of young people in the present, impose social and cultural co-evolution in the future. Traditional villages risk losing their cultural identity and community cohesion.

At the same time, the integrated approach is increasingly taking shape: digitalization and emerging technologies / remote work, IoT (sensors, drones), AI for agriculture, precision systems, traceability and waste reduction, ecological monitoring and restoration of natural fertility, integration of renewable energy are becoming indispensable. A concept in this sense is that of "Smart Villages", i.e. the adoption of digital technologies to reduce the opportunity gap without destroying local identity.

[NB – (1) The concept of "Smart Village" directly related to the way to access European funds for this transition; (2) IoT (Internet of Things) represents the nervous system of the farm, transforming raw data into direct profit, without depending on subsidies].

From what has been presented, we can highlight a series of challenges. Adapting rural areas to today's world is no longer just an option, but an existential necessity in the face of a volatile global context. The transition to new development models must simultaneously address 3 major challenges: (1) Resilience in the face of multiple crises, a situation in which rural areas must become a buffer against climate, energy and food crises; (2) Food security ensured by the transition from intensive export agriculture to local renewable systems; (3) Energy independence ensured by the use of biomass, solar and wind energy at the community level (rural prosumers).

Analyzing these challenges, we must associate them with today's major trend, namely the management of accelerated urbanization. This is because urbanization does not only mean migration to the city, but also the transformation of the countryside into an "urban periphery". It becomes imperative to resolve the urban-rural relationship. Basically, the countryside should not be just a "reservation" or a bedroom for the city, but an equal economic partner that provides ecosystem services (clean air, food, water, energy, recreation).

The transition to new development models is becoming a necessity. The traditional extractive model (resources sent to the city) is being replaced by well-known concepts: Circular

economy; Bioeconomy, where the valorization of agricultural waste into high-value-added products is supported; Responsible tourism, through which a sustainable valorization of cultural and natural heritage is carried out, without its degradation [agrotourism, rural tourism, ecotourism]; Demographic revitalization, based on attracting "digital nomads" and young people through modern infrastructure (roads, energy, high-speed internet, basic medical and educational services).

1.1. Literature review

The concerns along this line briefly refer to: resilience theory [7,14, 24], polycentric governance [19], complex systems [3,15,17], agroecology [1,2,20,], ecological economics [5,22], included as sources from reference journals (Q1): Science, Global Environmental Change, Ecology and Society, Philosophical Transactions B, etc. All of these actually allow the positioning of the DARbio concept and model that we propose in this paper, as an integrative extension of the socio-ecological paradigm.

A major conceptual shift occurred with the development of systems theory and sustainability science [21,23], which highlighted the role of feedback loops, nonlinearity, and leverage points in complex systems. This perspective was later consolidated [3], which proposed a "systemic view of life," based on the interconnectedness and dynamic equilibrium between biological and social domains [10,13]. These contributions are landmarks of our study that laid the epistemological foundations for understanding agro-rural systems as integrated socio-ecological systems, characterized by co-evolutionary dynamics and multi-scale interactions.

The literature review highlights a clear trend towards integration, complexity and sustainability, but a "unifying paradigm" capable of coherently correlating all dimensions of development is missing. We would like to point out that the theory that records the concept of bioharmony [9], an approach also operationalized through the DARbio Model, aims to provide such a framework, emerging as a new generation model for agro-rural development in the context of global systemic transformations.

As a model, we approach the issue of "bioharmonism" in which the approach describes an organizing principle (concept) and a path of action (a potential doctrine) that dynamically manifests itself in a wide spectrum, from the microscopic and individual (organismic) level, to

the societal, biospheric and cosmic level. This "axis" is approached in the direction in which the complexity of matter leads emergently to the emergence of life and self-consciousness (according to modern physical theories).

The way this approach is carried out is linked to a series of specific processes. Thus, bioharmonism essentially represents the structuring of ideas in a conceptual and explanatory model, which states that life, society and consciousness evolve between living systems and their environment, through the following PROCESSES that induce dynamic and rhythmic balances of Reality, namely: co-viability, co-evolution, co-regulation, systemic coherence and co-decision.

The motivation for the approach is related to the difference between the types of development of rural space, namely that beyond the volume of production or income, what is of interest today is especially the quality of the rural ecosystem, social cohesion, resilience and well-being of people. In this context, the aim of the approach is to adapt to the requirements of the coming decades and find solutions for the transition towards a performing and sustainable agro-rural development. Therefore, we consider it appropriate to approach the future of rural development through the bioharmonist model that can transform the village from a passive space into an active one (i.e. a rural cybernetic system) in which resources, community and technology interact permanently, generating societal harmonization through added value, thus building a balanced, performing and sustainable agro-rural ecosystem.

The novelty of the approach consists in a real paradigmatic leap, namely, the transition from sectoral, fragmented and reactive development to an integrated, processual and emergent development, based on the co-evolution of natural and socio-economic systems. The ontological change is addressed: from "system" to "integrated living organism", along the line of integrating the basic dimensions of bioharmonism, the transition from "mechanisms" to "bioharmonic processes" and the introduction of emergence as a principle of development. The idea of sustainability is reconfigured as follows: from conservation to regeneration, resilience as an emergent property (resulting from bioharmonization, not an imposed objective), and as a major methodological innovation is the policy addressed, the administrative strategy [10,11] and, especially,

the bioharmonic quantification of rural development.

From the above, the main objective of the work results, which is the application of bioharmony processes in the development of a new conceptual model, aiming for a paradigmatic leap, namely: THE BIOHARMONY AGRO-RURAL DEVELOPMENT MODEL. As subsequent objectives, we address the following aspects: (1) Achieving a coherent vision with an emergent and applicable purpose, essentially we refer to the community, environment, economy and culture which are viewed as interdependent systems with the potential for multi-level and multi-level integration. (2). Specifying the components and dynamics of the model in which essentially we refer to details regarding the strategy for agro-rural adaptation and integration on multiple societal levels, both technical-economic and socio-cultural and environmental, based on digitalization, precision agriculture, ecological monitoring systems, blockchain for traceability (data storage in a computer network). (3). Applications in the development process through appropriate public policies and the transition towards societal bioharmony of rural areas which essentially emphasizes social cohesion, inclusion, education and the transmission of cultural heritage with the aim of high-performance managerial perspectives and multiple benefits.

2. Working Methodology

This research adopts a mixed-methods design, integrating conceptual, analytical and operational approaches. Methodologically, the epistemological foundation is anchored in: complex systems theory, socio-ecological paradigm and the conceptual framework of bioharmony, developed by Romulus Gruia (Theory of Basal Bioharmonism and Theory of Generalized Bioharmonism). Therefore, the proposed methodology is not exclusively descriptive, but aims to operationalize an integrative model, capable of quantifying and evaluating bioharmony processes in agro-rural systems, and beyond.

Essentially, the data used includes primary data (semi-structured interviews, questionnaires, field observations) and secondary data (statistical databases / Eurostat, INS; local reports; GIS and satellite data). In most cases, a triangulated approach was used to increase validity.

As a method of analysis techniques, we mention data analysis carried out through elements of multivariate statistical analysis, network analysis, dynamic system models, and comparative evaluation (e.g. between different territories). Regarding the emergent dimension, a series of agent-based models (building reality from the bottom up through computational simulations) and scenario simulations were used.

3. Results and Discussions

To begin with, we consider it more than appropriate to approach the need to move towards a new development paradigm covering today's requirements, an idea summarized in Figure 1.

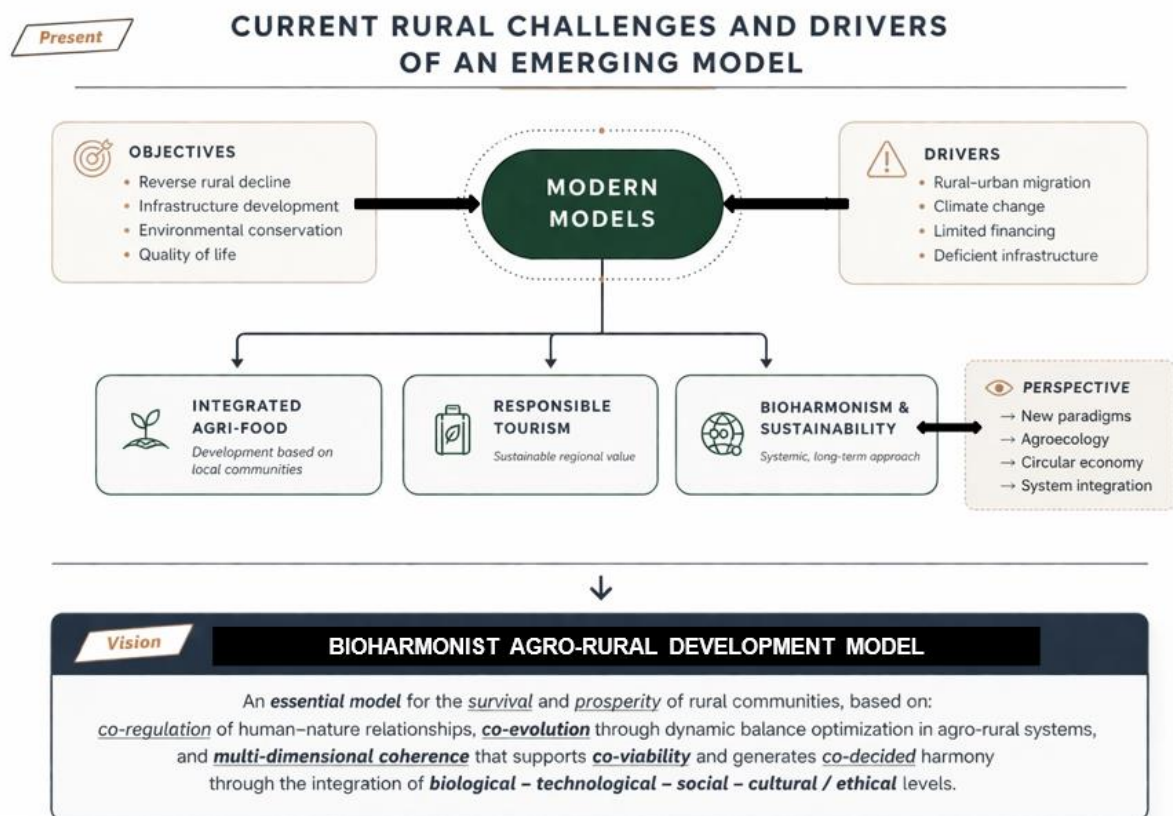


Fig. 1. Evolution of the development mode of the rural area with the transition towards the bioharmonic agro-rural development model

An important step is the definition of the type of rural development we are referring to, namely the Development of Agro-Rural Development by Bioharmonism. This is a coherent development framework with a holistic, participatory and sustainable valence, which integrates the ecological, economic, social, cultural and technological dimensions of rural communities in a polyvalent and multi-level manner.

The main goal is to create a sustainable and attractive ecosystem of rural areas, based on resilient, adaptable agro-rural anthroposystems capable of generating sustainable added value.

Along these lines, the proposed model aims at bioharmonic synergy through the fusion point between the LOCAL LEVEL

("polyvalent"), which generates resilience and cultural/ecological identity, with the SYSTEMIC LEVEL ("multi-level") which provides the digital, logistical and legislative infrastructure.

The hypothesis aims for this synergistic resilience to be economically efficient (profitable) and systemically effective (non-polluting and regenerative), which can lead to the target of societal emergence, which in this case represents the emergence of the new higher order in the rural space.

Essentially, the AXIS OF THE EMERGENCY OF THE DEVELOPMENT OF AGRO-RURAL BIOHARMONISM MODEL (DARbio Model) is eloquently described by the defining synthesis phrase:

"BIOARMONIST AGRO-RURAL" = *Holism* + *Sustainability* + *Participation* + *Technology* + *Economic Diversification* + *Social Cohesion* + *Resilience*.

Therefore, it becomes relevant to analyze the relationship between standard rural development and the transition to the integrated agro-rural development model through the sustainability and resilience offered by the path of societal

bioharmony and generally informational bioharmony.

This approach is necessary in order to counteract the disharmony of the present and to optimize the dynamics of rural space development in the coming decades through the bioharmony model. To understand this evolution, we specify in synthesis, through a block diagram, the structural and functional elements of the proposed model (fig.2).

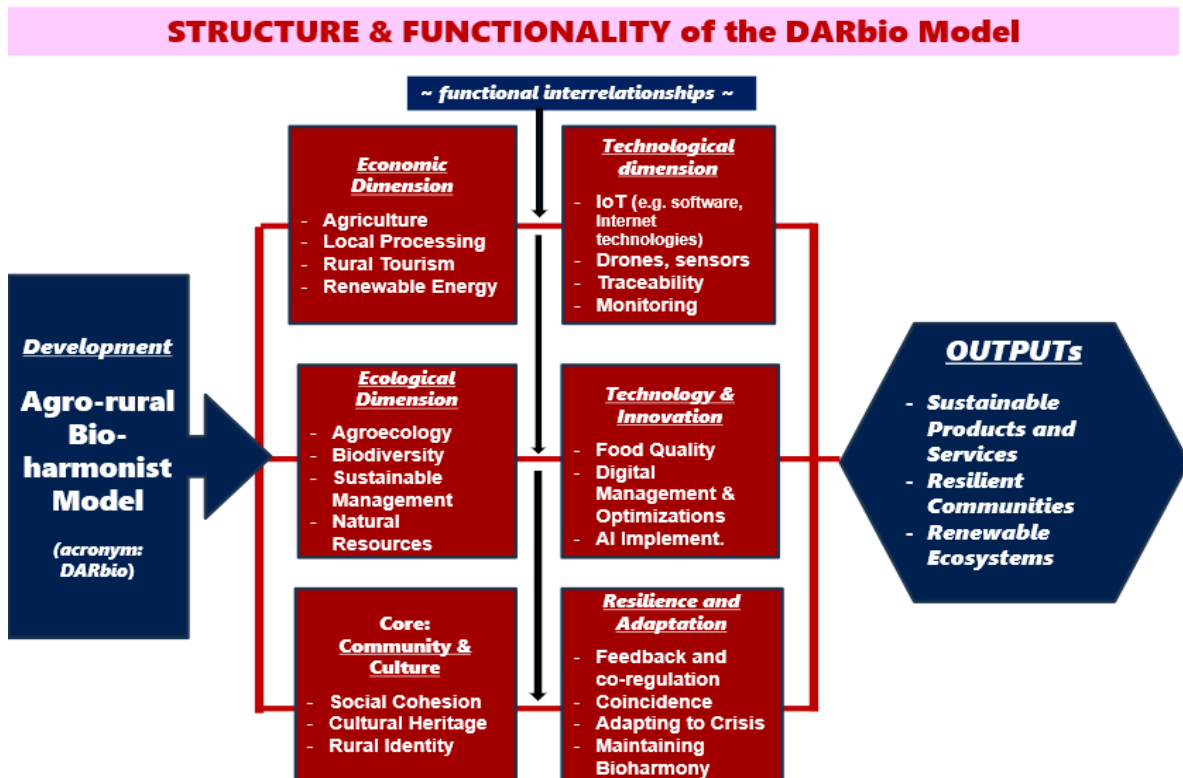


Fig. 2. Components of the holistic rural ecosystem based on the bioharmonist agro-rural development model

All these structural and functional elements are found concretely in the reality of rural space and

implicitly in the solutions that underlie the dynamics of a bioharmonious agro-rural development (fig.3).

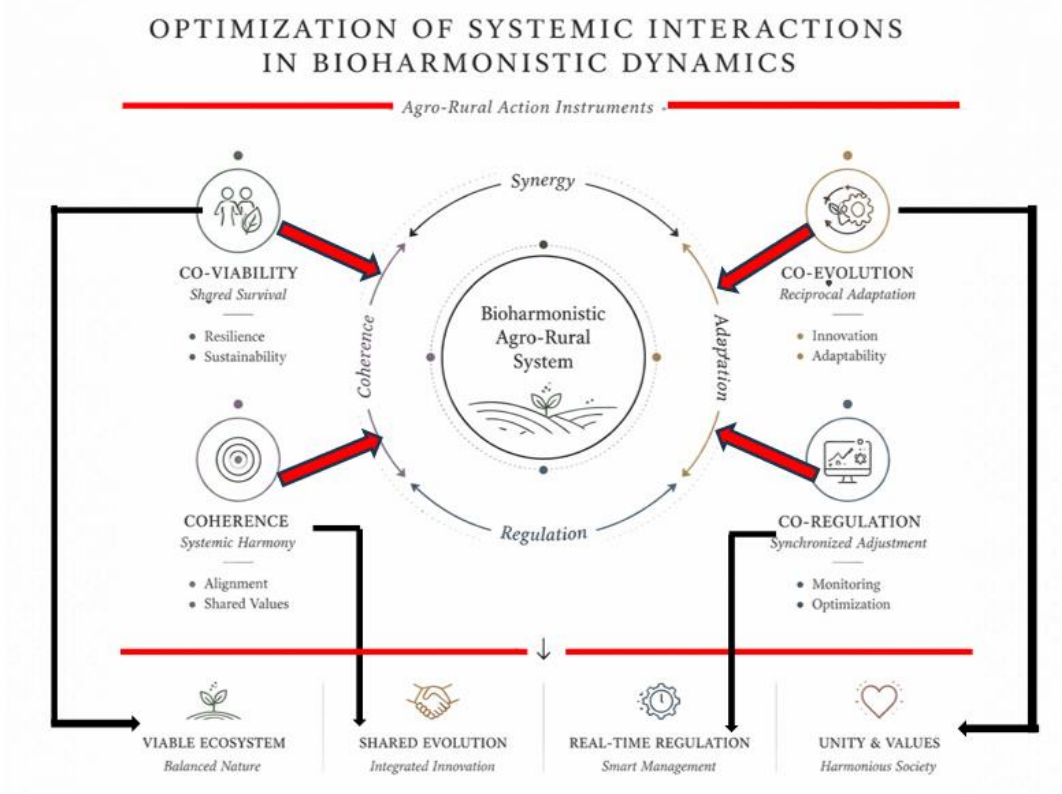


Fig. 3. Implementation of various agro-rural development solutions in relation to the specific processes of the DARbio Model

Considering the complexity of the problem, it becomes useful to develop a coherent strategy for applying the model (table 1).

Table 1. Strategy for the Application of the Darbio Model

No.	STRATEGIC PRINCIPLES	SHORT SPECIFICATION
1	Adopting an Integrated strategic framework	➤ Elaboration of a bioharmonic agro-rural development plan at local and regional level, with economic, ecological and social indicators.
2	Promoting community participation	➤ Encouraging the involvement of residents in decision-making and project implementation. ➤ Developing the capacity of communities to manage their own resources and projects.
3	Investments in technology and innovation	➤ Integration of digitalization, IoT, precision agriculture and ecological monitoring systems. ➤ Supporting startups and innovative local initiatives.
4	Agroecology and sustainability	➤ Adopting regenerative and environmentally friendly agricultural practices. ➤ Protecting biodiversity and natural heritage
5	Economic diversification and integrated chains	➤ Creating short supply chains and cooperation between production, processing and tourism. ➤ Capitalizing on cultural and natural identity for the development of sustainable rural tourism.
6	Education and human	➤ Vocational training programs for youth and rural entrepreneurs. ➤ Education in sustainability, technology and community

	development	management.
7	Continuous monitoring and evaluation	➤ Use of economic, environmental and social performance indicators. ➤ Adjusting strategies based on results and emerging needs.

The premise from which we start in applying the mentioned strategy is the need to assess the level of systemic bioharmony as accurately as possible. A necessary step for quantifying the parameters of the DARbio model is the objectification of the approach achieved through a detailed metricization. We refer to the fact that all the proposed indicators constitute a de facto

integrated framework for assessing agro-rural bioharmony. In this way, comparisons can be made between different areas, zones and regions, so that the model becomes a tool for drafting public policies.

Specifically, we refer to three groups of indicators: structural (*table 2*), functional (*table 3*) and composite (*table 4*).

Table 2. *Quantification of the Degree of Bioharmony of Agro-Rural Development Through Structural Indicators*

BIOHARMONISTIC INDICATORS	PRIMARY STRUCTURAL INDICATORS	OBJECTIVE
I. ECOLOGICAL BIOHARMONY (ECO) - the natural system (soil, water, biodiversity)	ECO 1 – Soil Balance Index	☞ measures: the stability of the edaphic ecosystem (biologically active soil, a living organism)
	ECO 2 – Water Use Efficiency Index	☞ reflects: co-regulation of water resources
	ECO 3 – Chemical Pressure Index	☞ objective: minimization without loss of yield
	ECO 4 – Functional Biodiversity Index	☞ measures: the coexistence of the agricultural system with nature
II. TECHNOLOGICAL BIOHARMONY (TECH) - technological system (drones, sensors, software)	TECH 1 – Degree of agricultural digitalization	☞ level of technological integration
	TECH 2 – Interoperability index	☞ reflects: technological coherence
	TECH 3 – Operational autonomy index	☞ transition to adaptive system
	TECH 4 – Interventional precision index	☞ measures: finesse of technological action
III. BIOARMONIE SOCIETAL BIOHARMONY (SOC) - human system (farmers, community)	SOC 1 – Rural Digital Literacy Index	☞ essential for adoption
	SOC 2 – Technological Inclusion Index	☞ avoids rural polarization
	SOC 3 – Community co-participation Index	☞ reflects: social co-evolution
	SOC 4 – Rural Quality of Life Index	☞ real impact on the community
IV. ECONOMIC BIOHARMONY (ECON) - the economic system	ECON 1 – Rural Digital Literacy Index	☞ not just quantity, but sustainable quality
	ECON 2 – Input-output efficiency	☞ measures: cost/benefit ratio
	ECON 3 – Economic resilience index	☞ major role of AI + sensors
	ECON 4 – Digital value added	☞ measures: traceability / value relationship of products

Table 3. Characterization of Functional Bioharmonist Indicators ("Co-")

INTERVAL	INTERPRETATION OF PROCESS INDICES				
	Co-viability Index (CVI = sustainability)	Co-evolution Index (CEI = adaptability)	Co-regulation Index (CRI = stability)	Coherence Index (CI = harmonized elements)	Co-decision Index (CDI = polycentric bioharmonistic governance)
0 – 20	Non-viable system (severe degradation)	Inert system (evolutionary deadlock)	Critical imbalance	Systemic fragmentation	Critical level: highly centralized dysfunctional decision
20 – 40	Fragile viability	Slow evolution	Structural instability	Weak coherence	Weak emergence with reduced coherence between decision-making levels
40 – 60	Moderate viability	Adaptive evolution	Partial regulation	Functional coherence	Moderate - Transition to bioharmonization with visible processes of co-evolution
60 – 80	Good viability	Accelerated evolution	Stable system	High coherence	Advanced with functional bioharmonization, operates on the basis of co-viability and co-regulation
80 - 100	Optimal viability (regenerative system)	Synergistic co-evolution (nature–society–technology)	Homeo-stasis bio-socio-ecological	Integrative coherence (identity + functionality)	Co-decision is expressed through optimal bioharmonization, with long-term sustainability and self-regulation

Table 4. Synthetic Interpretation Approached Through Bioharmonic Indicators Composites

No.	INDEX	INTERPRETATION
1	Bioharmonic Convergence Index (BCI)	0 – 20: sharp divergence 20 – 40: stagnation 40 – 60: slow convergence 60 – 80: stable convergence 80–100: accelerated convergence
2	Causal Divergence Index (CaDI)	0 – 20: high stability 20 – 40: moderate variation 40 – 60: latent instability 60 – 80: high instability 80–100: major systemic risk
3	Systemic Resilience Index (SRI)	0 – 20: likely collapse 20 – 40: difficult recovery 40 – 60: average resilience 60 – 80: good resilience 80–100: high systemic resilience
4	Index of Bioharmonism Agro-Rural (IBAR)	0 – 20: agro-rural area as a functional system 20 – 40: agro-rural area as a fragile system 40 – 60: agro-rural area as a transitional system with functional elements 60 – 80: agro-rural area as a performing system through advanced functional bioharmonization 80–100: agro-rural area as a mature bioharmonistic system

The multitude of these indicators attempts to cover the complexity of the development of the agro-rural area, ending with the global index, as previously mentioned, namely, the Agro-Rural

Bioharmonism Index (or more explicitly: Index by Bioharmonism of Agro-Rural = IBAR).

Essentially, this is a multi-dimensional composite indicator that quantifies the degree of agro-rural bioharmonization through the synergistic and emergent integration of ecological, technological, economic and societal dimensions, evaluated through the processes of co-viability, co-evolution, co-regulation and coherence, with the aim of optimizing the decision through convergence (co-decision-making), with systemic resilience, or in a divergent direction (as the case may be).

It should be noted that the development of the model is directly linked to the level of development of the area taken into account, taking into account that there are areas where the level of societal development is high, medium or low. This differentiation can be highlighted through the IBAR index through the degree of bioharmonization of the area, which is a pragmatic assessment that can guide and support the strategy of public policies necessary to be applied in the analyzed rural space (fig. 4).

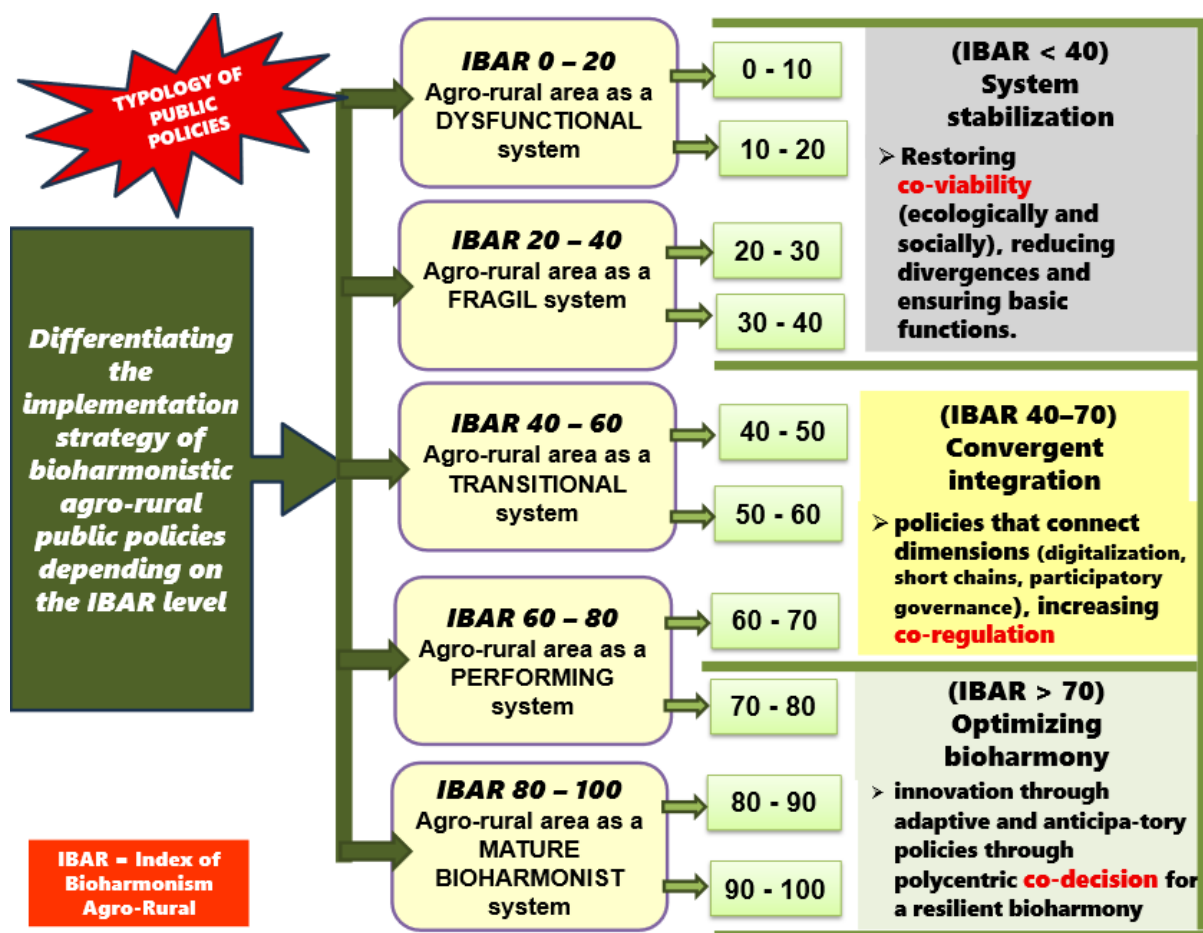


Fig. 4. Applications of the DARbio model through public policies adapted to the level of local rural development

The adaptation of public policies at the zonal level (as for example in the mountainous rural area) is observed, so that by objectifying the applied management, the resulting co-decision becomes a diagnostic tool for governance. Concretely, a clear transition is reflected: from centralized control → to emergent co-decision → to polycentric bioharmonization.

Practically in the bioharmonic architecture of agro-rural development, the ICD (Index of Co-

Decision) and the IBAN (Agro-Rural Bioharmonism Index) are complementary, that is, the ICD is a process indicator (quality of governance and co-decision), and the IBAN is a structural-systemic indicator (the level of bioharmonization of the agro-rural system). Thus, the relationship between them is one of emergent cause-effect type, respectively: the increase in coherent decision-making processes has as an effect systemic bioharmonization.

In other words, the ICD–IBAN correlation highlights the fact that: agro-rural bioharmonization cannot exist without functional co-decision. ICD is not just an auxiliary indicator, but a fundamental determinant of the performance of the agro-rural system, providing an operational framework for adaptive, participatory and sustainable public policies.

Therefore, the approach to public policies necessary for the coherent and efficient development of the future development of the agro-rural area, offered by the DARbio Model, has the capacity to guide and adapt, thus being able to propose and set the strategy of the Government Policy ("policy-ready") and the related Programs, specific to the geographical space of our country (*table 5*).

Table 5. *Public Policy Proposals Based on the DARbio Model*

Public Policy Group	Purpose / Opportunity	Programms
I. POLICIES FOR CO-VIABILITY (ICV)	Integrated sustainability: environmental–economic–social	1. National regenerative agroecology program 2. Local food autonomy policy 3. Integrated rural services program 4. Agricultural income stabilization
II. POLICIES FOR CO-EVOLUTION (ICE)	Adaptation, innovation, nature-society synergy	5. Agro-rural innovation ecosystem 6. Rural climate adaptation strategy 7. Green technological transition policy 8. Diversification of the rural economy
III. POLICIES FOR CO-REGULATION (ICR)	Balance, self-regulation, resilience	9. Production–consumption balance policy 10. Reduction of external dependence 11. Participatory rural governance 12. Rural energy autonomy
IV. POLITIOCI PENTRU COERENȚĂ (ICO)	Alignment of values, structures, and actions	13. Aligning public policies with local specificities 14. Revitalizing rural cultural identity 15. Strengthening social capital 16. Rural-urban integration
V. CROSS-CUTTING INTEGRATION POLICIES (IBAR)	The model generates a new type of public policy: → from "sectoral" → to systemic → from "subsidies" → to functional balance → from "economic growth" → to societal bio-harmony and systemic effectiveness	17. IBAR national monitoring system 18. Bio-harmonist budgeting 19. Bio-harmonist territorial contracts 20. Education for rural bio-harmonism

Essentially, public policies support development through a series of high-performance management perspectives and multiple benefits, such as the creation of smart village networks ("Smart Villages"), the implementation of smart technologies, the circular economy, the global connectivity of local producers, but also tourism responsible for the culture and nature of rural space and, especially for the future, renewable energy.

It is appropriate to mention in summary that unlike traditional, sectoral and linear models, the *DARbio Model* proposes an integrative, process-

oriented and emergent approach, based on the dynamic co-evolution of ecological, economic, technological and societal subsystems. We emphasize the originality of the model, which supports the ontological reconfiguration of agro-rural systems as living socio-ecological organisms, with an emphasis on bioharmonistic coherence and the ability to generate resilience as an emergent property. By integrating the processes of co-viability, co-regulation, co-evolution and systemic coherence, DARbio provides a basis for regenerative and adaptive

development in the context of global uncertainty and complexity.

CONCLUSIONS

(1) The proposed MODEL of rural development is inevitable and strategically necessary because the current approach, focused on productivity and subsidies, no longer meets future needs, taking into account climate change, rural depopulation, economic crises and global pressures, so it becomes more than appropriate to adopt the new model, that of BIOHARMONY AGRO-RURAL DEVELOPMENT.

(2) THE TRANSITION towards bioharmonic agro-rural development is essential for the survival and prosperity of rural communities through multi-functional and multi-level integrations, because beyond being an ecological ideal, it adopts, through fundamental bioharmonic structures (biological, technological, economic and societal harmony) and bioharmonization processes (co-viability, co-evolution, co-adaptation, coherence, co-decision), a practical strategy for increasing the quality of life and sustainable valorization of local resources.

(3) APPLICATIONS on multiple dimensions (economy, environment, technology and social life), in a holistic approach to the bioharmonic agro-rural model, have the potential to create a zonal ecosystem and a sustainable, resilient and adaptable rural anthroposystem, based on agroecology, digitalization and community participation, as benchmark elements of harmonizing dynamic balances in an economically efficient and systemically effective development.

(4) PRAGMATIC, the paradigm shift through the new model induces a government strategy that offers the possibility of applications through new public policies and specific management, of moving from standard rural development to bioharmonic agro-rural development, in short, from centralized planning (top-down) to a participatory approach and, at the same time, from intensive exploitation of resources to co-evolution based on the sustainable regeneration of ecosystems and communities.

(5) BIOHARMONIST PUBLIC POLICY is not uniform, but calibrated to the state of the system, aiming to maximize coherence and synergy between dimensions, through a

continuous process of adaptive co-decision in relation to IBAR.

(6) THE MULTIPLE BENEFITS of the bioharmonic agro-rural model essentially aim at the sustainability and resilience of development through the dynamics of emerging integrations, as follows:

- Increasing the resilience of communities and food autonomy.
- Environmental protection and regeneration of natural resources.
- Cultural and social valorization of rural communities.
- Economic diversification through rural tourism, agro-industry and renewable energy.

References

1. Altieri, M. A. (1995). *Agroecology: The science of sustainable agriculture*. Westview Press.
2. Altieri, M. A. (2002). *Agroecology: The science of natural resource management for poor farmers in marginal environments*. *Agriculture, Ecosystems & Environment*, 93(1–3), 1–24.
3. Capra, F., & Luisi, P. L. (2014). *The systems view of life: A unifying vision*. Cambridge University Press.
4. Carpenter, S. R., Walker, B., Anderies, J. M., & Abel, N. (2001). From metaphor to measurement: Resilience of what to what? *Ecosystems*, 4(8), 765–781.
5. Daly, H. E. (1996). *Beyond growth: The economics of sustainable development*. Beacon Press.
6. De Schutter, O. (2010). *Agroecology and the right to food*. Report presented at the United Nations Human Rights Council.
7. Folke, C. (2006). Resilience: The emergence of a perspective for social-ecological systems analyses. *Global Environmental Change*, 16(3), 253–267.
8. Folke, C., Carpenter, S. R., Walker, B., Scheffer, M., Chapin, T., & Rockström, J. (2010). Resilience thinking: Integrating resilience, adaptability and transformability. *Ecology and Society*, 15(4), 20.
9. Gruia, R., (2019). *Bioarmonismul – de la teorie la o ideologie de viitor*, Editura Clarion Braşov, ISBN : 978-606-94470-6-2, 27-48.
10. Gruia, R., (2019). *Ideologia bioarmonistă – izvor de regenerare politică într-o lume în schimbare*, Editura Clarion Braşov, ISBN: 978-606-94470-7-9 13-41.
11. Gruia, R., (2020). *Romania's territory administrative renewal in convergence with*

- resource balance and agri food potential, *Annals of the Academy of Romanian Scientists Series Agriculture, Silviculture and Veterinary Medicine Sciences*, Online ISSN 2344 – 2085, Volume 9, Number 2/2020, 69-81.
12. Gruia, R., Popescu, Agatha, Gaceu, L., (2024). The bioharmonized reconnection of the agricultural system in Romania's territory in the process of administrative reorganization, *Scientific Papers Series Management, Economic Engineering in Agriculture and Rural Development* Vol. 24, Issue 3, 2024 PRINT ISSN 2284-7995, E-ISSN 2285-3952.
 13. Gruia, R., Gaceu, L., Oprea, Oana, (2025). The Pillars of Societal Bioharmonism a Conceptualist Contribution to the Evolution of the Contemporary Society, *Challenges* 2025, 16(1), 16;
 14. Holling, C. S. (1973). Resilience and stability of ecological systems. *Annual Review of Ecology and Systematics*, 4, 1–23.
 15. Holling, C. S. (2001). Understanding the complexity of economic, ecological, and social systems. *Ecosystems*, 4(5), 390–405. <https://doi.org/10.1007/s10021-001-0101-5>
 16. Meadows, D. H., Meadows, D. L., Randers, J., & Behrens, W. W. (1972). *The limits to growth*. Universe Books.
 17. Ostrom, E. (2009). A general framework for analyzing sustainability of social-ecological systems. *Science*, 325(5939), 419–422.
 18. Ostrom, E. (2010). Polycentric systems for coping with collective action and global environmental change. *Global Environmental Change*, 20(4), 550–557.
 19. Pretty, J. (2008). Agricultural sustainability: Concepts, principles and evidence. *Philosophical Transactions of the Royal Society B*, 363(1491), 447–465. <https://doi.org/10.1098/rstb.2007.2163>
 20. Meadows, D. H. (2008). *Thinking in systems: A primer*. Chelsea Green Publishing.
 21. Raworth, K. (2017). *Doughnut economics: Seven ways to think like a 21st-century economist*. Chelsea Green Publishing.
 22. Senge, P. M. (2006). *The fifth discipline: The art and practice of the learning organization* (Rev. ed.). Doubleday.
 23. Walker, B., Holling, C. S., Carpenter, S. R., & Kinzig, A. (2004). Resilience, adaptability and transformability in social–ecological systems. *Ecology and Society*, 9(2), 5.
 24. West, G. B. (2017). *Scale: The universal laws of life and death in organisms, cities and companies*. Penguin Press.

FROM INNOVATION TO RISK: INSIGHTS INTO THE GERMAN BIOMATERIALS MARKET FOR START-UPS AND SMES

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Abstract: *The German biomaterials market has experienced significant growth, driven by advances in medical technology and sustainability-oriented innovations. Start-ups and SMEs play a central role in developing and commercializing products such as biodegradable plastics, 3D-printed biocompatible scaffolds, spider silk, and nanoparticle-based therapies. However, these enterprises face unique challenges due to limited resources, regulatory complexities, and heightened technological and market risks. This study investigates the primary risk factors encountered by start-ups and SMEs in the German biomaterials sector using a mixed-methods approach. A literature review of risk management frameworks was combined with qualitative insights from eight stakeholders, including company managers, a student representative, and a policymaker. Results indicate that the most widely applied analytical tools are SWOT, what-if, and worst-case analyses, with risk assessments often performed throughout all stages of innovation projects. Financial, operational, and market-related risks emerged as the most significant concerns. Despite recognizing the value of risk management—such as mitigating project failures and supporting decision-making—participants reported inconsistent practices and a lack of specialized software tools. Key barriers identified include logistical, financial, and regulatory constraints. The study highlights critical mitigation strategies, including securing raw material supply, enhancing financial resources through public funding, and implementing regularized risk management processes. While limited by a small sample size ($N = 8$), the findings provide valuable insights that can inform managerial practice and policy support for innovative enterprises in the biomaterials sector. The paper concludes with recommendations for expanding the research through larger, longitudinal studies to strengthen the evidence base.*

Keywords: *Risk Management, Supply Chain Risk Management (SCRM), SMEs / Small and Medium Enterprises, Start-ups, Biomaterials*

1. Introduction

The commercial viability of biomaterials is constrained by inherent production costs, performance limitations compared to fossil-derived counterparts, and the lack of established market infrastructure, resulting in significant competitive pressure from petroleum-based materials. Small firms must, furthermore, contend with raw material and (bio-) chemical variability, limited technological data, and uncertain market dynamics. These uncertainties complicate commercialization and require robust approaches to risk estimation and mitigation. Within this context, comprehensive enterprise risk assessments are essential for identifying key risks and designing effective mitigation strategies

in biobased industries (de Assis et al., 2017; Pellicer et al., 2017).

Germany has emerged as a leading hub for biomaterial innovation, driven largely by start-ups and small and medium-sized enterprises (SMEs). These firms develop high-value applications across healthcare, packaging, textiles, and advanced manufacturing. Examples on sustainability and high-tech innovation in bioeconomy are biodegradable leather alternatives produced using mycelium as raw material source, cellulose-based packaging as plastic replacement, and manufacturing of spider silk for both medical and industrial utilization (Williams et al., 2022; Yaradoddi et al., 2020; Hughes-Castleberry, 2023).

Current research on supply chain risk management (SCRM) mainly focuses on large

multinational corporations and large supply chains, often overlooking the distinctive operational constraints and vulnerabilities of SMEs (Vishnu et al., 2019). Risk factors and mitigation pathways differ significantly between younger and more established SMEs, demonstrating that strategies optimized for large firms may not be effective for smaller, resource-limited enterprises (Foli et al., 2022). In the German biomaterials market, SMEs often struggle includes limited data on customer and provider perceptions, unclear regulatory pathways, and a lack of financial strategies tailored to supply chain disruptions and volatile raw material prices. Furthermore, research on sustainability and scalability is scarce, especially concerning the long-term environmental impacts of biomaterials and their potential for mass production (Kanyepe et al., 2025; Malesios et al., 2020). Studying risk management in this sector is therefore not only academically relevant but also strategically important for business and policy.

By equipping start-ups and SMEs with effective risk assessment frameworks, Germany can reinforce its position as a global leader in sustainable innovation while advancing societal health and contributing to global sustainability goals.

This paper builds directly on established scholarship on entrepreneurship under uncertainty, particularly work highlighting the internationalization and innovation challenges of SMEs and the resilience required in volatile conditions. Research on SMEs shows how resource constraints shape innovation strategies and collaborative behaviors, while analyses of entrepreneurial finance emphasize the role of alternative financing and resilience strategies during prolonged crises (Audretsch & Guenther, 2023). The distinctive challenges faced by biomaterials start-ups, including technological risk, market uncertainty, and high capital requirements, echo broader themes in entrepreneurial finance research.

This study extends Guenther's insights to an emerging field of entrepreneurship at the intersection of sustainability and advanced manufacturing (Groh et al. 2025, Belitski et al., 2022). This paper addresses two research questions: (1) What major risks affect start-ups and SMEs in the biomaterials sector, and how can they be mitigated? (2) What financial and logistical barriers constrain biomaterial innovation, and what solutions can be addressed? The topic's relevance lies in the convergence of

economic growth, societal well-being and environmental sustainability. The biomaterials market is projected to grow rapidly, particularly in healthcare, packaging, and construction, creating opportunities for SMEs to strengthen Germany's competitiveness, generate high-value employment, and diversify the economy (Gonzales-Gemio et al., 2020; Scheau et al., 2024). Biomaterials also offer safer and more sustainable solutions in medicine, e.g., as biocompatible implants, drug delivery systems and regenerative scaffolds (Lopez et al., 2010). Moreover, biomaterials address environmental challenges through biodegradable and recyclable alternatives (De Jesus & Mendonça, 2018; Mahmud et al., 2024; Parrilli et al., 2023; Rajvanshi et al., 2023).

2. Literature Review

2.1. Biomaterials and risk management challenges for SMEs

Biomaterials are substances engineered to interact with biological systems for therapeutic, diagnostic, or technological purposes. They can be natural or synthetic, spanning metals, ceramics, polymers, and composites, and are designed to ensure biocompatibility while minimizing adverse immune responses (Agrawal et al., 2023; Song et al., 2022). A comprehensive definition provided by Williams (2009) described biomaterials as substances "...engineered to take a form which, alone or as part of a complex system, is used to direct, by control of interactions with components of living systems, the course of any therapeutic or diagnostic procedure, in human or veterinary medicine."

This definition was later refined to emphasize their role in steering therapeutic and diagnostic processes through controlled interactions with living systems (Zhang & Williams, 2019).

Biomaterials play a pivotal role in transformation, progressing from passive materials to bioactive substances that promote wound healing and regeneration. Further applications such as tissue-engineering scaffolds, drug-delivery systems, and bioresorbable implants have been, thus, enabled (Detsch et al., 2018).

In packaging and industrial applications, mycelium and circular biomanufacturing processes convert organic waste into sustainable products such as plastics, lubricants, and surfactants (Barta et al., 2024). Emerging research also explores microorganisms and

enzymes for plastic waste valorization, opening new sustainability pathways (Bao et al., 2023). Germany plays a central role in advancing biomaterials research, supported by interdisciplinary institutions such as the Max Planck Institute or Fraunhofer Institute. Industrial actors are pioneering breakthroughs in bioprinting and sustainable biomaterials. Market projections indicate rapid growth, with the polymeric biomaterials sector expected to reach nearly USD 9 billion by 2030 at a CAGR of 14.6% (Bella et al., 2024).

Despite this growth potential, SMEs in the biomaterials sector face significant barriers to innovation and commercialization. Limited time, scarce financial and human resources, and insufficient access to tailored guidance often constrain their ability to conduct comprehensive risk assessments (Bella et al., 2024). Entrepreneurs' attitudes toward risk further shape these practices, with smaller firms often relying on intuition and qualitative assessments rather than quantitative models (Weber & Kokott, 2024). Particularly start-ups tend to underestimate risks, navigating highly uncertain environments with swift but less formalized decision-making. This aligns with Belitski et al. (2022) and Groh et al. (2025) findings on how SMEs struggle with resilience under conditions of uncertainty, often relying on informal practices rather than structured frameworks.

Commercializing biomaterials is especially challenging given regulatory hurdles, shifting healthcare demands, and the need for capital-intensive research. Strengthening academia-industry partnerships is therefore critical for accelerating translation into viable products. Comprehensive risk assessments and tailored commercialization strategies are not optional but essential to ensure success in areas such as implants, regenerative medicine, and tissue engineering (Brassescio et al., 2024). This echoes Guenther's work on the ability-willingness paradox in small firms, which highlights that even when opportunities exist, SMEs may lack either the capacity or the willingness to engage in collaborations that reduce risk (Guenther et al., 2023).

Within the broader bio-based industries, risk analysis practices often rely on simpler qualitative tools (e.g., sensitivity analysis) rather than probabilistic models, due to ease of use and interpretability. Financial risks, especially cost and price volatility, are usually prioritized over technical, regulatory, or market-related risks (de

Assis et al., 2017). However, this reliance on traditional financial metrics often results in a disconnect between formal risk assessment and its application in strategic decision-making. This is consistent with Groh's et al. (2025) work, who demonstrate that entrepreneurial finance under extended crises requires more adaptive, resilient approaches to risk management beyond traditional financial metrics.

Jernström et al. (2017) suggest that SMEs in the bio-based sector face particular types of challenges and several critical factors were identified: (1) funding accessibility: securing adequate financial resources is essential for SMEs to invest in necessary technologies, research, and development within the bio-based industry; (2) technological capabilities: possessing or developing the appropriate technological expertise enables SMEs to innovate and remain competitive in the bio-based market; (3) market knowledge: a deep understanding of market dynamics, customer needs, and industry trends allows SMEs to make informed decisions and effectively position their products or services; (4) regulatory environment: navigating complex regulations and compliance requirements is crucial, as these can pose significant barriers or facilitators to market entry for SMEs; and (5) collaborative networks: building partnerships with research institutions, industry players, and other stakeholders can provide SMEs with valuable resources, knowledge, and market access opportunities.

All together, these insights highlight the tension between the scientific and industrial potential of biomaterials and the practical limitations faced by SMEs. Risk management emerges as a critical enabler for bridging innovation and commercialization, ensuring that SMEs can navigate uncertainty while contributing to Germany's competitiveness in the bioeconomy. Building on Günther's contributions to understanding entrepreneurial finance, resilience, and SME dynamics, this study positions biomaterials innovation as a timely context in which her theoretical insights can be extended to new sustainability-driven industries.

2.2. Biomaterials innovation and market penetration within the German landscape

The German biomaterial field within the biotechnology sector presents a dynamic yet challenging environment for innovation. While 2023 witnessed strong start-up activity and

renewed venture capital inflows, turnover and employment declined, and access to early-stage financing and public markets remains limited. Despite these hurdles, prospects for clinical and technological advancements are optimistic, driven by progress in personalized medicine, regenerative therapies, and sustainable biomaterials (Ort & Bronsema, 2025). A key trend shaping the industry is the adoption of automation and digitalization. Bioregions across Germany are investing in scalable platform technologies, including robotic systems for high-throughput screening, 3D printing of scaffolds, and the integration of artificial intelligence into production workflows. These innovations not only accelerate research but also improve quality assurance and sustainability (Spring & Haase, 2025).

The sector's diversity requires customized strategies. Publicly listed companies such as BioNTech, Evotec, and QIAGEN dominate in scale, revenues, and employment, while also advancing precision medicine. In sustainability, firms like BRAIN Biotech are developing bio-based industrial applications. Venture capital-backed enterprises, including AmSilk and Formo, stand out for biomaterial innovations such as spider silk and animal-free cheese, while independently funded firms like Miltenyi Biotec and NanoTemper Technologies provide critical tools and services (Ort & Bronsema, 2025). Financing trends indicate growing interest in investor. In 2023, twelve industrial biotech firms raised a record €207 million to develop innovative foods and biomaterials, with Formo securing €55 million for animal-free cheese production. Regenerative medicine continues to drive demand for biocompatible materials in orthopedics, ophthalmology, dentistry, surgery, and cosmetics, while underutilized resources, such as meat industry by-products, present opportunities for novel biomaterial constructs (Patshina et al., 2021).

Despite these opportunities, several barriers hinder market penetration. Economic competitiveness is constrained by high production costs and limited economies of scale, necessitating supportive financing mechanisms like subsidies and tax incentives (Harris et al., 2018; Makepa & Chihobo, 2024). Regulatory uncertainty, including unclear biocompatibility standards and evolving EU requirements, slows commercialization (Prestwich et al., 2012). Public awareness and acceptance remain low, often hindered by misconceptions, greenwashing,

and inconsistent labeling (Filho et al., 2021; Hairon Azhar et al., 2022; Manu et al., 2022). Policy imbalances further limit development, as biomaterials often lack the structured incentives available in other sectors like biofuels (Hermann et al., 2011; Dammer et al., 2013; de Vicente Bittar & Di Serio, 2023). Intellectual property (IP) protection is critical for establishing competitive advantage, attracting investment, and supporting start-up growth (Beltrán-Urvina et al., 2025; Balaji & Ponniah, 2023). Finally, scalability and technological limitations challenge commercialization, with fermentation processes and feedstock volatility affecting cost competitiveness (Wellenreuther et al., 2022; Börner & Zinn, 2024; Hess & Tumuluru, 2024).

These dynamics are particularly relevant for SMEs, which often operate under higher uncertainty and tighter resource constraints. Research shows that traditional risk management strategies designed for large multinational supply chains are not always suitable for start-ups (Vishnu et al., 2019). SMEs require tailored mitigation strategies that align with their vision, capabilities, and critical success factors. Financing gaps, regulatory complexity, and technological hurdles make robust risk management essential for navigating market uncertainties and achieving sustainable growth. Günther's research on entrepreneurial finance, SME resilience, and innovation under uncertainty underscores how smaller firms navigate volatile environments, make resource-constrained investment decisions, and leverage collaboration networks to mitigate risk (Audretsch & Guenther, 2023; Guenther et al., 2023; Groh et al., 2025). By applying these insights to the German biomaterials (sustainability-driven and high-tech context) sector, this study emphasizes how SMEs can successfully commercialize innovative biomaterials while navigating financial, regulatory, and technological risks, thus extending Guenther's legacy.

2.3. Translating biomaterials from laboratory to market

Biomaterial commercialization depends on a set of interdependent strategic factors, playing market selection a central role. Decisions regarding the initial geographic target for regulatory approval influence market size, competitive dynamics, regulatory burden, cost uncertainty, and reimbursement opportunities. Well-informed market entry strategies form a

foundation for converting laboratory-stage biomaterial innovations into viable clinical or commercial products (Balconi et al., 2010).

Equally critical are scalability and technology transfer (TT). Production scalability must consider capacity, market readiness, and the biomaterial's ability to retain mechanical integrity and biological efficacy during upscaling, while integrating environmental safety and waste minimization in line with ISO 13485 standards (2016). TT bridges research and commercialization, with Technology Transfer Centers (TTCs) in the EU, thus facilitating intellectual property management, market evaluation, funding acquisition, and interactions among researchers, entrepreneurs, investors, and policymakers.

SMEs face notable barriers in engaging with TT activities (Hilkenmeier et al., 2021), including, but not limited to: (1) Restricted internal R&D capabilities, constraining the ability to innovate or absorb new technologies; (2) Difficulty identifying suitable collaboration partners, especially for SMEs inexperienced in research networks; (3) Resource constraints, such as limited financial and human capital; (4) Limited absorptive capacity, affecting the effective integration of external knowledge; and (5) Risk perceptions, including CEO turnover, revenue volatility, regulatory shifts, competition, and succession uncertainties in family firms (Glowka et al., 2024).

Achieving commercial viability and regulatory compliance requires harmonizing safety, efficacy, and market demands. Continuous post-market surveillance is vital for detecting adverse effects and guiding product refinement. A robust R&D foundation, early stakeholder engagement, and adherence to regulatory frameworks, augmented by ISO guidance, are essential for the effective and sustainable integration of biomaterials into products. Iterative assessments and strategic early-stage planning are indispensable for navigating the complex path from innovation to patient or consumer benefit (Jurczak et al., 2024).

2.4 Benchmarking Risk Management Practices in Biomaterial related SMEs and Start-Ups

Several frameworks and examples provide useful benchmarks for SMEs and start-ups in managing risks within the biomaterials sector. BIORIMA (Biomaterial Risk Management)

develops an Integrated Risk Management (IRM) framework for nano-biomaterials used in Advanced Therapeutic Medicinal Products (ATMPs) and medical devices. The framework offers validated tools for risk identification, assessment, and mitigation, including exposure monitoring, hazard evaluation, and safer-by-design approaches. A web-based Decision Support System assists SMEs in evaluating risk/benefit profiles and accelerating time-to-market for nano-biomaterials (<https://cordis.europa.eu/project/id/760928>).

SME-focused SCRM methodology (Jüttner & Ziegenbein, 2009) provides a practical approach for SMEs facing global supply chain risks. Based on the classical phases of risk identification, assessment, and mitigation, the method incorporates IT support to address SMEs' resource constraints and organizational limitations. While simplified, this model offers a structured, actionable framework for smaller firms in materials and chemical sectors.

Clinical translation and regulatory compliance in biomaterials introduce additional complexities. Modern biomaterials are designed for specific clinical functions, requiring strict adherence to the EU's Medical Device Regulation (MDR) and In Vitro Diagnostic Regulation (IVDR), alongside ISO standards. Adoption of safe-by-design (SbD) and function-by-manufacturability (FbM) principles is increasingly recognized as essential to ensure safety, regulatory compliance, and efficient product development (Jurczak et al., 2024). Early integration of these principles reduces recalls, supports market access, and balances innovation with regulatory requirements. These benchmarks illustrate how SMEs and start-ups can structure risk management practices to navigate operational, regulatory, and clinical challenges.

3. Methodology

3.1. Supply chain risk assessment instrument

To evaluate risk management practices in SMEs within the biomaterials sector, a Supply Chain Risk Management Maturity (SCRMM) scale was adapted from Dellana et al. (2022). Originally developed to measure organizational maturity in managing supply chain risks, this scale was refined through expert consultation and extensive research. For this study, the SCRMM instrument was incorporated into a structured questionnaire used during interviews (Supplementary Information). The questionnaire

was further enhanced by the works of de Assis et al. (2021), who examined how organizations in the bio-based industry assess and analyze risks in capital investment decisions, and by Mechali & Boche (2025), who investigated the impact of supply chain risk management practices on operational performance in pharmaceutical manufacturing. These studies helped tailor the instrument to the context of German biomaterials SMEs, ensuring relevance to both financial and operational risk dimensions. Qualitative data were collected through in-depth online face-to-face interviews with six SME representatives conducted in June 2025. The structured questionnaire served as both a data collection tool and a discussion guide, while allowing flexibility to capture additional insights. The questionnaire comprised five sections: (1) socio-demographic profile of the respondent; (2) organizational information; (3) risk assessment practices for organizations performing risk evaluations; (4) risk management practices for organizations not conducting formal assessments; and (5) additional barriers to biomaterial innovation. This approach provided a comprehensive understanding of risks, critical success factors, and operational challenges within the German biomaterials landscape.

3.2. Study population and sampling strategy

The study targeted managers responsible for operations in SMEs and start-ups within the German biomaterials sector. Participation was voluntary, with assurances of anonymity, optional responses, and post-study access to results. A mixed-methods approach combining quantitative and qualitative data collection was conducted between March and August 2025. Initially, 18 SMEs and start-ups were contacted, of which six participants confirmed involvement.

To enrich the sample, the scope was expanded to include a biomedicine technology student and a local politician from a region actively promoting biotechnological firms. Each interview followed a preliminary agenda tailored to the interviewee's expertise, focusing on identifying and assessing risks and critical success factors. Discussions lasted typically between 60 and 90 min and included both structured questionnaire items and an open discussion segment, allowing participants to provide additional insights. Table A.1 (Supplementary Information – upon request) summarizes the invited firms (participant anonymity is maintained throughout this study).

3.3. Data analysis approach

A mixed-methods approach was employed to integrate quantitative and qualitative data collected concurrently. Quantitative data from Sections 1–4 of the questionnaire were sorted, coded, and analyzed in Excel. Due to the small sample size, descriptive statistics (including frequency, percentage, mean, and standard deviation) were used to summarize responses. Qualitative data from Section 5 of the questionnaire were analyzed manually using a mixed-method analysis. Key themes were identified, focusing on management of primary risk factors such as finance, logistics, competition, regulatory frameworks, and policy. Findings were then presented narratively, complemented by representative quotations from participants. This approach enabled triangulation, enhancing validity and confirming insights across quantitative and qualitative dimensions (Kuckartz, 2014; Mayring, 2014).

4. Results

4.1. Demographic and organizational profile of participants

Table A.2 (Supplementary Information – upon request) summarizes the demographic characteristics of the study participants. While the small sample size limits generalizations, some patterns emerged. The group showed gender balance, with half of them being over 40 years old. Many held multiple roles within their organizations due to the small company size. Notably, 50% of respondents had a PhD, and 62% reported over 10 years of experience in their current or related organizations. Table A.3 outlines the organizational characteristics of the participating firms. The sample included companies from agro-industry (2), textiles (1), construction (1), alternative energy (1), and healthcare (1). Half operated exclusively in Germany, while the others had offices in additional European countries. Founding years ranged from 1989 to 2025.

All respondents held management positions. In terms of financial performance, two firms reported no revenue in 2024, two generated under €1 million, and two SMEs achieved revenues between €10–50 million.

4.2. Quantitative Insights from Risk Management Practices

Table 1 presents the quantitative results from Section 3 of the questionnaire (Supplementary Information). Although the small sample size ($N = 4-5$) limits generalization, several patterns emerged. Participants reported agreement that their organizations conduct regular risk assessments for investments (3.8 ± 0.4) but strongly disagreed about having written guidelines for these processes (1.3 ± 0.4). While some firms had designated risk officers or departments, responses varied widely (3.8 ± 1.5). Supply chain risk management was consistently rated as a priority (4.6 ± 0.5), with agreement that managing risks improves competitiveness (3.6 ± 1.0) and minimizes disruptions (4.6 ± 0.8). Information sharing with partners was moderate (3.4 ± 0.8), though cost data was rarely shared (2.2 ± 1.0).

Risk assessments were performed regularly, but frequencies differed (weekly, monthly, or project-based). Simulation of risk events was common (3.5 ± 0.5), yet contingency planning remained underdeveloped (3.4 ± 0.4). Neutral

responses were recorded for supply chain flexibility (3.0 ± 1.7) and maturity of systematic review processes (3.0 ± 1.2), reflecting the young age of many firms. Strong agreement was found regarding the importance of internal communication: sharing risk information across departments (4.8 ± 0.4) and maintaining organization-wide awareness (4.4 ± 0.5) were viewed as critical to resilience. Firms also reported high integration of risk management practices (4.2 ± 0.4).

Qualitative risk outcomes were prioritized in investment decision-making (4.5 ± 0.5), while deterministic and probabilistic results played a smaller role (both 3.7 ± 0.9). Risk management was seen as inclusive and participatory (4.0 ± 1.3), higher than comparable studies in pharmaceutical SMEs (Mechal & Boche, 2025). Supply chain audits were regularly conducted (4.4 ± 1.2), with strong agreement on the value of contingency planning (4.4 ± 0.5) and its contribution to loss minimization (4.8 ± 0.4). Conversely, insurance was rarely considered central to risk mitigation (1.8 ± 1.0), as firms often maintained only legally required coverage.

Table 1. Analysis of the SCRM practices

Scale: 1 Strongly disagree, 2 Disagree, 3. Neutral, 4. Agree, 5. Strongly agree	<i>N</i> ¹	<i>Av.</i>	<i>md</i>	<i>SD</i>	<i>Abs</i>
1. My organization performs a clear and concise risk assessment for investments (including, but not limited to) quantitative and qualitative methods	4	3.8	4	0.4	4
2. My organization has a written guideline or procedure on how to perform risk assessment for investments	4	1.3	1	0.4	4
3. A formally dedicated department or employee conducts risk assessments for investments in my organization	5	3.8	4	1.5	3
4. Managing risks in the supply chain is a top priority in our organization	5	4.6	5	0.5	3
5. We believe that managing risks in the supply chain makes us more competitive.	5	3.6	4	1.0	3
6. We believe that managing risks in the supply chain helps to minimize disruptions	5	4.6	5	0.8	3
7. We typically share risk data with our supply chain partners	5	3.4	4	0.8	3
8. We typically share costs of risk impacts with our supply chain partners	5	2.2	3	1.0	3
9. Risk assessment is frequently performed	5	3.2	4	1.5	3
10. I often simulate risk events to assess our ability to respond effectively	4	3.5	3.5	0.5	4
11. When a risk event occurs, I usually have a well-defined contingency plan available to reduce the impact of the event	5	3.4	3	0.8	3
12. Our supply chain employs flexible facilities to cope with changing conditions or markets.	5	3.0	4	1.7	3
13. Our organization employs a mature systematic process for reviewing and improving our risk management system effectiveness	4	3.0	3.5	1.2	4
14. We routinely share risk-specific information across departments within our organization.	5	4.8	5	0.4	3
15. We make sure all employees in our organization have a good understanding of our internal risk management process	5	4.4	4	0.5	3

16. Our organization exhibits a high degree of internal integration for risk management	5	4.2	4	0.4	3
17. Our organization has a mature internal risk management process that ensures our internal operations are not easily disrupted	5	3.8	4	0.7	3
18. Qualitative risk assessment outcomes (non-numerical outcomes) are ALWAYS considered in the investment decision-making process	4	4.5	4.5	0.5	4
19. Deterministic outcomes (e.g. sensitivity analysis) are ALWAYS considered in the investment decision-making process	3	3.7	3.0	0.9	5
20. Probabilistic outcomes are ALWAYS considered in the investment decision-making process	4	3.8	3.5	0.8	4
21. In the organization, risk management practices are inclusive and participatory	5	4.0	5.0	1.3	3
22. My organization categorizes the supply chain risks as high, medium & low	5	4.0	4.0	0.9	3
23. My organization undertakes continuous supply chain performance audits (quality, cost, delivery)	5	4.4	5.0	1.2	3
24. The supply chain contingency planning is a critical element of the Business for my organization	5	4.4	4.0	0.5	3
25. My organization plan contributes to loss minimization, safe assets and risk mitigation	5	4.8	5.0	0.4	3
26. My organization considers insurance as a key for mitigating supply chain risks	5	1.8	1.0	1.0	3

¹N=counts; Av. = Average; md=median; SD= standard deviation; Abs = abstentions

4.3. SMEs and Start-up interview analysis

Sections 3 and 5 of the questionnaire went into deeper analysis to determine further elements linked to risk management. Participants were asked in which project stage(s) risk assessment was performed, allowing them to check all that apply. Three out of five participants confirmed that risk assessment is performed at all stages of project development, one mentioned only conception, and one mentioned only conception and execution. In a similar approach, de Assis et al. (2021) determined that from their sample in the bio-based industry, 80% perform risk assessment during feasibility stages, and less than 50% performed it at early stages (initiation and conception). This research determined that 60% of the sample indicated the need to do risk assessment at all stages, which agrees with the literature, as there is naturally a higher number of uncertainties and unknowns at initial project phases, with 100% of the sample agreeing with the conception of the project. Ergo, decisions taken at the early stages will undoubtedly have a higher impact on investment value and project revenue.

All participants mentioned the use of both qualitative and quantitative methods combined to assess risks. When asked what type of software they were using to assess said risk, all of them confirmed using Microsoft Excel spreadsheets, one mentioned using software developed "in-house", while other two participants mentioned

the additional use of specialized software like <https://osapiens.com> or Enterprise Resource Planning (ERP). None of the participants mentioned using any of the common software products (@Risk, Crystal Ball, DPL, etc.). This aligns with a statement found widely in the literature, that given the size and financial restriction of SMEs, usually there is no additional investment in software tools for risk management. Parallely, this also shows the great abundance, diversity and heterogeneity in risk assessment tools used among the participants, which corroborates initial thoughts about the needs of each firm to have tailor made solutions for their own risk assessment needs.

Participants also answered what analytical approaches are used to perform risk assessment. Figure 1 shows that, although a broad diversity of analytical approaches was mentioned, the most voted ones were SWOT analysis and the What-if analysis. This result overlaps with those obtained by de Assis et al. (2021). Although sample size of N = 5 is too small and not recommendable to convert to percentages, as it may result misleading, it was used in this case exceptionally, in order to have a more comfortable view of the results using the data collected in the paper as a benchmark or reference value. Interesting, in both cases, SWOT analysis received a higher voting, probably because qualitative tools are generally simpler, requiring less detailed information, not relying on advanced software, and serving as a foundation for subsequent

quantitative analyses. The what-if analysis was in this sample studied almost double as the reference value, whereby in the paper, the worst-case analysis was two times higher than in the sample studied here. Due to the small sample size of this study, further quantitative comparisons are limited. Cost-benefit analysis does not have a benchmark, as the authors excluded it from the

analysis as it is not really a risk assessment tool. Traffic light system was included in this study only, as it was one of the answers provided by one participant. Raw data values of Figure 1 are found in Supplementary Information (upon request).

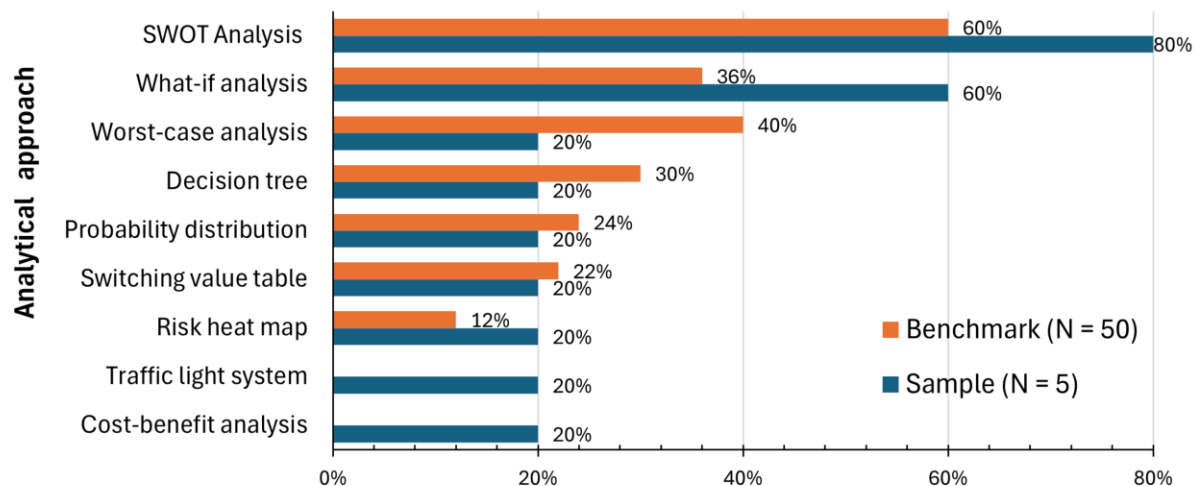


Fig. 1. Analytical approaches used to perform risk assessment (N = 5). Blue bars: values from this study. Orange bars: reference values from de Assis et al. (2021)

These results differ, e.g., with those proposed by Kheir et al. (2022). Their findings indicate that from a sample of seven participating start-ups (involved in the development, commercialization, and quality control of (bio-)medical devices), they predominantly rely on other tools like Failure Mode and Effects Analysis (FMEA) and combine it with other approaches such as Hazard Analysis, Corrective and Preventive Actions (CAPA), or SWOT analysis to strengthen risk identification during development phases. Overall, their results suggest that FMEA is the most widely applied method among those participants.

Figure 2 shows the answers when participants were asked to identify which specific sources of risk are considered by their organization when performing risk assessment, allowing them to check all that apply. The top three sources of risk to be considered when performing risk assessment are highlighted in pink. Besides financial, market and sales, and operational, other sources were also mentioned, i.e., TRL, resources, timing, SCM, social and environmental regulations. Product value and resource availability were also mentioned during

the interview (result not shown). Similar as before, and only for comparison reasons, values were plotted using reference values provided by de Assis et al. (2021). Results overlap with those from de Assis, confirming the importance of financial risks, followed by market and sales, and operational.

Noticeably, de Assis' paper further differentiates among type of participant (either upper or middle management). As this study does not use these criteria, reference values used here come from the upper management only. Again, the comparison among values is very limited due to the small number of participants (N = 5).

These results are in agreement to those shown by de Assis et al. (2021), where the top three sources of risk perceived in their sample were financial, market and technology, with operational on the fourth position of ranking. Similarly, these results also align with those published by Kheir et al. (2022), with a sample of seven start-ups in the biomedical device field.

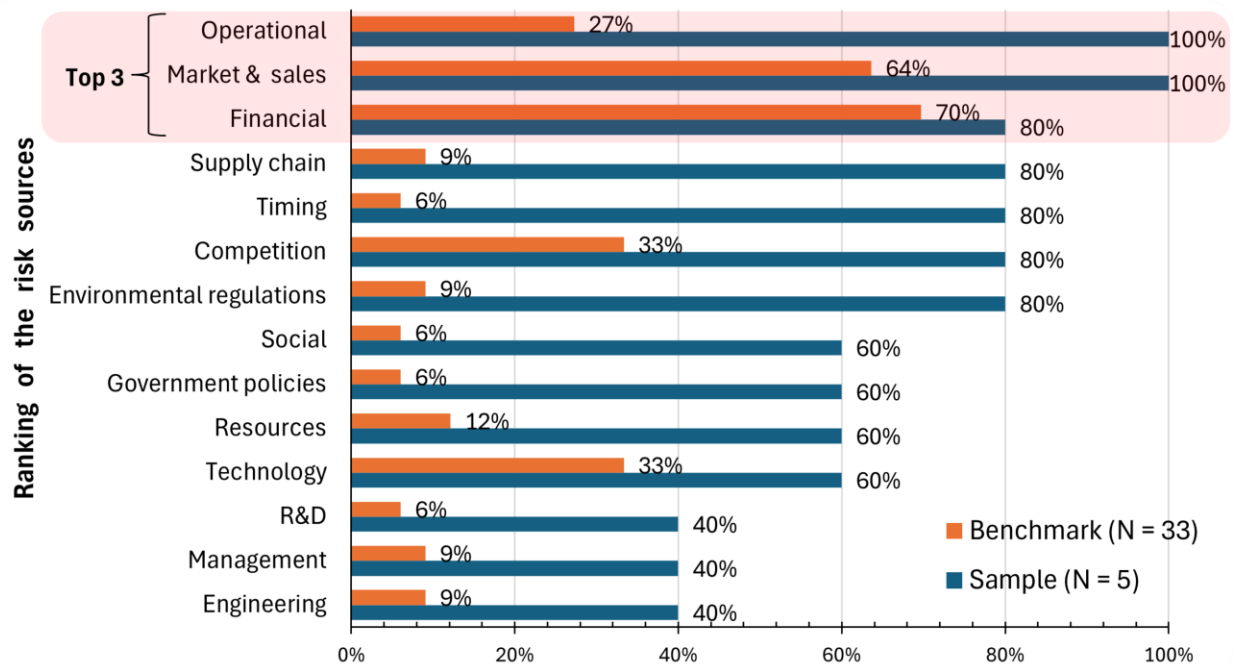


Fig. 2 Specific sources of risk considered by the organization when performing risk assessment ($N = 5$). Blue bars: values from this study. Orange bars: reference values from de Assis et al. (2021). Pink shadow indicates the perceived top 3 sources of risk to consider when performing risk assessment

A key objective of this study was to identify concrete strategies implemented by SMEs and start-ups to mitigate risks (Section 5 of the questionnaire). Participant responses highlighted a spectrum of approaches, ranging from relational and communication-focused practices to more procedural and analytical strategies. Relational mechanisms were strongly emphasized. P1 stressed the role of effective communication and organizational agility, while P5 described open dialogue, continuous monitoring, and reciprocal engagement with producers as critical enablers of trust and resilience across supply chains. These perspectives align with du Plessis & Linke (2022), who identified communication as a cornerstone of effective risk management in dynamic environments. Other participants highlighted more control-oriented strategies. P2 focused on ensuring raw material quality and compliance, underlining the importance of supplier reliability, especially in healthcare-related contexts. P4 described contractual agreements and systematic checks to stabilize supply chains, while P6 combined contractual safeguards with evidence-based methods such as three-point estimation and time management adjustments. Collectively, these contributions illustrate how SMEs employ a hybrid mix of relational, contractual, and analytical practices to balance flexibility with operational stability.

Finally, participants identified the top three benefits of conducting risk assessment. The most important were reducing project failures and developing risk mitigation strategies. Although results differ somewhat from de Assis et al. (2021), where “better understanding of risks for decision-making” was most frequently cited, the findings still show strong alignment on the value of failure reduction and proactive strategy development. Despite the small sample size, these results confirm that SMEs in bio-based industries recognize risk assessment as a key enabler of resilience and continuity.

4.4. Firms Without Formal Risk Assessment

Two participants reported not conducting formal risk assessments (Section 4 of the questionnaire). While they acknowledged the value of having guidelines, they admitted their organizations lacked awareness of the tangible benefits of frequent assessments. Their approach was described as reactive, i.e., “going with the flow”, with risks addressed only after arising. As one participant noted: “We perceive risk on a daily basis... we do not know if we are going to be successful at all with this start-up... but the general perception is that we do not feel that risks are too high.”

This mindset aligns with findings from du Plessis & Linke (2022), who observed SMEs often treat risk management as part of day-to-day operations rather than as a structured process. Similarly, de Araújo Lima et al. (2020) emphasize that while SMEs are more vulnerable due to weaker financial structures and limited flexibility, they often lack proactive risk management, undermining resilience and long-term value creation. The participants' main concern was economic viability, particularly reducing final product costs. Despite this, they did maintain business insurance, reflecting at least some risk awareness. Their perceptions echo Dvorsky et al. (2021), who argue that optimism bias and tolerance for ambiguity often lead managers to dismiss risk assessment as bureaucratic. For early-stage firms, priorities such as fundraising, development, and market entry overshadow risk management unless externally required. Start-ups in biomaterials face further challenges, as many existing frameworks are designed for larger corporations, making them too complex, costly, or resource-intensive. Moreover, codified assessments, i.e., ISO 14971 (2019), tend to focus on technical product risks, often neglecting business or organizational risks. Under evolving EU MDR/IVDR requirements, this gap may expose start-ups to additional vulnerabilities. As argued by Chakabva et al. (2021), SMEs must strategically align resources to operationalize risk management, strengthen resilience, and maintain competitive advantage.

4.5. Perspectives from political and educational stakeholders

To broaden the research scope, two complementary perspectives were included: a political figure from the Straubing–Lower Bavaria region and a medical engineering student. The political interviewee emphasized the central role of renewable resources and sustainability in regional development. Institutions such as the Deggendorf Institute of Technology, the BioCampus, and the Technical University of Munich (TUM) drive innovation, with about 40% of activity concentrated in the Straubing-Sand harbor area. Key R&D efforts focus on bioplastics, polysaccharides, and bio-based scaling processes, while start-ups face persistent capital constraints and market-entry barriers. Public skepticism was noted as a challenge, highlighting the importance of

fostering openness toward sustainable innovations.

Support mechanisms were identified, including shared laboratories, municipal coordination services, and funding from Bavarian and federal sources. Successful regional initiatives, such as a biogas plant initially met with public resistance but later widely accepted during the energy crisis, illustrate how societal acceptance can evolve. Nevertheless, the sustainability ecosystem remains highly funding-dependent, with calls for tax incentives, private investment, and interdisciplinary collaboration to reduce institutional silos. The medical engineering student expressed strong interest in research and further study, while recognizing gaps in risk management education. Although only a few seminars touched upon the subject, the participant intuitively recognized the need for frequent and adaptable assessments. Identified risks included financial, resource, and procurement challenges, alongside barriers in scaling production and ensuring investor confidence. While patents were seen as providing strong competitive protection, the participant stressed the importance of continuous updates about the know-how, policies, and market analysis.

Overall, these insights complement organizational perspectives by showing how policy, education, and individual awareness intersect with SME and start-up realities. They also underline that while institutional support exists, financial, educational, and collaborative gaps remain critical obstacles in advancing risk management practices and biomaterial innovation.

4.6 Barriers in risk management

Section 5 of the questionnaire explored barriers in risk management (Figure 3). The data suggest that IP protection, policy imbalance, technological limitations, and competitors are not perceived as major barriers. Competition is generally low, as most firms face only one or two local or national rivals. Technical barriers were mostly linked to digital infrastructure gaps, requiring capacity growth to match demand. Instead, the most significant barriers identified were financial and logistical. Participants highlighted the challenges of expanding networks, selecting highly specialized suppliers, and managing funding constraints, particularly in early-stage start-ups. Establishing laboratory

infrastructure and diversifying client portfolios were also seen as risky, given the limited resources available to small firms.

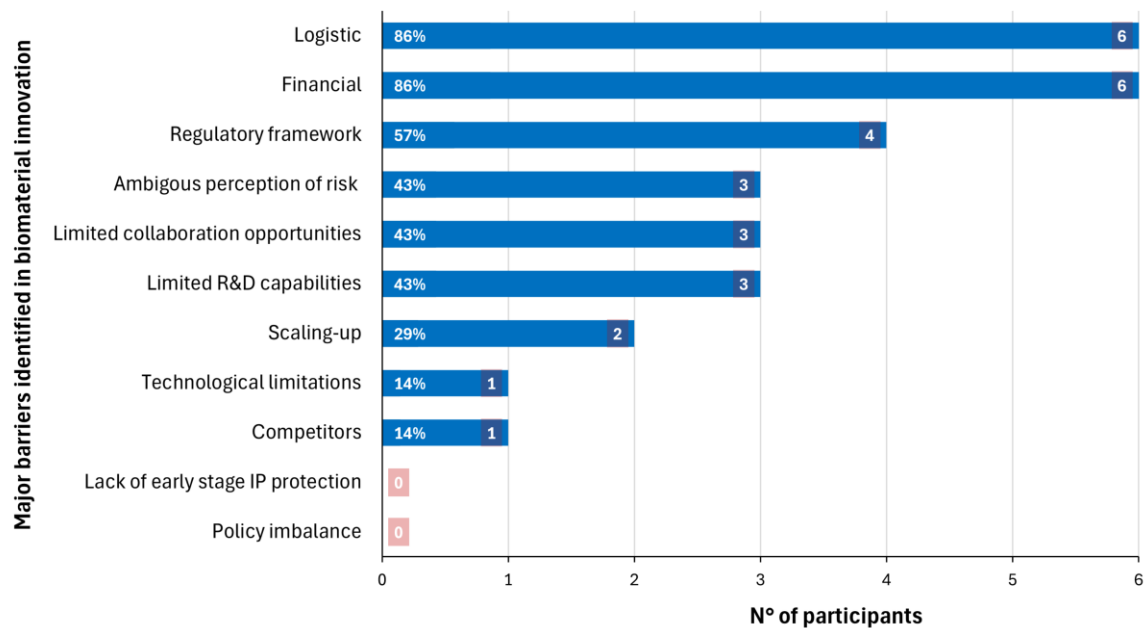


Fig. 3. Identification of major limitations experienced by participants ($N = 7$). Blue bars: number of participants (% values related to the same sample are given as a guide at the beginning of the bars)

One participant noted that regulatory frameworks are not barriers but rather clear guidelines for manufacturing and provider selection, reducing uncertainty. Other barriers frequently cited in the literature, such as limited R&D capacity, weak collaboration, or inconsistent team perceptions of risk, were not consistently confirmed in this study, indicating they may depend heavily on firm type and maturity. Overall, the top three barriers emerging from this study were: (1) Financial limitations; (2) logistical challenges; and (3) regulatory requirements. These findings echo Glowka's et al. (2024) observations that SMEs selectively perceive risks, often underestimating broader issues such as digitalization or climate change.

The authors argue that risk perception itself is a crucial dimension in SME risk management, shaping how firms manage uncertainty and making strategic decisions. Here, future research could explore how different types of barriers interact to form distinctive risk profiles in biomaterial SMEs and start-ups.

5. Discussion

The biomaterials sector is a highly innovative and future-oriented industry with strong growth prospects driven by rising demand for sustainable solutions. For start-ups and SMEs, survival and long-term growth in this uncertain environment

can be significantly enhanced through effective risk management (RM). Insights from diverse stakeholders—including managers, policymakers, and a student—strengthen the practical relevance of this study and demonstrate how tailored, holistic RM approaches improve applicability for small firms. Moreover, the small size of SMEs can be an advantage, enabling faster decision-making and more adaptive responses to disruptions. Several opportunities emerge for biomaterials SMEs. Policy initiatives at national and EU levels can ease financial and regulatory pressures, while collaboration with universities, research institutes, and innovation hubs supports knowledge exchange and joint solution development. The sector also presents scope for SME-specific RM frameworks, addressing a gap in both research and practice. Growing awareness of sustainability and circular economy principles further reinforces the relevance of biomaterials within the global transition toward greener technologies. However, the study also has limitations. The small sample size ($N = 8$) restricts generalizability, and reliance on qualitative data introduces subjectivity. The diversity of biomaterials subsectors is not fully captured, and the absence of longitudinal data limits insights into how risks and mitigation strategies evolve over time. In addition, proposed mitigation measures lack quantitative validation, while SMEs continue to

face challenges such as regulatory complexity, supplier dependence, and underdeveloped enterprise risk management systems.

External threats further challenge the resilience of biomaterials SMEs. Regulatory uncertainty, particularly in medical and biotech applications, high dependence on external funding, rapid technological change, and shifting legislation can destabilize business models. Market uptake is also constrained by consumer skepticism toward novel biomaterial products. Broader global disruptions—such as supply chain shocks, energy shortages, and geopolitical instability—disproportionately affect SMEs due to their limited buffers, underscoring the need for adaptable RM practices. The findings highlight several practical implications. While SMEs often lack resources to implement comprehensive RM systems, RM should be viewed not only as a resilience mechanism but also as a strategic tool for sustainable growth. Collaboration with universities, research centers, and industry partners enables access to expertise and infrastructure, reduces costs, and fosters innovation, with policymakers playing a key enabling role. Financial risk remains central due to long development cycles and uncertain commercialization pathways, requiring integrated funding strategies and proactive engagement with public support schemes. Digitalization—such as real-time monitoring and predictive analytics—offers additional potential for SME-oriented RM solutions. Overall, early and tailored integration of RM into business models is essential for biomaterials SMEs. Scaled-down, flexible tools—such as scenario analysis, SWOT assessments, and supplier evaluations—are often more effective than complex frameworks designed for large firms. Beyond operational concerns, social acceptance and reputational risks must also be actively managed through transparency, stakeholder engagement, and responsible innovation. Innovation ecosystems and shared infrastructures further strengthen RM by enhancing collaboration, legitimacy, and trust, reinforcing the link between effective risk management, sustainability, and successful market integration in the biomaterials sector.

6. Conclusion

Existing research in the biomaterials sector has largely emphasized financial or enterprise-level risk management, leaving a gap in integrated approaches tailored to SMEs and start-ups. This

study addresses that gap by examining current risk management (RM) practices among German biomaterials SMEs and start-ups and demonstrating that RM is a critical determinant of stability, resilience, and long-term viability. While many firms lack formalized frameworks, even structured and simplified RM practices can generate tangible benefits. Importantly, RM should be understood not merely as a compliance tool but as a strategic mechanism that supports sustainable growth and competitive differentiation in resource-constrained organizations (Henschel & Lantzsch, 2022; Guenther et al., 2023).

The findings indicate that operational, financial, and market risks pose the greatest challenges. Key vulnerabilities include feedstock volatility, limited access to capital, dependence on specialized suppliers, and demand uncertainty, while regulatory complexity may constrain innovation despite generally being perceived as supportive. Risk mitigation therefore requires a multi-layered approach combining strategic adaptability with structural responses. Although participants primarily rely on basic tools such as Excel-based analyses, these practices reflect early-stage maturity and may evolve as firms gain experience.

Financial and logistical constraints emerged as the most significant barriers to innovation. Limited capital restricts R&D investment, scaling, and supply chain diversification, while logistical dependencies heighten operational risk. Collaborative solutions—such as strategic partnerships, shared infrastructure, and public-private initiatives—can transform these constraints into collective opportunities (Auer & Rauch, 2021). From a regional perspective, diversified yet technologically related industrial environments foster knowledge recombination and adaptability, enhancing resilience among SMEs operating under high uncertainty (Fornahl & Guenther, 2010). The inclusion of perspectives from policymakers and a student highlights the importance of supportive policy frameworks and human capital development. Targeted public initiatives can ease financial and regulatory constraints, while education and entrepreneurship training are essential for preparing future innovators to navigate scientific and economic uncertainty.

Overall, the study underscores that proactive and holistic RM—combined with collaboration, financial foresight, and stakeholder engagement—is essential for enabling

biomaterials SMEs and start-ups to innovate, scale, and contribute to sustainable technological transitions. Future research should expand sample size, geographical scope, and stakeholder diversity to deepen understanding of financial, regulatory, and societal dimensions shaping innovation and risk management in the biomaterials' ecosystem.

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References

1. Agrawal, R., Kumar, A., Mohammed, M. K., & Singh, S. (2023). Biomaterial types, properties, medical applications, and other factors: a recent review. *Journal of Zhejiang University-SCIENCE A*, 24(11), 1027-1042.
2. Audretsch, D. B., & Guenther, C. (2023). SME research: SMEs' internationalization and collaborative innovation as two central topics in the field. *Journal of Business Economics*, 93(6), 1213-1229.
3. Auer, V. & Rauch, P. (2021). Wood supply chain risks and risk mitigation strategies: A systematic review focusing on the Northern hemisphere. *Biomass and Bioenergy*, 148, 106001.
4. Balaji A.K. & Ponniah V. M. (2023) The role of the patent system in fostering innovation and entrepreneurship. *International Journal of Business Management & Research*, 13(2), 47-52.
5. Balconi, M., Brusoni, S., & Orsenigo, L. (2010). In defence of the linear model: An essay. *Research policy*, 39(1), 1-13.
6. Barta, D.-G., Simion, I., Tiuc, A.-E., & Vasile, O. (2024). Mycelium-Based Composites as a Sustainable Solution for Waste Management and Circular Economy. *Materials*, 17(2), 404.
7. Bao, T., Qian, Y., Xin, Y., Collins, J. J., & Lu, T. (2023). Engineering microbial division of labor for plastic upcycling. *Nature communications*, 14(1), 5712.
8. Belitski, M., Guenther, C., Kritikos, A. S., & Thurik, R. (2022). Economic effects of the COVID-19 pandemic on entrepreneurship and small businesses. *Small business economics*, 58(2), 593-609.
9. Bella, R. L. F., et al. (2024). Small- and Medium-Sized Enterprises: Trends and Future Perspectives for Sustainability and Digitalization in Germany. *Sustainability*, 16(16), 6900.
10. Beltrán-Urvina, L. I., Acosta-Andino, B. F., Gallegos-Varela, M. C., & Vallejos-Orbe, H. M. (2025). Intellectual Property as a Strategy for Business Development. *Laws*, 14(2), 18.
11. Börner, T. & Zinn, M. (2024). Key challenges in the advancement and industrialization of biobased and biodegradable plastics: a value chain overarching perspective. *Frontiers in Bioengineering and Biotechnology*, 12, 1406278.
12. Brassesco, M. E., Cortez, J., Triacca, V., Payen, J., & Bayon, Y. (2024). Translating Ideas into Commercial Biomaterial Devices: A Path to Improving Healthcare. *ACS Biomaterials Science & Engineering*, 10(4), 1910-1920.
13. Chakabva, O., Tengeh, R., & Dubihlela, J. (2021). Factors inhibiting effective risk management in emerging market SMEs. *Journal of Risk and Financial Management*, 14(6), 231.
14. Dammer, L., Carus, M., Raschka, A., & Scholz, L. (2013). Market Developments of and Opportunities for biobased products and chemicals. *nova-Institute for Ecology and Innovation*. Pg 63-68.
15. de Araújo Lima, P.F., Crema, M., & Verbano, C. (2020). Risk management in SMEs: A systematic literature review and future directions. *European management journal*, 38(1), 78-94.
16. de Assis, C.A., et al. (2017). Risk management consideration in the bioeconomy. *Biofuels, Bioproducts and Biorefining*, 11(3), 549-566.
17. de Assis, C. A., Suarez, A., Prestemon, J. P., Stonebraker, J., Carrillo, C., Dasmohapatra, S., ... & Gonzalez, R. (2021). Risk analysis, practice, and considerations in capital budgeting: Evidence from the field for the bio-based industry. *BioResources*, 16(1), 19-45.
18. De Jesus, A. & Mendonça, S. (2018). Lost in transition? Drivers and barriers in the eco-innovation road to the circular economy. *Ecological economics*, 145, 75-89.
19. de Vicente Bittar, A., & Di Serio, L. C. (2023). Do innovation policies support micro and small enterprises to overcome barriers?. *Innovation & Management Review*, 21(2), 137-152.
20. Dellana, S., Rowe, W. J., & Liao, Y. (2022). A scale for measuring organizational risk management maturity in the supply chain. *Benchmarking: An International Journal*, 29(3), 905-930.

21. Detsch, R., Will, J., Hum, J., Roether, J.A., & Boccaccini, A.R. (2018). Biomaterials. In: Kasper, C., Charwat, V., Lavrentieva, A. (eds) *Cell Culture Technology. Learning Materials in Biosciences*. Springer, Cham.
22. Diameh, J. T., Oluwatobi, B. T., Daniels, C., Sunday, O. E., Nelson, C. A., & Quaye, M. (2025). Integrating AI-driven predictive analytics in project risk management to optimize decision-making and performance efficiency. *Int. J. Eng. Technol. Res. Manag*, 9, 373-389.
23. du Plessis, D. G., & Linke, A. (2022). Risk management implementation in SMEs investigated through a lens of ERM maturity models. In *Risk Management: Insights from Different Settings* (pp. 115-139). Cham: Springer International Publishing.
24. Dvorsky, J., Belas, J., Gavurova, B., & Brabenec, T. (2021). Business risk management in the context of small and medium-sized enterprises. *Economic Research-Ekonomska Istraživanja*, 34(1), 1690-1708.
25. Filho, W.L.; et al. (2021) An assessment of attitudes towards plastics and bioplastics in Europe. *Sci. Total Environ.*, 755, 142732.
26. Foli, S., Durst, S., Davies, L., & Temel, S. (2022). Supply chain risk management in young and mature SMEs. *Journal of Risk and Financial Management*, 15(8), 328.
27. Fornahl, D., & Guenther, C. (2010). Persistence and change of regional industrial activities: The impact of diversification in the German machine tool industry. *European Planning Studies*, 18(12), 1911–1936.
28. Glowka, G., Hule, R., & Zehrer, A. (2024). Risk perception of SMEs: strategic risks, family-related risks, external risks. *Risk Manag.* 26, 17.
29. Gonzales-Gemio, C., et al. (2020). Responsible Innovation in SMEs: A Systematic Literature Review for a Conceptual Model. *Sustainability*, 12(24), 10232.
30. Groh, A. P., Guenther, C., Schweizer, D., & Vismara, S. (2025). Entrepreneurial finance in an extended period of crises. *Small Business Economics*, 1-14.
31. Guenther, C., Belitski, M., & Rejeb, N. (2023). Overcoming the ability-willingness paradox in small family firms' collaborations. *Small Business Economics*, 60(4), 1409-1429.
32. Hairon Azhar, N. N., Ang, D. T. C., Abdullah, R., Harikrishna, J. A., & Cheng, A. (2022). Bio-based materials riding the wave of sustainability: Common misconceptions, opportunities, challenges and the way forward. *Sustainability*, 14(9), 5032.
33. Harris, J. J., Lu, S., & Gabriele, P. (2018). Commercial challenges in developing biomaterials for medical device development. *Polymer International*, 67(8), 969-974.
34. Henschel, T. & Lantzsich A. D. (2022) The Relationship Between ERM and Performance Revisited: Empirical Evidence from SMEs. In: Florio, C., Wieczorek-Kosmala, M., Linsley, P. M., & Shrives, P. (Eds.) *Risk management: insights from different settings* (Vol. 20). Springer Cham.
35. Hermann, B.G., Patel, M.K., & Blok, K. (2011). Current policies affecting the market penetration of biomaterials. *Biofuels, Bioproducts and Biorefining*, 5(6), 708–719.
36. Hess, J.R. & Tumuluru, J.S. (2024). Biomass Supply Chain Logistics: Challenges and Technological Advancements. In: Bisaria, V. (eds) *Handbook of Biorefinery Research and Technology*. Springer, Dordrecht.
37. Hilkenmeier, F., Fechtelpeter, C., & Decius, J. (2021). How to foster innovation in SMEs: Evidence of the effectiveness of a project-based technology transfer approach. *The Journal of Technology Transfer*, 1-29.
38. Hughes-Castleberry, K. (2023) Bioengineered spider silk without critters. *Nat Biotechnol* 41, 1665–1667.
39. ISO 13485 (2016) Medical devices - Quality management systems - Requirements for regulatory purposes.
40. ISO 14971 (2019) Medical devices - Application of risk management to medical devices
<https://www.iso.org/obp/ui/en/#iso:std:iso:14971:ed-3:v1:en>
41. Jernström, E., Karvonen, V., Kässä, T., Kraslawski, A., & Hallikas, J. (2017). The main factors affecting the entry of SMEs into bio-based industry. *Journal of Cleaner Production*, 141, 1-10.
42. Jiménez, A., Arrieta, Y., Nuñez, M. A., & Villanueva, E. (2024). Management of strategic risks for the sustainability of SMEs in the manufacturing sector in Antioquia. *Sustainability*, 16(5), 2094.
43. Jurczak KM, van der Boon TAB, Devia-Rodriguez R, Schuurmann RCL, Sjollema J, ..., & van Rijn P. (2024). Recent regulatory developments in EU Medical Device Regulation and their impact on biomaterials translation. *Bioeng Transl Med*.10(2):e10721.
44. Jüttner, U., & Ziegenbein, A. (2009). Supply chain risk management for small and medium-sized businesses. In *Supply chain risk: A handbook of assessment, management, and performance* (pp. 199-217). Boston, MA: Springer US.
45. Kanyepe, J., Musasa, T., & Wilbert, M. (2025). Supply Chain Risk Factors,

- Technological Capabilities, and Firm Performance of Small to Medium Enterprises (SMEs). *Journal of Small Business Strategy*, 35(1), 115–128.
46. Kheir, O., Jacoby, A., & Verwulgen, S. (2022). Risk identification and analysis in the development of medical devices among start-ups: towards a broader risk management framework. *Medical Devices: Evidence and Research*, 349-363.
 47. Kuckartz, U. (2014). Mixed methods: methodologie, Forschungsdesigns und Analyseverfahren. Springer-Verlag, pg. 57-99.
 48. Lopez F, Di Bartolo C, Piazza T, Passannanti A, Gerlach JC, Gridelli B, & Triolo F. (2010) A quality risk management model approach for cell therapy manufacturing. *Risk Anal.* 30:1857-71.
 49. Mahmud MZA, Mobarak MH, Hossain N. (2024) Emerging trends in biomaterials for sustainable food packaging: A comprehensive review. *Heliyon*. 10(1):e24122.
 50. Malesios, C., Dey, P. K., & Abdelaziz, F. B. (2020). Supply chain sustainability performance measurement of small and medium sized enterprises using structural equation modeling. *Annals of Operations Research*, 294(1), 623-653.
 51. Makepa, D.C. & Chihobo, C.H. (2024). Barriers to commercial deployment of biorefineries: A multi-faceted review of obstacles across the innovation chain. *Heliyon*, 10(12).
 52. Manu, T., et al. (2022). Biocomposites: A review of materials and perception. *Materials Today Communications*, 31, 103308.
 53. Mayring, P. (2014). Qualitative content analysis: theoretical foundation, basic procedures and software solution. *Klagenfurt*. Pg. 55-107.
 54. Mechal, D. & Boche, B. (2025). The effect of supply chain risks management practices on operational performance of pharmaceutical manufacturing companies in Addis Ababa, Ethiopia: Analytical cross-sectional study. *PLoS One*, 20(5), e0321311.
 55. Ort, K. & Bronsema, V. (2025). German Biotechnology Report 2025. EY & BIO Deutschland e.V.
 56. Parrilli, M. D., et al. (2023). Environmental innovation across SMEs in Europe. *Technovation*, 119, 102541.
 57. Patshina, M. V., Voroshilin, R. A., & Osintsev, A. M. (2021). Global Biomaterials Market: Potential Opportunities for Raw Materials of Animal Origin. *Food Processing: Techniques and Technology*, 51(2), 270–289.
 58. Pellicer, E., Nikolic, D., Sort, J., Baró, M. D., Zivic, F., Grujovic, N., ... & Pelemis, S. (2017). *Advances in Applications of Industrial Biomaterials*. Cham Springer International Publishing.
 59. Prestwich, G. D., Bhatia, S., Breuer, C. K., Dahl, S. L., Mason, C., McFarland, R., ... & Trounson, A. (2012). What is the greatest regulatory challenge in the translation of biomaterials to the clinic?. *Science translational medicine*, 4(160),
 60. Rajvanshi, J., Sogani, M., Kumar, A., & Arora, S. (2023). Biomaterials: A Sustainable Solution for a Circular Economy. *Engineering Proceedings*, 59(1), 133.
 61. Scheau, C., Didilescu, A. C., & Caruntu, C. (2024). Innovative Biomaterials: The Cornerstone of Next-Generation Medical Solutions. *Journal of Functional Biomaterials*, 15(8), 218.
 62. Song, X., Tang, Z., Liu, W., Chen, K., Liang, J., Yuan, B., ... & Zhang, X. (2022). Biomaterials and regulatory science. *Journal of Materials Science & Technology*, 128, 221-227.
 63. Spring K. & Haase D. (2025) Bioregions as a hub for trends and innovations in life sciences, pg. 34-35, in German Biotechnology Report 2025. EY & BIO Deutschland e.V.
 64. Vishnu, C. R., Sridharan, R., & Kumar, P. R. (2019). Supply chain risk management: models and methods. *International Journal of Management and Decision Making*, 18(1), 31-75.
 65. Weber, M. M. & Kokott, P. (2024). Organizational Resilience and the Attention-Based View of the Firm—Empirical Evidence from German SMEs. *Sustainability*, 16(11), 4691.
 66. Wellenreuther, C., Wolf, A., & Zander, N. (2022). Cost competitiveness of sustainable bioplastic feedstocks—A Monte Carlo analysis for polylactic acid. *Cleaner Engineering and Technology*, 6, 100411.
 67. Williams, D.F. (2009). On the nature of biomaterials. *Biomaterials*, 30(30), 5897-5909.
 68. Williams, E., Cenian, K., Golsteijn, L. et al. (2022) Life cycle assessment of MycoWorks' Reishi™: the first low-carbon and biodegradable alternative leather. *Environ Sci Eur* 34, 120.
 69. Yaradoddi, J.S., et al. (2020) Biodegradable carboxymethyl cellulose based material for sustainable packaging application. *Sci Rep* 10, 21960.
 70. Zhang, X., & Williams, D. (Eds.). (2019). *Definitions of biomaterials for the twenty-first century*. Elsevier. Pg. 15-23.

RESEARCH ON THE AMOUNT OF AVAILABE BIOMASS AND ITS USE

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Abstract: The role of use of renewable sources will continue to grow after 2025, so that electricity production from these sources will account for 40% in 2030. Biomass is seen as a major alternative energy source, widely used around the world. Romania has a biomass potential estimated at 3.3 PJ (7594 thousand toe) per year, which represents 20% of total primary resource consumption in 2020. In order to achieve significant fuel production, it is necessary to use all agricultural land, utilize land left in degradation, and reforest exploited land. Wood covers more than 10% of primary energy demand in many countries in Africa, Asia, Latin America, and Europe (Austria, Finland). China and Brazil have become competitors in the energy market in the field of biomass energy production. Currently, biomass energy is produced through combustion processes and steam turbine power generation, including cogeneration systems.

Keywords: energy density, biomass, wood, briquettes

1. Introduction

The energy produced from biomass in 2023 represents 3.1 x 10⁵ toe (tons of oil equivalent) or 13.6 M for electricity production and 6.2 x 10⁵ toe or 27.2 MJ for heat production. This amount is equivalent to 5% of all energy supplied globally, thereby reducing the greenhouse effect on the environment.

In Europe, renewable energy has an average annual growth rate of 3.4% between 2000 and 2023. Turkey is an energy important country, with more than half of its energy consumption coming from imports.

Energy demand in Turkey has grown by 6-8% in recent years. In 2023, renewable energy sources increased by 15% in terms of energy production, of which biomass accounted for 9%. Another country that has placed a major emphasis on producing energy from renewable sources in Hungary. Recently energy production from alternative sources has begun to grown in Hungary, at a rate of approximately 3.6% with estimates that by the end of 2028 it will reach 4% of electricity production and 10-11% of total energy production will come from renewable sources. During the decomposition of biomass when volatile substances in the biomass evaporate, mineral elements such as magnesium,

aluminum and calcium are found in the remaining ash.

Biomass ash consists of zinc, cadmium, chromium, and magnesium, which are substances that can be affect the environment.

Wood from temperate zone is low in ash, containing around 0.2-1%, trees from tropical zones contain 4% ash. The ash content of wood represents the mineral part remaining after combustion to a constant, at a temperature of 800 °C + 50 °C, of a sample of the material analyzed, incinerated under well-defined conditions.

Ash consists of a moisture of soluble minerals (10-25% of total ash), composed of potassium, chlorides, magnesium, iron and insoluble minerals (75-90%) consisting of silicates, phosphates, oxides and other inorganic chemicals. The ash resulting from biomass is considered a residue containing metal oxides such as potassium oxide, magnesium oxide and sodium oxide.

2. Materials and method

The determination of the calorific value is almost similar to that of coal (as a solid fuel) and with few differences compared to liquid (gasoline, diesel) or gaseous (methane gas, biogas) fuels. The combustion of wood biomass

requires the presence of a flame and oxygen to maintain the combustion process.

A temperature of 300 °C is required for dry wood to reach a state of ignition. Combustion requires a certain amount of air, namely 0.6 kg of oxygen for one kilogram of dry wood.

Wood combustion is a chemical process of decomposition, into its main chemical elements.

The main chemical elements found in wood fuel are carbon, nitrogen, oxygen and minerals for ash. As combustion progresses, the wood catches fire and burns, and the gases formed by combining the chemical elements of the wood

with the elements of mater and oxygen are burned.

Combustion involves a number of stages:

- evaporation of mater;
- ignition;
- thermal decomposition of chemical elements;
- combustion of chemical elements to form combustible gases and combustible gases;
- combustion of combustible gases;
- combustion of carbon.

In figure 1 is presented the sketch of a water heating system

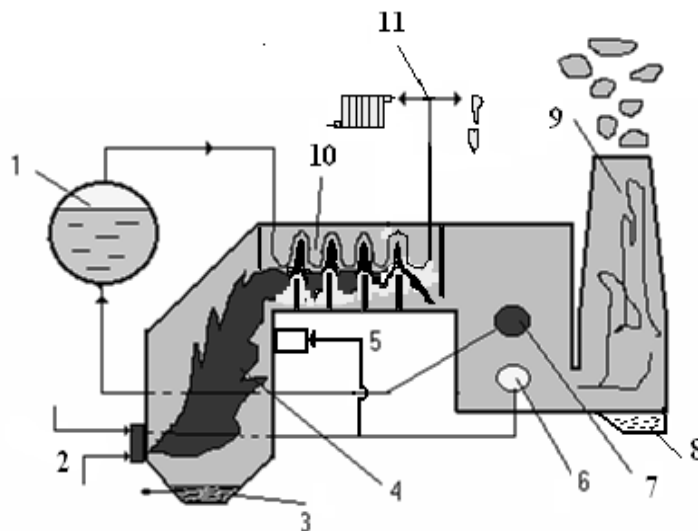


Fig. 1. The sketch of a water heating system

1 - heat water tank; 2 - primary air; 3 - ash grill; 4 - flame; 5 - preheated secondary air; 6 - air direct; 7 - water; 8 - fire ash; 9 - chimney pot; 10 - heat exchanger; 11 - radiator

Determining the calorific value of wood biomass using an explosive combustion calorimeter is a difficult method that requires a long period of time.

Knowing the calorific value of biomass is necessary, in order to calculate the amount of fuel. The prediction can be obtained by the following two methods:

- based on chemical elements;
- based on chemical compounds.

The number of tests required by the regulations is 10 tested samples (ASTM D 3286-96, DIN 51900-1, 2000, Dihoiu, 1995). The installation used to determine the calorific value of woody biomass was the XRY-1C explosive combustion calorimeter, produced by Shanghai Changji Geological Instrument Co.

Before performing the actual test, the calorimeter bomb is calibrated with benzoic acid (benzoic acid with a known calorific value of

26463 kJ/kg is used). Figure 2 shows the working method for perform the test (Figure 2).

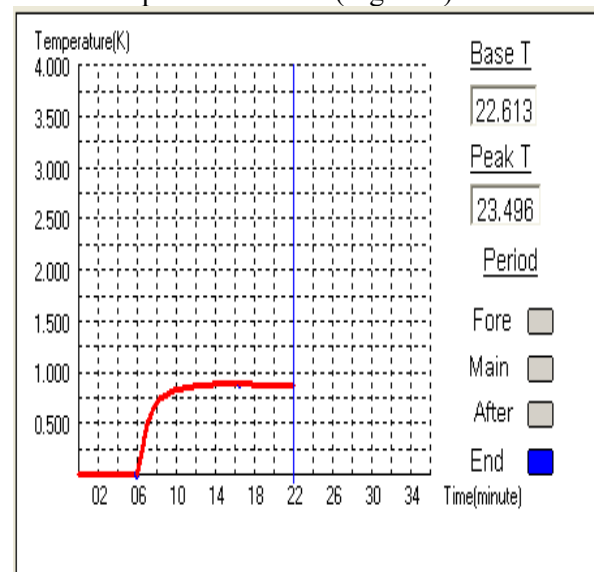


Fig. 2. Working diagram

Figure 3 shows the sketch for calorimeter bomb.

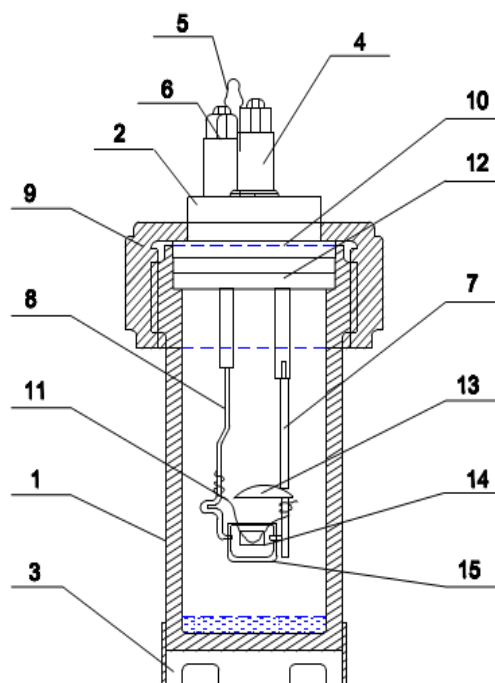


Fig.3. Sketch for calorimeter bomb

The process of determining the calorific value of wood material refers first to the preparation of the raw material and the installation, then to the actual determination and finally to obtaining the fuel results. Preparing the wood material for testing consists of taking a small portion of spruce or sugar cane pellets (0.6-0.8 grams of the whole material).

The weighed sample must have an accuracy of 0.0002 grams. The sample must be clean, made from freshly cut wood because old wood doesn't have all the volatile and flammable substances. This sample is placed in a porcelain crucible and placed in a laboratory oven, in order to dry at 103 ± 2 °C. It is checked by successive weighing until the difference between two successive weighing is less than twice the processing precision.

The test sample 1 is tied to the cotton thread 2 and placed in the bomb crucible 3. Tie the nickel wire 4 to the sample and the cotton thread, then position the protective cap 5 correctly. The crucible is connected to the calorimetric bomb 11 through 2 electrodes 7 and 8. By screwing on the cap of the cylinder 11 is converted to the oxygen cylinder through calorimeter bomb 12, registering 30 atmospheres.

The test contains three different periods, respectively:

- The initial period (fore), which aims to determine the temperature variations, of the water in the calorimeter, due to the exchange of heat with the outside before burning. During this period, usually 5 minutes, the precision thermocouple temperature is displayed and read minute by minute.
- The main period ("main") begins with the ignition of the sample and has as a consequence the increase of the water temperature in the calorimetric vessel, due to the burning of the wood particle and the emission of heat.
- The final period ("after") aims to determine the average temperature variation of the water in the calorimeter due to the heat exchange with the outside, after combustion. For the oak briquettes $U = 0\%$, $m = 0.6854$ g, higher caloric power = 18980 kJ/kg, lower caloric power = 18517 kJ/kg, energy density = 13.47 kJ/cm³, burning speed = 463 kJ/min, $U = 10\%$, $m = 0.3920$ g, higher caloric power = 16704 kJ/kg, lower caloric power = 14820, energy density = 7.12 kJ/cm³, burning speed = 313 kJ/min, $U = 20\%$, $m = 0.1180$ g, higher caloric power = 15612 kJ/kg, lower caloric power = 13287 kJ/kg, energy density = 2.63 kJ/cm³, burning speed = 86 kJ/min, $U = 50\%$, $m = 0.6580$ g, higher caloric power = 10870 kJ/kg, lower caloric power = 4913 kJ/kg, energy density = 1.83 kJ/cm³, burning speed = 47 kJ/min. The variation of the energy density for oak briquettes is presented in Fig. 4.

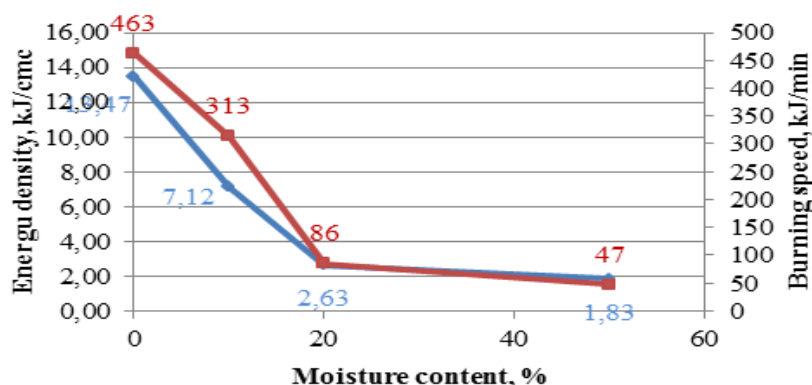


Fig. 4. The variation of the energy density for oak briquettes

For the straw briquettes $U = 0\%$, $m = 0.7860$ g, higher caloric power = 18724 kJ/kg, lower caloric power = 17622 kJ/kg, energy density = 15.48 kJ/cm³, burning speed = 608 kJ/min, $U = 10\%$, $m = 0.5830$ g, higher caloric power = 15795 kJ/kg, lower caloric power = 14984, energy density = 9.04 kJ/cm³, burning speed = 358 kJ/min, $U = 20\%$, $m = 0.5320$ g, higher caloric power = 11983

kJ/kg, lower caloric power = 10421 kJ/kg, energy density = 7.13 kJ/cm³, burning speed = 228 kJ/min, $U = 50\%$, $m = 0.4560$ g, higher caloric power = 2893 kJ/kg, lower caloric power = 2167 kJ/kg, energy density = 1.25 kJ/cm³, burning speed = 24 kJ/min.

The variation of the energy density for straw briquettes is presented in Fig. 5.

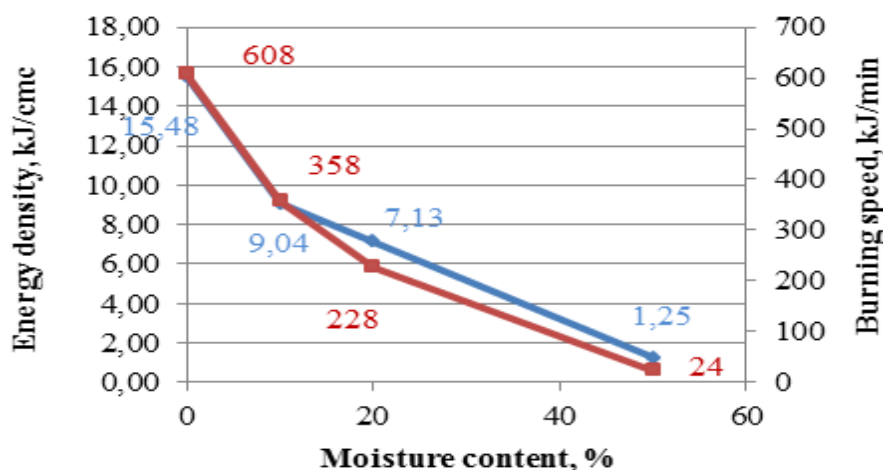


Fig.5. The variation of the energy density for straw briquettes

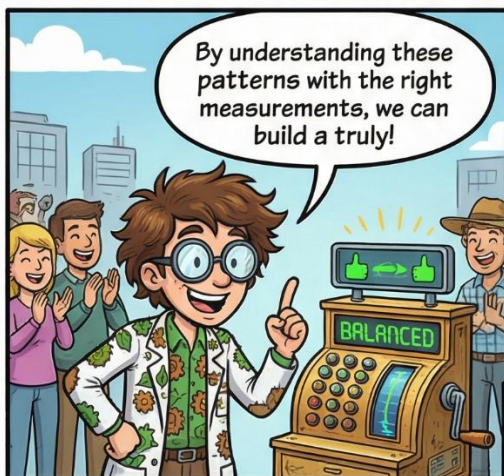
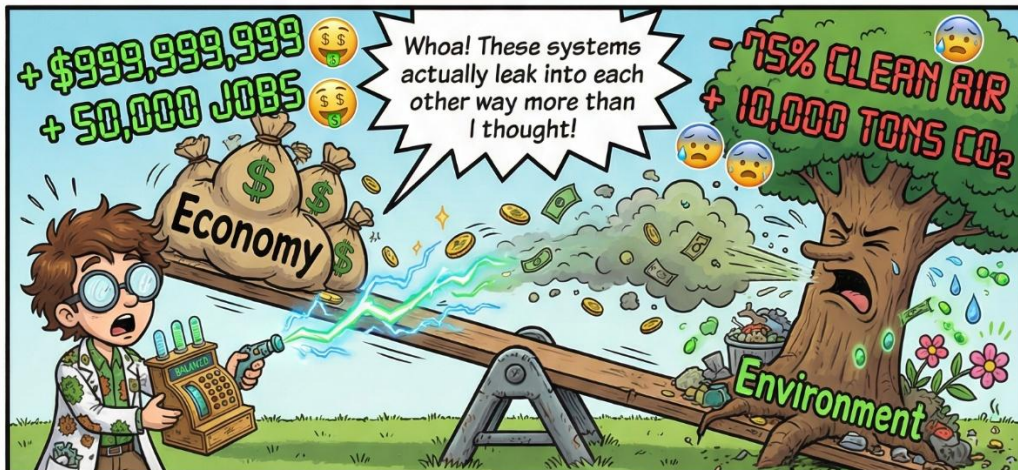
3. Conclusions

Combustion is one of the most important thermal chemical processes for energy production. Combustion processes are only possible in the presence of oxygen, which is introduced into the firebox through combustion air. Increasing the calorific value of biomass through the torrefaction process represents a current research and investment direction in all countries.

References

- Abassi, S.A, Nipanay, P.C., Schaumberg, G.D. Bioenergy potential of eight common aquatic weeds, Biological Wastes, vol.34, No.4, pag.359-366, 1990;
- Doniță, N., Ceianu, I., Purcelan, S, Beldie, A. Ecologie forestieră, Ed. Ceres București, 1977;
- Feng, S., Cheng, S., Yuan, Z., Leitch, M., Xu, C. Valorization of bark for chemicals and materials: A review. Renewable and Sustainable Energy Reviews, vol.26, pag.560-578, 2013;
- Fernandez, L. M.J., Carrasco G.J.E. Suitability of thermo-chemical corrections for determining gross calorific value in biomass, Thermochemica Acta, vol.468, pag.101-107, 2008;
- Filipovici, J. Studiul lemnului, Editura didactică și pedagogică, București, 1984;

6. Friedl, A., Padouvas, E., Rotter, H., Varmuza, K. Prediction of heating values of biomass fuel from elemental composition, *Anal Chim ACTA*, vol.554, pag.191-198, 2005;
7. Gavrilescu, D Energy from biomass in pulp and paper mills, *Environmental Engineering and Management J.*, pag.537-546, 2009;
8. Grîu, T., Lunguleasa, A. Factors of influence combustion. *Proceedings Advances in Environment Technologies, Agriculture, Food and Animal Science, International Conference WSEAS*, pag.143-147, 2013;
9. Grotheim, K. Toorefaction and densification of biomass fuels for generating electricity, *Milestone 9 Report*. Minneapolis: Bepex International LLC, 2011;
10. Haugland, N. Guideline for classification of ash from solid biofuels and peat utilised for recycling and fertilizing in forestry and agriculture, *NT Technical Report*, TR 613, 2013;
11. Hu, X.Y., Dong, C.Q., Yang, Y.P., Zhang, J.J. The effect of biomass pyrolysis gas reburning on N₂O emission in a coa-fired fluidized bed boiler. *Chinese Science Bulletin*, Vol.56, Nr.14, pag.1429-1433;
12. Isabel, M., Jorge, G., Ines, M. Pereira, H. Fractioning and chemical characterization of barks of *Betula pendula* and *Eucalyptus globules*. *Industrial Crops and Products*, vol.41, pag.299-305, 2013;
13. Ionescu. M.F. Biomasa forestieră lemnoasă, un potential energetic nefolosit încă pe deplin de România, anul XX, Nr.36, pag.86-89, 2015;
14. Juran, M. Calitatea produselor, Ed. Tehnică, București, 1973;
15. Lako J., Hanesok J, Yuzhakova T. Biomass-A source of chemicals and energy for sustainable development, *Environmental Engineering and Management Journal*, vol. 7(5), pp. 499-509, 2009;
16. Larsson, S.H., Rudolfsson, M., Nordwaeger, M., Olofsson, L., Samuelsson, R. Effects of moisture content, torrefaction temperature and the temperature in pilot scale pelletizing of torrefied Norway spruce, *Appl. Energy*, vol.102, pag.827-832;
17. Lăzăroiu G, Mihăescu L. Combustion of pitcoal-wood biomass briquettes a boiler test-facility, *Environmental Engineering and Management Journal*, pp 595-601, 2008;
18. Lunguleasa A. The calorific power of wooden biomass, *Bulletin of the Transilvania University of Brasov-Series II*, vol.2(51), pp.65-70, 2010;
19. Mărăscu-Klein, V. Aspects regarding the implemntation of waste products management in Romania, *Revista de inginerie industrială-Recent*. Ed. Universității Transilvania din Brașov, vol.7, Nr.1(16), 2006;
20. Moya R., Tenorio C. Fuelwood characteristics and its relation with extractives and chemical properties of ten fast-growth species in Costa Rica, *Biomass and Bioenergy*, vol.56, pp.14-21, 2011;
21. Nielsen NPK, Gardner D. Importance of temperature, moisture content a species for the conversion process of wood residues to fuel pellets, *Wood Fiber* vol.41, pp 414-425;
22. Pawlicka, A., Waliszewska, B. Chemical composition of selected species of exptoc wood derived from the region of Africa. *Acta Scientiarum Polonorum-Silvarum Calendarum Ratio et Industria Lignaria*, vol.10, Nr.1, pag.37-41, 2011;
23. Petrovici, V.Gh., Agache, C. *Chimia și prelucrarea chimică a lemnului*, Universitatea Transilvania din Brașov, 1999;
24. Prasertsan S., Sajjakulnukit B. Biomass and bioenergy in Thailand: Potential, opportunity and barriers, *Renewable energy*, vol.31, Nr.5, 2006;
25. Rahmann A, Masood, M.A. Influence of size and shape in the strength by briquettes, *Fuel Process Technology*, vol.22, pp125-145,2013;
26. Teuch O, Hofeanuer A, Troger F, From J. Basic properties of specific wood-based materials carbonised in a nitrogen atmosphere, *Wood Science and Technology*, Springer, vol.38, nr.3, 2004;
27. Spirchez, C., et al. (2017). Influence of microwave sterilization on the lignocellulosic biowaste streams conversion process using *Pleurotus* sp. *Romanian Biotechnological Letters* Vol., No. x, 2017.
28. Spirchez, C., Lunguleasa, A., Gaceu, L. (2019). Researches on grape husk waste obtained from the winery and its use as pellets for combustion. *Wood Res*, 64, 549-556.
29. Spirchez, C., Lunguleasa, A., Prună, M., Gaceu, L., Forfotă, R., Dumitrache, I. (2019). Research on the Calorific Value of the Hardwood Species. *Acta Technica Corviniensis-Bulletin of Engineering*, 12(1), 111-114.
30. Uslu A, Faaji A.P.C, Bergman P.C.A Pre-treatment technologies, and their effect on international bioenergy supply chain logistics. *Techno-economic evaluation of torrefaction, fast pyrolysis and pelletisation*, *Energy*, vol. 33(8), pp. 1206-1223.



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