



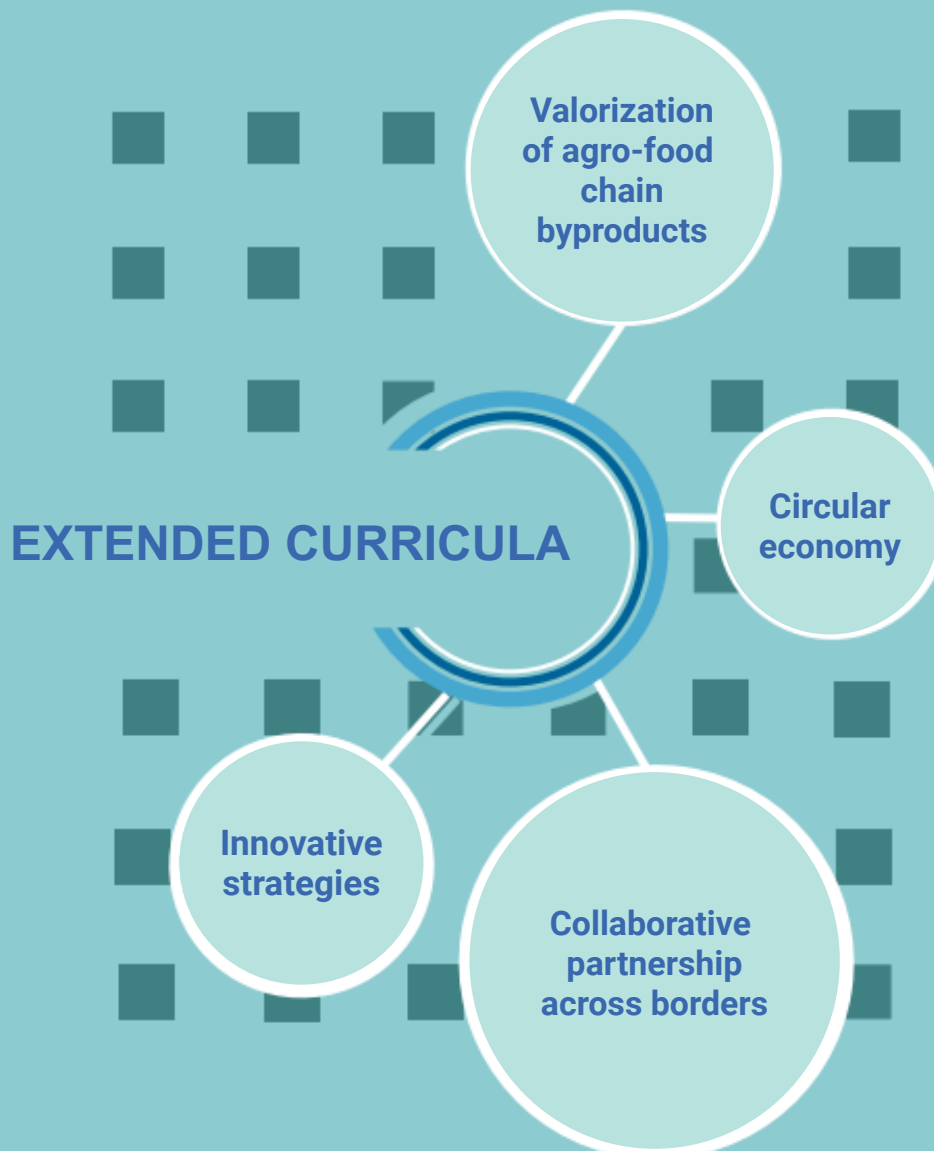
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Project Reference: 2024-1-R001-KA220-HED-000246776

# Enhancement of Agro Food Chain Byproducts through Innovative and Sustainable Methods

eAfoBy



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Objectives	<p>The curriculum establishes the cognitive skills and abilities necessary to experts and specialists regarding the agro food chain by-products management. The objective is to improve the knowledge of students and specialists in the field of agro food chain by-products enhancement through innovative and sustainable methods in order to promote innovation and best practices in agro-food valorization. This knowledge enhances the capacity of students and specialists to address complex challenges in agriculture, food production, control and food safety, food technologies and human nutrition requirement.</p>
Cognitive skills	<p>The curriculum outline the cognitive skills and competencies essential for handling agro food chain byproducts with a central role on nutrition, food safety, food control and new sustainable methods valorization. The curriculum highlight the scientific and technical knowledge about agro food chain byproducts from each country to the trainers, in term of source generation, amount generated by year, current strategies used in each country for their valorization, the agro food chain byproducts impact on the environment, climate and sustainable resources.</p> <p>Cognitive skills development should be aligned with critical thinking, problem-solving, sustainability awareness, and technical expertise.</p> <ol style="list-style-type: none"> <li>1. Analytical Thinking <ul style="list-style-type: none"> <li>Evaluating byproduct utilization in agro-food chains</li> <li>Assessing sustainability challenges and opportunities</li> <li>Identifying inefficiencies in current byproduct management systems</li> </ul> </li> <li>2. Problem-Solving Skills <ul style="list-style-type: none"> <li>Developing innovative solutions for waste reduction and repurposing</li> <li>Designing sustainable processing methods for byproducts</li> <li>Addressing environmental and economic impacts</li> </ul> </li> <li>3. Research and Inquiry <ul style="list-style-type: none"> <li>Conducting scientific research on agro-food waste management</li> <li>Applying biochemical and technological principles to byproduct enhancement</li> <li>Analyzing case studies and real-world applications</li> </ul> </li> <li>4. Decision-Making and Strategic Thinking</li> </ol>





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	<p>Weighing economic, environmental, and social factors in byproduct valorization</p> <p>Selecting appropriate technologies for sustainable processing</p> <p>Integrating circular economy principles into agro-food chains</p> <p>5. Digital and Technological Literacy</p> <p>Utilizing digital tools for byproduct analysis and optimization</p> <p>Applying data-driven approaches to sustainability practices</p> <p>Understanding automation and smart technologies in agro-food processing</p> <p>6. Interdisciplinary Collaboration</p> <p>Engaging with experts from food science, agriculture, engineering, and business</p> <p>Applying cross-disciplinary knowledge to enhance sustainability</p> <p>Developing communication skills for knowledge-sharing and policymaking</p> <p>7. Creativity and Innovation</p> <p>Generating novel applications for agro-food chain byproducts</p> <p>Exploring bio-based product development</p>
<p>Professional skills</p>	<p>The professional skills should be in line with the current requirements of the agri-food industry, sustainability and circular economy.</p> <p>Technical and scientific skills</p> <p>1. Application of the principles of biochemistry and biotechnology in the valorization of by-products</p> <p>Identifying and using modern technologies for processing and reusing agri-food by-products</p> <p>Quality control and food safety of by-product products</p> <p>2. Innovation and product development skills</p> <p>Creating new sustainable products based on agri-food by-products</p> <p>Use of innovative methods of extraction and transformation of bioactive compounds</p>





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	<p>Development of eco-friendly packaging and environmentally friendly technologies</p> <p>3. Economic and resource management skills</p> <p>Application of circular economy principles in agri-food</p> <p>Evaluation of the economic feasibility of by-product valorization processes</p> <p>Planning and optimization of the supply chain and distribution of the products obtained</p> <p>4. Sustainability and environmental protection skills</p> <p>Implementation of strategies to reduce food waste and agri-food waste</p> <p>Assessment of the environmental impact of recovery processes</p> <p>Development of sustainable agricultural and industrial practices</p> <p>5. Digital skills and the use of advanced technologies</p> <p>Using artificial intelligence and sensors to optimize recycling and reuse processes</p> <p>Data analysis to improve the efficiency of the agri-food chain</p> <p>Familiarization with software and equipment specific to the agri-food industry</p> <p>6. Research and development skills</p> <p>Conducting studies and experiments to improve the valorization of by-products</p> <p>Application of scientific methods for testing and validation of new products</p> <p>Publication and dissemination of agri-food research results</p> <p>7. Interdisciplinary communication and collaboration skills</p> <p>Working in multidisciplinary teams for the implementation of innovative projects</p> <p>Presenting and promoting sustainable solutions to stakeholders (farmers, processors, consumers)</p> <p>Developing partnerships between academia and industry</p>
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<p>Competence units</p>	<p>Competence units can be structured to cover technological, economic, sustainability and research aspects.</p> <ol style="list-style-type: none"> <li>1. Analysis and characterization of agri-food by-products <ul style="list-style-type: none"> <li>Identification and classification of agri-food by-products</li> <li>Assessment of the chemical composition and nutritional potential of by-products</li> <li>Application of physicochemical and microbiological analysis methods</li> </ul> </li> <li>2. Innovative technologies for capitalizing on by-products (agro food chain by products valorisation) <ul style="list-style-type: none"> <li>Implementation of bioconversion methods (spontaneous fermentation, controlled fermentation, solid state fermentation, anaerobic digestion, enzymatic pretreatments)</li> <li>Application of bioactive compound extraction technologies (supercritical CO<sub>2</sub>, ultrasound, microfiltration, enzymatic-assisted extraction, microwave-assisted extraction, pressure-based extraction techniques, steam explosion, subcritical water extraction, pressurized liquid extraction, pulsed electric field extraction, high voltage electrical discharge)</li> <li>Use of sustainable processing techniques (dehydration, microencapsulation, fermentation, bioconversion, nanotechnologies)</li> </ul> </li> <li>3. Sustainable product and packaging development <ul style="list-style-type: none"> <li>Manufacture of new food products based on agro food chain by-products</li> <li>Development of biodegradable and edible packaging</li> <li>Testing and validation of innovative agro food chain by-product products</li> </ul> </li> <li>4. Circular economy and resource management <ul style="list-style-type: none"> <li>Application of circular economy principles in agri-food</li> <li>Optimization of the value chain of sub-production</li> <li>Evaluation of the economic feasibility of reuse processes</li> </ul> </li> <li>5. Environmental impact and sustainability of processes <ul style="list-style-type: none"> <li>Life cycle analysis of by-products and environmental impact</li> </ul> </li> </ol>
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	<p>Implementation of waste and carbon reduction strategies</p> <p>Enforcement of environmental rules and legislation on the use of agri-food by-products</p> <p>6. Research and innovation in the agri-food sector</p> <p>Development of research projects to capitalize on by-products</p> <p>Application of scientific methods for testing and validating innovative solutions</p> <p>Publication and dissemination of results in the agri-food field</p> <p>7. Food quality and safety management</p> <p>Application of contaminant traceability and control methods</p> <p>Risk management and compliance with legal regulations</p> <p>8. Interdisciplinary communication and collaboration</p> <p>Developing skills for working in multidisciplinary teams</p> <p>Presenting and promoting innovative solutions to industry and consumers</p> <p>Creating partnerships between academia and the agri-food sector</p>
<p>Elements of innovation</p>	<p>The elements of innovation must integrate advanced technologies, circular economy concepts and sustainable solutions.</p> <p>1. Advanced technologies for the valorization of agri-food by-products</p> <p>Emerging biotechnologies: the use of enzymes, microorganisms and genetic engineering to turn waste into value-added products.</p> <p>Environmentally friendly extraction processes: green methods such as supercritical CO<sub>2</sub> extraction, ultrasonic extraction and microfiltration for the recovery of bioactive compounds.</p> <p>Nano and microencapsulation: protecting and stabilizing bioactive compounds for use in the food and pharmaceutical industries.</p> <p>2. Creating innovative products from agri-food by-products.</p> <p>Functional ingredients: development of dietary supplements, prebiotics and probiotics from agri-food by-products.</p>





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	<p>Bio-based materials: production of bioplastics, biodegradable packaging or sustainable textiles from agri-food waste.</p> <p>3.Sustainability and circular economy</p> <p>Agri-food upcycling: transformation of by-products into premium value-added products (e.g. fruit peels transformed into antioxidant powders).</p> <p>Zero Waste Farming: integration of agricultural production systems that use all resources without generating waste.</p>
<p>The impact</p>	<p>The "Enhancement of Agro Food Chain Byproducts through Innovative and Sustainable Methods" curricula has a multi-dimensional impact, influencing environmental sustainability, economic development, technological innovation, and education.</p> <p>1. Environmental Impact</p> <p>Reduction of agro-food waste: Encourages the efficient utilization of byproducts, reducing landfill waste and lowering greenhouse gas emissions.</p> <p>Promotion of circular economy: Supports sustainable practices by converting waste into valuable resources.</p> <p>Decreased pollution: Reduces soil, water, and air contamination through eco-friendly waste management technologies.</p> <p>2. Economic Impact</p> <p>Creation of new business opportunities: Encourages the development of startups and industries focused on waste valorization.</p> <p>Cost reduction for agro-food companies: Helps businesses minimize disposal costs and generate profit from byproducts.</p> <p>Job creation: Supports employment in green and sustainable industries.</p> <p>3. Technological and Scientific Advancements</p> <p>Development of innovative processing techniques: Introduces advanced extraction, fermentation, and bioconversion technologies.</p> <p>Encouragement of research and innovation: Promotes interdisciplinary studies for sustainable agro-food chain improvements.</p>





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	<p>4. Social and Educational Impact</p> <p>Empowerment of future professionals: Equips students with knowledge and skills in sustainability, innovation, and food science.</p> <p>Increased public awareness: Promotes responsible consumption and waste reduction in society.</p> <p>Collaboration with industry and policymakers: Bridges the gap between academia, industry, and governmental bodies for impactful policy changes</p>
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## EXTENDED CURRICULUM

### Chapter 1. Introduction - Classification of agro-food by-products

Agro-food by-products, such as peels, seeds, stems, bagasse, kernels, and husks, are produced during food processing. Typically, these by-products have been discarded and sent to landfills due to their excessive production and the lack of sustainable management practices, leading to various environmental, social, and economic challenges. These by-products represent valuable bioresources, as they possess significant compositional and nutritional properties, being rich in functional and bioactive compounds beneficial to human health. They can be repurposed to create new food ingredients or products for human consumption, facilitating their complete utilization and reintegration into the food supply chain. This aligns with the circular bioeconomy model, resulting in revenue, business opportunities, and employment (Gómez-García, R.; et al., 2021)

The classification of agro-food by-products in the context of enhancing agro-food chain byproducts through innovative and sustainable methods can be based on different criteria such as source, composition, utilization potential, and processing methods.

#### 1. Classification by Source

- Plant-based By-products: Derived from fruits, vegetables, cereals, legumes, and oilseeds.
- Fruit and vegetable peels, seeds, and pomace (e.g., orange peels, apple pomace, tomato skins) (Difonzo et al., 2022)
- Cereal bran and husks (e.g., wheat bran, rice husk, corn cobs) (Anal & Panesar, 2021)
- Oilseed meals (e.g., soybean meal, rapeseed meal, sunflower cakes) (Fernandez F., 2024)
- Animal-based By-products: Derived from meat, dairy, and fish processing industries.
- Meat and bone meal, offal, blood, collagen, gelatin (Gómez-García, R.; et al., 2021)





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- Whey from dairy processing (Anal & Panesar, 2021)
- Fish waste (heads, bones, skin, viscera) (Fernandez, 2024)

## 2. Classification by Composition

- Carbohydrate-rich By-products: fruit pomace, cereal bran, potato peels (Difonzo et al., 2022)
- Protein-rich By-products: oilseed meals, fish waste, meat processing residues (Anal & Panesar, 2021)
- Lipid-rich By-products: spent cooking oil, fish oil by-products (Gomez-Garcia, 2021)
- Fiber-rich By-products: husks, fruit peels, lignocellulosic biomass (Fernandez, 2024)
- Bioactive Compound-rich By-products: polyphenol-rich grape pomace, carotenoid-rich tomato peels (Gomez-Garcia, 2021)

## 3. Classification by utilization potential

- *Food and Feed Applications:*
  - Functional food ingredients (dietary fiber, antioxidants) (Difonzo et al., 2022)
  - Animal feed (oilseed meals, fish waste) (Anal & Panesar, 2021)
- *Bioenergy and Biofuel Production:*
  - Biogas production (anaerobic digestion of organic waste) (Triviño-Pineda, A.-S.;2024)
  - Bioethanol and biodiesel production (lignocellulosic biomass, spent oils) (Mujtaba, M.; 2023)
- *Biopolymers and Biodegradable Packaging:*
  - Extraction of bioplastics (e.g., starch, chitosan, cellulose) (Inayatul M,2025)
- *Pharmaceutical and Cosmetic Uses:*
  - Extraction of bioactive compounds (polyphenols, flavonoids, proteins) (Fernandez, 2024)
- *Composting and Soil Amendments:*
  - Organic fertilisers and soil enhancers (e.g., composted fruit and vegetable waste) (Difonzo et al., 2022)





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#### 4. Classification by Processing Methods

- Mechanical Processing (Grinding, milling, pressing) (Anal & Panesar, 2021)
- Biological Processing (Fermentation, enzymatic hydrolysis) (Gómez-García, R.; et al., 2021)
- Chemical Processing (Extraction with solvents, acid/alkaline hydrolysis) (Fernandez, 2024)
- Thermal Processing (Drying, pyrolysis, torrefaction) (Difonzo et al., 2022).

#### Chapter 2. Technical knowledge about agro food chain byproducts from each country, in term of source generation, amount generated by year, impact on the environment, climate and sustainable resources).

Losses arising from processing and production activities within the agri-food sector are estimated to account for approximately 30% to 80% of the total yield, contributing to as much as 1.3 billion metric tons of food waste annually (Brennan, 2024), as depicted in Figure 1. According to Rațu, R.N. et al., 2023, agro-food by-products can be categorized according to the stage of the food chain in which they are generated, as follows (Fig 1):

Primary agricultural production:	Agro-food processing:	Distribution and trade:	Final consumption:
stems, leaves, husks, crop residues, animal manure;	fruit and vegetable peelings, pits, tescovine, cakes, bagasse, molasses;	expired or damaged products, non-compliant packaging;	food waste, prepared and uneaten food.

**Figure 1.** Classification of agro-food chain byproducts.

Approximately one-third of all food produced globally is either lost or wasted across the supply chain. Cereal processing constitutes a major contributor to global food loss, with an estimated 35% of cereal grains lost or wasted throughout the supply chain and 12.9% of all



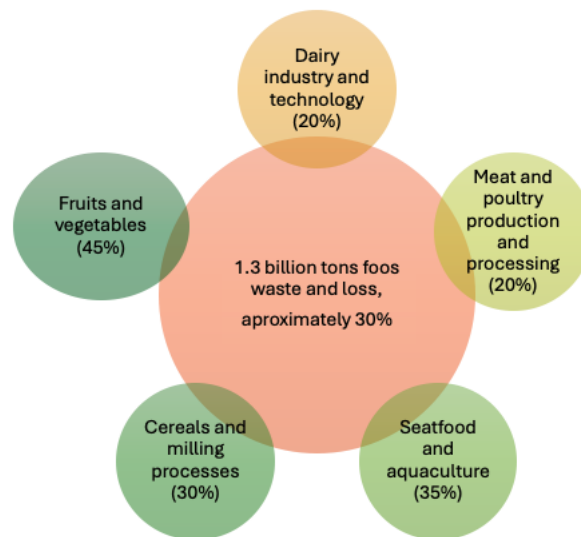


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food waste globally (Sharma et al., 2025), (Fărcaș et al., 2022). These losses occur across multiple stages, including pre-harvest and post-harvest handling, storage degradation, losses due to mycotoxin contamination, and waste at the consumer level (Sharma et al., 2025). A comprehensive analysis by the Joint Research Centre (JRC) indicates that the top seven EU countries—France, Germany, Poland, Italy, Spain, the United Kingdom, and Romania—account for roughly 75% of the EU-28’s total crop residue production (approximately 323 Mt per year), primarily from cereals, oilseeds, and permanent crops ([publications.jrc.ec.europa.eu](https://publications.jrc.ec.europa.eu)).



**Figure 2.** Estimated Global Annual Food Loss and Waste by Primary Sector (adapted and modified from Brennan et al., 2024)

Table 1 displayed the main byproducts identified in Romania, Spain and Italy, their source generation, environmental impact and quantities generated by year at a worldwide level as their valorization opportunities.





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**Table 1. Main identified byproducts in Romania, Spain and Portugal**

By-Product	Source generation	Estimated Annual Volume	Environmental Impact	Valorization Opportunities	References
Crop residues	Harvesting, milling processes, cleaning grain process, rice parboiling process,	~7.7 billion t/year (82.6% of global harvested biomass)	GHG emissions from open burning; soil erosion; particulate pollution	Biochar, biofertilizers, lignocellulosic bioenergy, biogas	Lefavre et al., 2023, Fărcas et al., 2022
Brewer spent grain	Beer brewing process	~40 million tons worldwide/year	Methane/CO <sub>2</sub> emissions from decomposition	Protein/fiber ingredients; in food production (pastries, breads, crackers, muesli, extrudates), biogas, food packaging, bioplastics - polyhydroxyalcanates (PHA); bioethanol, animal feed	Chetrariu 2020, Petit et al., 2020,
Fruit & vegetable waste	Postharvest handling, transportation inefficiencies, quality standards,	~1.3 billion t/yr	Landfill methane; nutrient leaching	Industrial applications (textile industry, chemical industry, renewable energy, health industry, food industry), natural pigments, encapsulation	Rapa et al., 2024, Ramzan et al., 2025, Ingale et al., 2025





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Apple pomace	Apple processing (juice, jam, vinegar, cider)	~4 Mt/yr	High moisture spoilage; high COD in effluents	Pectin; polyphenols; dietary fiber; vinegar; probiotic matrix, biogas, propionic acid, bioethanol, pharmaceutical industry, food industry	Vlad et al., 2022, Farcas et al., 2022, Pascoalino et al., 2025
Plum by-products	Plum processing (juice, nectar, jam, dried plum, alcoholic and non-alcoholic beverage)	≈5–8 Mt/yr	Phenolic-rich leachates; seed toxicity	Bioactive oils; edible films from kernel proteins, cosmetics, pharmaceutical and food industries, biofuel	Aaqib Sheikh et al., 2023, Ahmed et al., 2023, Rodríguez-Blázquez et al., 2024, Katnic et al., 2022.
Olive pomace	Olive extraction oil	~40 Mt/yr (primarily EU)	Soil/water contamination via phenolics which make them non-biodegradable and phytotoxic	Bioactive extracts; prebiotic oligosaccharides; food industry biochar, bioenergy, cosmetics, wastewater treatment, pharmaceutical, food packaging materials, food human and animal supplement's	Gomez-Cruz et al., 2023; Enaine et al., 2023; Fotiadou et al., 2024, Loschi et al., 2024





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Winery by-products	Wine technological process	~14 Mt/yr	High phenolic load affecting soil and water quality; significant wastewater (lees) effluents, groundwater contamination with risk on human and aquatic population	Extraction of polyphenols, tartaric acid, dietary fiber; production of wine lees yeast extract, anaerobic digestion for biogas; bioactive-enriched packaging films, biodegradable plastic, metal adsorbent, animal feed (ruminants)	Karastergiou et al., 2024; Matias et al., 2025
Citrus residues	Citrus processing (juice, jams, different fruit formulations,	~15–25 Mt/yr 56Mt/year UE fruit processing industries from which 2.5 Mt/year orange	Acidic residues; limonene toxicity; high COD/BOD, low pH	D-limonene; pectin; flavonoids; biopolymers, active film packaging, possible plastic substitute, food industry, bioethanol production, animal feed	Manakas et al., 2025; Rawat et al., 2024; Andrade et al., 2023
Coffee byproducts	Coffee industry	~ 10 millions of coffee husk waste	Methane release, CO <sub>2</sub> , contribute to the global warming, toxic phytochemical compounds	biosorbents for water treatment, food ingredient, cosmetics, fertilizer, bioethanol, biomass, biochar, food packaging	(Choe, 2025; Costa et al., 2025; Oliveira et al., 2021; Tamilselvan et al., 2024)





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Microalgal by-products	Agar, alginate, carrageenan production	Microalgal dry biomass: ~50,000 t/year; Spirulina ~12,000 t, Chlorella ~6,600 t. Residual streams (post-extract) likely tens of thousands of tonnes.	Large-scale disposal of fibrous seaweed wastes can burden coastal ecosystems or landfills	Valorisation via biogas, biofertilizers, and biorefining mitigates waste while delivering added-value products.	(Abreu et al., 2023), (Zhang et al., 2024), (Bojorges et al., 2023.)
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GHG – greenhouse gases; COD -chemical oxygen demand; BOD -biochemical oxygen demand.



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### **Chapter 3- National and European legislation regarding the valorization and storage of agro-food chain byproducts.**

Reducing and preventing food waste is increasingly recognized as an important and impactful way to reduce the ecological footprint of the food system and achieve a sustainable and resilient food system, contributing to global food and nutrition security (Wunder et al., 2018).

It is now well known that food industries generate huge amounts of lignocellulosic by-products from the processing of beer, wine, sugar cane, coffee sugar, vegetables and fruits, among others, which are generally rejected as waste and often considered environmental pollutants. These food by-products include a wide range of shells, seeds, stems, roots, pulp residues, bagasse and husks, which, despite their nutritional value, are still rejected by the industries (Gómez-García et al., 2021).

Globally, the current disposal and mismanagement of agro-food by-products have demonstrated a negative impact on the environment and on social and economic sectors (Gómez-García et al., 2021). In addition to the high social and economic costs, food losses and waste contribute to climate change, with a global carbon footprint of approximately 8% of total global anthropogenic greenhouse gas emissions, and represent a waste of limited resources such as land, energy and water (Wunder et al., 2018).

In this case, the environment is contaminated by greenhouse gas emissions, as these organic materials are often simply disposed of in landfills or burned to avoid the accumulation of microorganisms, parasites and pests (Gómez-García et al., 2021).

Furthermore, these current food waste management strategies, including landfilling, incineration, composting and animal feeding, are not considered sustainable or environmentally friendly strategies. These management strategies also involve the social





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sector, since some respiratory diseases can occur due to toxic pollutants released into the air, decreasing the quality of human life (Gómez-García et al., 2021).

On the other hand, from an economic point of view, the concept of circular economy has promoted appropriate strategies for the management and valorization of these by-products to reduce pollution and promote sustainable bioeconomic growth across industries, designing and creating new revenue streams. Such improvements could be achieved through a full valorization of these food biowastes, as they retain a high content of bioactive molecules with added value, which could be extracted and used as new industrial raw materials, as they have been shown to possess several bioactive applications (Gómez-García et al., 2021).

Food by-products are a source of many useful bioactive compounds, dietary fibers, fatty acids and proteins, which have great potential in the development of new food products and the promotion of the circular economy and sustainability (Knežević N. et al., 2021).

The EU, through initiatives such as the European Green Deal and the Farm to Fork Strategy, has sought to address these challenges by encouraging sustainable agricultural practices. Despite these efforts, the successful implementation of such policies faces two significant challenges: insufficient regulation in some areas and overly strict regulation in others. On the one hand, the absence of clear and standardized regulatory frameworks for the recovery of agricultural waste has hindered the full integration of agri-food residues into a circular economy (Nicastro R. et al., 2024).

Agricultural waste, which includes residual biomass from food production and processing, represents an untapped resource for bio-based products such as bioenergy, bioplastics and biofertilizers. Despite the promising potential of these products, regulatory frameworks such as the EU Directive 2008/98/EC on waste have struggled to provide clear guidance for the recovery of these materials (Nicastro R. et al., 2024).

### **3.1. European legislation on the recovery and storage of by-products from the agri-food chain**

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### **Ø EU Regulation 2017/625**

This regulation sets out rules for official controls along the agri-food chain to ensure compliance with food safety, animal health, and plant health rules.

### **Ø EU Regulation 2019/1009**

This regulation provides a legal pathway for specific recovered products like struvite and biochar, but there is a need for more comprehensive legislation for other bio-based materials.

### **Ø EU Directive 2008/98/EC on waste**

This directive promotes the waste management hierarchy, encouraging prevention, reuse, recycling and energy recovery, and sets requirements for the management of food waste, including in the agri-food sector.

### **Circular Economy Package (2018)**

- Includes legislative changes to promote reuse and recycling, particularly in the agri-food sector.
- Target: reduce food waste by 50% by 2030.

The circular economy is a key part of the European Union strategy for sustainable growth. It focuses on reducing waste, reusing materials and improving resource efficiency. As part of the European Green Deal, the Circular Economy Action Plan aims to close material loops and reduce dependence on finite resources. This approach could not only support environmental objectives, but would also boost innovation, create jobs and strengthen the EU economy, helping to achieve climate neutrality by 2050. However, a delay in clear legislative action has hindered the shift towards sustainable agricultural practices, in particular as regards regulatory frameworks supporting circular economy models in agriculture (Nicastro R. et al., 2024).





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### **3.2. National Romanian legislation on the valorization and storage of by-products from the agri-food chain**

#### **Ø Law no. 211/2011 on the waste regime**

Law No. 211/2011 was repealed by Emergency Ordinance No. 92/2021, which transposes the requirements of Directive 2008/98/EC on waste and Directive (EU) 2018/851. Under this law, by-products were defined as substances or objects resulting from a production process whose main objective was not their production, but which met certain conditions, such as certain and legal subsequent use, without being subjected to further processing.

#### **Ø Law no. 217/2016 on reducing food waste**

Law no. 217/2016 regulates measures to prevent and reduce food waste in the agri-food chain. Economic operators in the agri-food sector are obliged to take measures to prevent food waste at all stages of food production, processing, storage, distribution and marketing. The measures provided for include:

- Selling products close to expiration at a reduced price.
- Transferring food through donation or sponsorship for human consumption.
- Directing by-products not intended for human consumption to authorized processing units.
- Transforming agri-food products that have become unfit for human or animal consumption into compost or biogas.
- Directing products remaining after completing the previous stages to authorized neutralization units.

This law was amended by Law No. 49/2024.

**Law No. 49/2024**, adopted in March 2024, introduces the obligation for all operators in the agri-food sector to take measures to prevent food waste, in order to achieve the objective of reducing food waste by 50% by 2030.





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### **Ø Law no. 249/2015 on the management of packaging and packaging waste**

Law no. 249/2015 regulates the management of packaging and packaging waste, establishing measures for the prevention of waste production, the reuse of packaging, recycling and other forms of its recovery. Economic operators in the agri-food sector are responsible for the collection and recovery of packaging waste generated, including through recycling or reuse, in accordance with the principles of the circular economy.

### **Ø Government Decision No. 51/2019**

Government Decision no. 51/2019 approves the Methodological Norms for the application of Law no. 217/2016. These norms establish the measures to prevent food waste in the agri-food chain and the responsibilities of economic operators in this regard. It also establishes the obligation for economic operators to implement at least two measures to prevent food waste before ordering the neutralization of the food waste generated.

Law No. 217/2016 and the amendments brought by Law No. 49/2024 are in line with European regulations on the management of by-products in the agri-food chain. They promote the prevention of food waste, the protection of public and animal health, and support the transition to a circular economy in the agri-food sector.

### **Ø Order No. 168/2023 of the National Sanitary, Veterinary and Food Safety Authority (ANSVSA)**

This order regulates the official control of establishments that process, store, transport, exploit and market products of non-animal origin, in accordance with the European Regulations on food hygiene and official controls.

### **Ø Emergency Ordinance no. 92/2021 regarding the waste regime**

Emergency Ordinance No. 92/2021 regulates waste management in Romania, including in the agri-food sector. It requires economic operators in the agri-food sector to take measures to





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prevent food waste, prioritizing the use of food products for human consumption, and if this is not possible, for animal feed or for recovery through compost or biogas.

### 3.3. Portugal national legislation on the valorization and storage of by-products from the agri-food chain

Table 2 displayed the main Portuguese national legislation.

Directive (Decreto-Lei)	Date	Scope	Key Provisions	References
Decreto-Lei n.º 102-D/2020 Novo Regime Geral da Gestão de Resíduos (nRGGR)	10 Dec 2020	Waste management and by-product valorization	<ul style="list-style-type: none"> <li>- Defines criteria for classifying by-products (Art. 5)</li> <li>- Requires separate storage and intended further use</li> <li>- Enables valorization via composting, anaerobic digestion, animal feed, energy recovery</li> </ul>	<a href="https://diariodarepublica.pt/dr/detalhe/decreto-lei/102-d-2020-150908012">https://diariodarepublica.pt/dr/detalhe/decreto-lei/102-d-2020-150908012</a>
Decreto-Lei n.º 152-D/2017	11 dec 2017	Consolidated Waste Management Systems Regime)	<ul style="list-style-type: none"> <li>Regulates organic waste flow, including packaging waste and bio-waste</li> <li>- Mandates separate collection and potential recovery of biodegradable agri-food waste</li> </ul>	<a href="https://diariodarepublica.pt/dr/detalhe/decreto-lei/152-d-2017-114337042">https://diariodarepublica.pt/dr/detalhe/decreto-lei/152-d-2017-114337042</a>

### 3.4. Spanish national legislation on the valorization and storage of by-products from the agri-food chain

Table 3 highlighted the main Spanish national legislation

Legal Instrument	Date	Scope	Key Provisions	Official Reference (BOE)
Ley 7/2022, de 8 de abril	8 Apr 2022	Waste and contaminated soils for a circular economy	Defines 'byproduct' and end-of-waste criteria; establishes waste management hierarchy	<a href="https://www.boe.es/buscar/act.php?id=BOE-A-2022-5809">https://www.boe.es/buscar/act.php?id=BOE-A-2022-5809</a>
Real Decreto 1528/2012, de 8 de noviembre	8 Nov 2012	Animal by-products not intended for human consumption	Transposes EU Regulation 1069/2009; regulates collection, storage, use of animal by-products	<a href="https://www.boe.es/buscar/doc.php?id=BOE-A-2012-14165">https://www.boe.es/buscar/doc.php?id=BOE-A-2012-14165</a>
Orden TED/92/202	8 Feb 2022	Classification of olive pomace	Administrative conditions for declaring olive mill	<a href="https://www.boe.es/diario_boe/txt.php?id=BOE-A-2022-2328">https://www.boe.es/diario_boe/txt.php?id=BOE-A-2022-2328</a>





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2, de 8 de febrero		residues as by-products	residues as by-products (non-waste)	
Ley 1/2025, de 1 de abril	1 Apr 2025	Prevention and valorization of food loss and waste	Framework for reduction, separation, and valorization of agri-food losses and surplus	<a href="https://www.boe.es/buscar/doc.php?id=BOE-A-2025-6597">https://www.boe.es/buscar/doc.php?id=BOE-A-2025-6597</a>

#### Chapter 4. Current strategies used in each country for agro-food chain byproducts valorization

**Romania** has been actively developing and implementing strategies to valorize byproducts from the agro-food chain, aiming to reduce waste, promote sustainability, and support the circular economy.

A key strategy involving the extraction of valuable bioactive compounds (such as polyphenols, vitamins, and antioxidants, etc.) from agri-food by-products, which supports the use of by-products such as apple pomace and chestnut peel for high-value applications, was performed in the period 2017-2023, at the National Institute of R&D for Biological Sciences, Romania. The project facilitated the transfer of knowledge and technology from the research institute to small and medium-sized enterprises (SMEs), especially those in the agriculture and agro-food sectors, producers of phyto-pharmaceuticals, nutritional supplements, natural beverages, and manufacturers of biomass extraction equipment (<https://proiecte.incdsb.ro/FITOCOMP/#scop>).

A solid example of innovative valorization of agri-food by-products in Romania can be exemplified by several recent projects. One of them is reported by UASVM Bucharest, the project focuses on the development of a Good Practices Code for food processing into dried products and natural additives or colorants, focusing on the creation of extracts and powders from underutilized fruit peels, pulps or whole fruits to reduce waste and increase the competitiveness of suppliers. Moreover, with outcomes including training sessions for farmers and processors, as well as dissemination through workshops, conferences and specialized

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platforms. The geographical balance among this project participant from Central, Eastern, Northern, and Southern Europe will ensure the project's relevance both throughout the EU and beyond (SUSORGPLUS, 2025 <https://www.susorgplus.eu/about>).

Start in January 2025, METROFOOD-RO EVOLVE project builds solid research and testing infrastructure in by-product valorization, and ADER 16.1.2 operationalizes these opportunities through a One Health certification scheme. Project funded through the Strategic Plan on Agriculture and Rural Development (ADER), focusing on the development of a national certification scheme for products and feed in the spirit of the One Health concept - integrating human, animal and environmental health. Both projects, carried out by IBA Bucharest, mark major steps towards sustainable, innovative, and regulated valorization of agro-food by-product resources in Romania. (<https://bioesurse.ro/blogs/media/conferin%C8%9Ba-lansarea-proiectului-metrofood-ro-evolve-29-ianuarie-2025>).

Another project running during 2021–2023, "Eco-sustainable bio-conversion of brewers spent grain towards complete valorization", aims to develop an innovative, eco-sustainable bioconversion system for the complete valorization of brewery spent grain (BSG), one of the most abundant by-products in the brewing industry (<https://ancafarcas.wixsite.com/sustainable-pce/disemination-2021-2023>)

Financial and strategic support is provided through instruments such as the National Rural Development Program (PNDR)—notably Sub-Measure 4.2—and the National Strategic Plan for Agriculture and Rural Development 2023–2027. These programs offer funding for technologies and infrastructure dedicated to the processing and reuse of agro-industrial by-products, directly supporting their valorization within a circular economy framework (<https://www.madr.ro/planul-national-strategic-pac-post-2020.html>). Finally, the broader policy context is shaped by Government Decisions no. 870/2013 and no. 942/2017, which establish Romania's integrated strategy for waste management, explicitly recognizing the role

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of agricultural and food sector residues in achieving sustainability goals. (<https://legislatie.just.ro/Public/DetaliiDocument/196382>)

In **Spain**, CARTIF is a private, non-profit applied research center established in 1994 at the University of Valladolid. Its core mission is to deliver innovative, cross-sectoral solutions that enhance industrial processes, systems, and products, thereby boosting competitiveness and fostering new business opportunities. On the other side, AGROALNEXT, financed by NexGenerationEU funds had a topic entitled *Comprehensive utilization of agri-food waste and its application in the development of active biodegradable packaging for food* (RES4PACK) where researchers at the Polytechnic University of Valencia are valorizing almond shells and grape stems from winemaking to obtain antioxidant and antimicrobial bioactive extracts, along with cellulosic materials for active food packaging—advancing circular economy goals. 3P-PACK. Actively compostable packaging made from banana peel for food packaging is another project based on agro-food chain valorization (<https://foodupv.webs.upv.es/proyectos-realizados/>).

In **Portugal**, Sovena group integrates olive-oil production with biodiesel and by-product valorization. Olive pomace and seeds are used to extract bioactive compounds or converted into bioenergy, while Cerealis group engages in valorization of cereal husks and bran—using them in fiber-rich ingredients, feed, or energy applications. FeedValue (INIAV), IntegraValor, Centre BIO: Bioindustries, Biorefineries, and Bioproducts, VALOR+, CircularTech are only some projects aiming to sustain agro-food chain valorisation (<https://blc3.pt/projects.php>)





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## Chapter 5. Assessment of the chemical composition and nutritional potential of by-products

The agri-food industry is one of the sectors generating the most organic waste. Many of these by-products have a rich nutritional composition of bioactive compounds, essential nutrients and fiber, yet they are often discarded without recovery, which contributes to environmental degradation and the waste of resources. According to the Food and Agriculture Organization of the United Nations (FAO, 2014), a large amount of food is lost or wasted globally along the supply chain.

Adopting sustainable management practices that priorities waste prevention, loss minimization, and the valorization of by-products and co-products is essential to achieving the goals of the 2030 Agenda for Sustainable Development. Such approaches promote the sustainability of food systems, help to mitigate malnutrition and encourage economic growth by optimizing the use of natural resources (Gómez-García et al., 2021; Despoudi et al., 2021). In this context, scientific and technological research, conducted in collaboration with companies in the sector, has played a central role in the characterization and valorization of agro-industrial waste, with the aim of safely and efficiently reintegrating it into the food chain (Leong & Chang, 2022; Özcan et al., 2023; Ritika et al., 2024).

### By-products of olive oil production

Olive oil production generates large volumes of by-products. These have a significant environmental impact. This is particularly the case in Mediterranean countries. The main residues are olive pomace, washing water and solid residues such as leaves and branches.

Olive pomace, consisting of skins, pulp and pits remaining after oil extraction, contains high levels of phenolic compounds, soluble and insoluble dietary fibres, and bioactive fatty acids. Recent studies have demonstrated its antioxidant, anti-inflammatory and antimicrobial properties, and it is considered a promising functional ingredient for use in foods, nutritional





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supplements and cosmetics (Nunes et al., 2018; Nunes et al., 2019; Nunes et al., 2021; Sousa et al., 2023).

However, the wastewater from the extraction process is rich in phenolic compounds and has a high organic load, posing a significant environmental challenge. However, it has been investigated as a potential source of natural antioxidants for use in the food, cosmetics and pharmaceutical industries (Nunes et al., 2016). Additionally, anaerobic digestion can produce biogas and convert these effluents into alternative energy sources (Hamdi, 1996; Bani Kheiredine et al., 2022; Vaz et al., 2024).

Lignocellulosic waste, such as leaves and branches, can be valorised by extracting bioactive compounds such as oleuropein and other polyphenols, which have been used in traditional medicine and are now found in nutraceutical products. Composting is also a viable method of producing organic fertiliser (Erbay & Icier, 2010; Yangui et al., 2021; Michailides et al., 2011).

### **By-products of wine production**

Wine production generates high volumes of waste, including grape pomace (composed of skins and seeds), particularly in producing countries such as Portugal, France, Italy and Spain. The composition of these by-products varies depending on the grape variety, the type of wine, and the technological process used.

Pomace from red wine production generally has a higher concentration of phenolic compounds due to prolonged contact with the skins during fermentation. The most relevant of these compounds are flavonoids, anthocyanins, proanthocyanidins and phenolic acids, which give them high antioxidant activity (García-Lomillo & González-SanJosé, 2017; Ilyas et al., 2021).

The seeds are particularly valued for their lipid content. They are a source of oils rich in unsaturated fatty acids. These acids include linolenic, oleic and palmitic acids. The seeds have emollient properties. They also have proven benefits for cardiovascular health. Promising applications in the food, cosmetics and pharmaceutical industries have been identified for these





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oils, as well as the phenolic extracts obtained from the seeds, with properties including anti-obesity, hypolipidemic, antimicrobial and intestinal microbiota regulating effects being demonstrated (Ferreira & Santos, 2022; Yang et al., 2021; Liu et al., 2020; Talebi et al., 2023; Ajit et al., 2021; Unusan, 2020).

### **By-products of the fruit processing industry**

The processing of fruit in industry creates different types of organic waste, such as peels, pulp, seeds and stalks. These have the potential to be used in food and technology. In particular, peels are rich in polysaccharides, phenolic compounds and dietary fibres with antioxidant activity (Nirmal et al., 2023; Teshome et al., 2023; Fierascu et al., 2020).

Among the compounds of interest is pectin, a structural polysaccharide with gelling, emulsifying and stabilising properties that is widely used in the food, cosmetics and pharmaceutical industries. Studies have identified alternative sources of pectin in melon, kiwi and pomegranate peels. These yields are comparable to traditional commercial sources (orange and apple) (Güzel & Akpınar, 2019; Picot-Allain et al., 2020; Frosi et al., 2023).

In addition to pectin, citrus waste contains significant amounts of sugars, organic acids, amino acids, proteins, essential oils, flavonoids and vitamins. These by-products have been successfully used to develop functional foods such as probiotic yoghurts that are both microbiologically beneficial and acceptable to consumers (Sharma et al., 2017; Dosoky & Setzer, 2018; Dias et al., 2020).

### **Coffee production by-products**

Coffee is one of the most widely consumed and valued beverages in the world. Its quality is determined by a variety of factors, including botanical variety, geographical origin, processing methods and storage conditions. Throughout the various stages of coffee bean processing, particularly during harvesting, processing and roasting, several by-products with high potential for valorisation are generated.





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Various agro-industrial residues are identified in fruit processing. These include immature and defective beans resulting from sorting and washing processes. Other residues include pulp and parchment, which are associated with wet processing. Then there are the husks obtained from the dry method. Silver skin is released during roasting. Finally, coffee grounds are produced when the beverage is prepared. (Alves et al., 2017; Murthy & Naidu, 2012). Of these by-products, coffee pulp is notable for its high content of bioactive compounds, fibre and caffeine, which give it antioxidant properties and beneficial effects on metabolic parameters. Its nutritional and functional profile has led to its recent inclusion in the ‘novel foods’ category by the European Food Safety Authority (EFSA, 2021).

Several studies have highlighted the potential of coffee pulp in the formulation of functional foods and nutritional supplements that can modulate lipid metabolism, control glycaemia and prevent metabolic diseases such as obesity and diabetes (Pérez et al., 2023; Gil-Ramírez et al., 2024; Rungraung et al., 2023; Bashir et al., 2024). Other relevant by-products, such as coffee grounds, contain significant amounts of phenolic compounds with antioxidant properties, and are being investigated for use in the food, cosmetics, and biomaterials industries (Saratale et al., 2020).

## **Chapter 6. Innovative technologies for agro food chain by-products valorization. Use of innovative methods of extraction and transformation of bioactive compounds**

The growing generation of agri-food by-products represents a significant environmental challenge, but also a valuable opportunity for the valorisation of bioactive compounds with potential applications in the food, cosmetic and pharmaceutical industries. By-products such as olive pomace and coffee silverskin contain high levels of phenolic compounds, organic acids, vitamins and dietary fibre. However, we must develop and apply innovative technologies to efficiently, safely and sustainably extract these compounds. This chapter looks at the main technological advances applied to the extraction and transformation of bioactive compounds





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from agro-industrial by-products. The focus here is on sustainable and green chemistry methods.

The conventional methods used are mostly based on the process of solid-liquid extraction, which involves the use of organic solvents like ethanol or methanol, often mixed with water. For instance, hydroethanolic solvents (1:1) at 40 °C for 60 minutes have been shown to effectively extract antioxidant compounds from olive pomace (Nunes et al., 2018). In the case of coffee silverskin, Costa et al. (2012) optimised extraction with 50% (v/v) ethanol-water, using an experimental design to maximise the yield of total antioxidant and phenolic compounds. While these techniques offer good yields, they are generally time-consuming, energy-intensive and solvent-intensive, and are not always compatible with the principles of green chemistry.

One of the most recent technological approaches is ultrasound-assisted extraction (UAE), which uses ultrasonic waves to promote acoustic cavitation and facilitate cell rupture and the release of bioactive compounds. Using only water as a solvent, this technique has been shown to allow phenolics to be recovered from olive pomace in just 5 minutes, achieving higher yields to those of conventional 60-minute aqueous extraction (Nunes et al., 2018). UAE has also been used to obtain coffee silverskin extracts with prebiotic properties (Machado et al., 2024).

Another promising technique is multi-frequency multimode modulated (MMM) technology, which combines multiple frequencies and vibration modes to increase extraction efficiency. Advantages such as eliminating the need to grind the sample and using water as a solvent are offered. In studies with coffee silverskin, greater recovery of antioxidants was allowed for in just 10 minutes by MMM technology, compared to the classic 60-minute extraction (Puga et al., 2017). Furthermore, this technology has been successfully scaled up to a pilot level while maintaining the quality of the extracts (Peixoto et al., 2022).





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The application of membrane systems (nanofiltration and reverse osmosis) allows the selective concentration of bioactive compounds and the separation of fractions with different applications. In the case of olive pomace, a patented integrated green extraction process was used, followed by membrane-assisted concentration, with the permeate fraction being used for irrigation at the same time (Nunes et al., 2019).

Other emerging approaches include microwave-assisted extraction, supercritical fluids, pulsed electric fields and high-voltage electrical discharges. These techniques have shown great potential in terms of efficiency, requiring low energy and reducing processing time while preserving the integrity of bioactive compounds (Soares et al., 2024).

Comparing the different methods applied to various agri-food by-products improves our understanding of the advantages and limitations of each approach. For example, in the case of coffee silverskin, conventional extraction using a 50% ethanol-water solution at 60 °C for 30 minutes maximised the recovery of phenolic compounds and antioxidant activity (Costa et al., 2012). Ultrasound-assisted extraction (UAE) in an aqueous medium allowed the production of extracts rich in soluble fibre and chlorogenic acids, providing prebiotic benefits (Machado et al., 2024). MMM technology, which does not require grinding, can provide a higher yield of compounds such as chlorogenic acid and caffeine in just 10 minutes with high energy efficiency (Puga et al., 2017; Peixoto et al., 2022).

Regarding olive pomace, conventional hydroethanolic extraction at 40 °C for 60 minutes resulted in the recovery of 487  $\mu\text{g}$  GAE/mL of phenolic compounds (Nunes et al., 2018). Using only water as a solvent and extracting for just 5 minutes, UAE obtained 402  $\mu\text{g}$  GAE/mL, achieving a higher yield than conventional aqueous extraction (257  $\mu\text{g}$  GAE/mL). The application of integrated green technology using membranes enabled the separation and concentration of phenolic compounds and tocopherols (Nunes et al., 2019). The results demonstrate that, while conventional methods can provide satisfactory results, innovative





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techniques are distinguished by their rapidity, environmental friendliness and high efficiency in extracting bioactive compounds, even under less extreme conditions.

The resulting extracts were incorporated into micro- and nanolipid carrier formulations (Fathi et al., 2022) to enhance the stability, bioavailability and delivery efficiency of active compounds. These formulations demonstrated adequate release profiles and are compatible with applications in food supplements and cosmetics. Additionally, silverskin extract exhibited antidiabetic potential by inhibiting intestinal glucose and fructose transport (Peixoto et al., 2022), as well as a prebiotic effect in promoting *Lactocaseibacillus paracasei* growth (Machado et al., 2024).

Technologies such as ultrasound-assisted extraction (UAE), multi-frequency multimode modulated (MMM) and membrane processes are highly promising for the valorisation of agri-food by-products, enabling the efficient, sustainable and economical extraction of bioactive compounds. These approaches align with the principles of the bioeconomy and the circular economy, thereby contributing to environmental sustainability and the development of innovative, functional products. Future studies should focus on optimising operational parameters and scaling up processes for industrial use.





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## **Chapter 7. Innovative and bio-sustainable methods of agro food chain byproducts valorization Implementation of bioconversion methods (spontaneous fermentation, controlled fermentation, solid state fermentation, anaerobic digestion, enzymatic pretreatments)**

Innovative and bio-sustainable methods of agro food chain byproducts valorization  
Implementation of bioconversion methods

Sustainable development goals need to be regenerative in order to promote sustainable approaches in food production and waste management with zero waste and functional food production to the well-being through food. The valorization of agro-food byproducts through innovative and bio-sustainable methods is critical to enhancing resource efficiency, reducing environmental impact, and promoting circular bio economies (Soccol et al., 2017).

Spontaneous and controlled fermentation techniques utilize native or selected microbial cultures to transform food residues into valuable products such as organic acids, enzymes, and bioactive compounds (Simone et al., 2023). Controlled fermentation with *Lactobacillus* spp and *Saccharomyces* spp. can convert fruit and vegetable pomace into probiotics, natural preservatives, and functional food ingredients (López-Gómez et al., 2020). Solid-state fermentation uses fungi to produce enzymes, pigments, and proteins on agro-waste substrates like cereal bran or fruit peels, offering an eco-friendly alternative with minimal water use.

Spontaneous fermentation consists in a natural fermentation process without added starter cultures, relying on native microbiota. Is commonly used for fruit and vegetable waste and other substrates for microbiota proliferation. Typically occurs in open tanks or fermenters under ambient conditions. Other interests of spontaneous fermentation are pomaces of olive, grape and other by-products rich in antioxidants that can gain with metabolites produced as for example short chain fatty acids relevant in gut health and general well-being. It interest as low-cost and the need of minimal infrastructure. The negative issues associated have to do with





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unpredictable results, spoilage and contamination risk. Also, variability in microbial activity and product quality can be important in achieving typical “terroir” associated products.

The characterization of typical microbiota of the products makes light in this approach of transforming a waste in value added by-products, important in terms of functional food production and regenerative waste management and development.

Controlled Fermentation, corresponds to fermentation using selected starter cultures to ensure consistency and safety, using substrates as fruit pomace, vegetable peels, cereal byproducts, dairy waste and it has the characteristics:

- Need of Controlled pH, temperature, oxygen levels using fermenters or bioreactors.
- The cultures used are typically bacteria as *Lactobacillus* spp. and yeasts as *Saccharomyces cerevisiae*.
- The benefits are the consistent production of bioactive compounds, enzymes, organic acids, used in developing functional foods and natural preservatives.

Some examples are: lactic acid fermentation of carrot peel to develop antimicrobial compounds for food packaging or feed.

Solid-State Fermentation -consists in fermentation on solid substrates with minimal free water, ideal for fungal cultures.

- Is adequate for agro-wastes like rice husk, fruit pomace, or wheat bran used as substrate.
- Inoculated with fungi like *Aspergillus niger*, *Rhizopus* spp., *Trichoderma* spp.
- Carried out in trays, columns, or packed-bed bioreactors.
- The benefits are the efficient production of enzymes, mycoprotein, flavor compounds, organic acids.
- Low water use, energy efficient.





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The challenges: difficult to scale and control temperature/humidity.

Anaerobic Digestion transforms organic residues such as fruit peels, vegetable waste, and manure into renewable biogas and nutrient-rich digestate (Kumar et al., 2021). Is another type of microbial breakdown of organic matter in absence of oxygen, producing biogas and digestate.

Common inputs:

- animal manure, vegetable waste, fruit peels, slaughter waste, wastewater treatment plants sludge.
- Requires sealed digesters with temperature control (mesophilic or thermophilic).
- Byproducts: methane-rich biogas and nutrient-rich digestate (used as fertilizer).

Benefits:

- Generates renewable energy and reduces greenhouse gas emissions.
- Digestate improves soil fertility and closes nutrient loops.

Challenges:

- Needs pretreatment for lignocellulosic biomass.
- Inhibition due to high-fat or acidic feedstocks.

As an Example:

- Anaerobic digestion of potato peel and dairy waste in co-digestion systems for biogas and compost.

Enzymatic Pretreatments - use of enzymes (cellulases, amylases, proteases) to break down complex polymers (cellulose, lignin, proteins) into fermentable units.





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#### Implementation:

- Applied to agro-wastes like straw, hulls, fruit pomace, or brewer's spent grain.
- Enzymes can be added before fermentation or digestion to enhance yield.

#### Benefits:

- Increases bioavailability of nutrients or fermentable sugars.
- Enables high-value product recovery (bioethanol, protein hydrolysates).
- Requires careful pH, temperature optimization.

#### Example:

Cellulase pretreatment of citrus peel improves bioethanol production or enhances soluble fiber extraction for food enrichment.

#### Integration Potential: Combined Bioconversion Approaches

##### Examples

- Enzymatic hydrolysis of fruit pomace → releases sugars.
- Controlled fermentation of hydrolysate using *Lactobacillus* → produces lactic acid.
- Remaining solids → solid state Fermentation to produce enzymes or biopolymers.
- Residue → anaerobic digestion for biogas and compost.

In general, these approaches aim to transform a waste into value added by-products with advantage for well-being.





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## Chapter 8 – Innovative and sustainable methods of agro food chain byproducts valorization

In the food industry, thermoplastic extrusion is classified as a High-Temperature, Short-Time (HTST) processing technology, as it facilitates the production of a broad spectrum of food and feed products with minimal modifications to the core equipment, provided that process parameters are appropriately controlled (Abilmazhinov et al., 2021).

Extrusion cooking offers several notable advantages, most prominently its ability to transform low-cost raw materials into a wide array of value-added products within short processing times. This method supports consistent, high-throughput production via a continuous and energy-efficient system (Offiah et al., 2018).

Extrusion systems can be operated under low, medium, or high shear conditions, depending on the characteristics of the input materials and the desired properties of the final product. Thermoplastic extruders are generally employed under high shear conditions. Low-shear, or cold extrusion, is commonly applied in the manufacture of products such as pasta and restructured meat items (Abilmazhinov et al., 2021).

Agricultural residues can be effectively utilized in the development of value-added products through extrusion processing, a highly versatile and energy-efficient technology capable of accommodating a wide range of heterogeneous raw materials (Dey et al., 2021).

Extrusion is a **continuous thermo-mechanical process** wherein a mixed blend of raw materials—typically moist, starchy and/or proteinaceous—is forced through a die under high pressure, shear, and moderate-to-high temperature (up to ~200 °C), resulting in texturization, cooking, shaping, and densification of the extrudate (Coton et al., 2020).

**Bioconversion refers** to the biological transformation of agro-industrial residues—such as fruit pomace, cereal husks, spent grains, and spent coffee grounds—into energy-rich products (e.g., biogas, bioethanol, biohydrogen, microbial lipids) by the action of microorganisms,





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enzymatic systems, or fermentative consortia (Kiran et al., 2014). Employing methods like anaerobic digestion, fermentation, and microbial lipogenesis—often combined in cascade biorefineries—this approach enables efficient waste valorization, greenhouse gas reduction, rural bioenergy deployment, and economic co-product generation.

Modern extraction technologies supported by advanced **thermal methods** have demonstrated significant potential in reducing both processing time and agro-industrial waste. Among these, emerging techniques such as subcritical water extraction and microwave-assisted extraction (MAE) have gained increasing attention, particularly for their effectiveness in extracting polyphenolic compounds from agro-food by-products. These methods facilitate rapid and efficient solute recovery due to enhanced mass transfer and desorption mechanisms, as cellular structures are disrupted, thereby improving the accessibility of target compounds to the solvent. Consequently, these processes achieve higher extraction efficiencies within shorter timeframes and with reduced solvent consumption compared to conventional approaches. Nonetheless, the elevated temperatures involved in such thermal methods may negatively impact polyphenol yields by inducing degradation reactions, including the formation of undesirable compounds such as 5-(hydroxymethyl) furfural (Duah Boateng et al., 2023).

The food industry is increasingly adopting innovative mild and non-thermal extraction technologies—such as ultrasound-assisted extraction, pressurized liquid extraction, supercritical fluid extraction, high hydrostatic pressure extraction, pulsed light, pulsed electric field, high voltage electrical discharge, microwave-assisted extraction, enzyme-assisted extraction—for the recovery of bioactive compounds. These techniques offer significant advantages over conventional thermal processing, including enhanced extraction yield and kinetics, operation under ambient or low-temperature conditions, reduced thermal degradation of heat-sensitive compounds, improved preservation of bioactivity, greater energy efficiency, and preferential use of food-grade and environmentally benign solvents (Arruda et al., 2021). A range of non-thermal extraction techniques—including ultrasound-assisted extraction,

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microwave-assisted extraction, supercritical fluid extraction, high-pressure extraction, and enzyme-assisted extraction—have garnered significant interest due to their enhanced energy efficiency, reduced or minimal solvent requirements, operational safety, and ability to yield high-quality extracts.

These innovative methodologies have been developed to address the limitations inherent in conventional extraction processes, such as long processing times, high energy consumption, and solvent-related concerns. Furthermore, these advanced approaches typically require significantly shorter extraction durations, thereby offering a more efficient and sustainable alternative to traditional methods (Sridhar et al., 2022).

**Microwave-assisted extraction (MAE)** employs microwave energy to facilitate the efficient recovery of valuable bioactive compounds from food waste, including natural colorants, essential oils, aromatic compounds, nutrients, antimicrobial agents, and flavor constituents. This technique represents a sustainable and environmentally friendly alternative to conventional extraction methods, offering advantages such as reduced energy and solvent consumption, shorter processing times, and enhanced extraction efficiency (Yudhister et al., 2025).

**Enzyme-assisted extraction** has been employed as an effective strategy for valorizing waste streams by facilitating the release of phenolic compounds from plant cell matrices. This method enhances extraction efficiency while preserving the structural integrity and bioactivity of the recovered phytochemicals (Brennan et al., 2024).

**Ultrasound-assisted extraction** markedly improves both the yield and rate of recovery of high-value compounds—such as antioxidants and polyphenols—from fruit and vegetable processing by-products, thereby enhancing process efficiency and sustainability. Additionally, this technique minimizes solvent consumption and effectively preserves the integrity of thermolabile bioactive constituents (Yudhister et al., 2025).





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Loncaric et al., 2020 used **pulsed electric field** (PEF), ultrasound assisted extraction (UAE) and high voltage electrical discharges (HVED) for the extraction of blueberry pomace phenolic compounds. Authors concluded that PEF method release a higher total polyphenols content compared with HVED or UAE method and that the extraction efficiency is influenced by several parameters, including: for HVED—solvent type, treatment duration, and discharge frequency; for PEF—solvent composition, electric field intensity, and number of applied pulses; and for UAE—solvent type, extraction temperature, and processing time.

Pressure-based extraction techniques—such as high hydrostatic pressure (HHP), pressurized liquid extraction (PLE), and supercritical fluid extraction (SFE)—have gained significant attraction in the agro-food sector due to their ability to extract high-value bioactive compounds (e.g., phenolics, anthocyanins, lipids) from food processing residues (e.g., pomace, bran, spent coffee grounds). These methods are environmentally favorable, often use food-grade solvents or CO<sub>2</sub>, and operate under mild thermal conditions to maintain compound integrity (Battistella Lasta et al., 2019, Visnjevec et al., 2024).

Pressurized Liquid Extraction (PLE) is recognized as an effective technique for the recovery of bioactive compounds—particularly phenolics—not only from primary plant matrices but also from agro-industrial residues and by-products. Compared to conventional extraction methods, PLE offers equivalent or superior yields while significantly reducing both solvent usage and processing time (Visnjevec et al., 2024).

**Steam explosion** is considered a promising physicochemical pretreatment technique capable of effectively disrupting the lignocellulosic architecture of biomass. This process alters the composition and structure of hemicellulose and lignin through a combination of high-pressure steam cooking and rapid decompression, which induces mechanical shear forces. Due to its efficiency in overcoming biomass recalcitrance, steam explosion has been widely adopted as a standard pretreatment method in biofuel production and lignocellulosic pulping applications (He et al., 2022). Padilla-Rascon et al., 2020 study confirms that olive stone by-

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products could be used for sugar production through treatments such as acid and steam explosion (195°C, 5 minutes), followed by a hydrolysis with enzymes.

Membrane-based, pressure-driven separation processes such as ultrafiltration, microfiltration and nanofiltration, offer numerous advantages for the recovery of labile compounds from dilute aqueous streams. These technologies are considered environmentally friendly, as they operate at relatively low temperatures (typically 20–60 °C), require minimal energy input, and do not necessitate the use of additional chemical reagents. Furthermore, they are amenable to automation, electrification, and compact system design. Owing to their selective permeability—governed by size, shape, and charge exclusion mechanisms—membrane processes exhibit exceptional efficiency in the fractionation of biological molecules, while preserving the structural and functional integrity of the recovered compounds (Papaioannou et al., 2022). In the context of membrane-based separation, polyphenols from agro food chain byproducts might be fractionated based on their molecular weight and the specific characteristics of the membrane employed. Typically, low-molecular-weight polyphenols are predominantly recovered in the retentate phase during nanofiltration (NF), owing to the selective permeability of the membrane (Castro-Muñoz et al., 2016).

## **Chapter 9 - Innovative and sustainable methods of agro food chain byproducts valorization (dehydration, microencapsulation, nanotechnologies).**

Food by-products are very perishable, posing a challenge for the food and pharmaceutical industries to ensure their microbiological safety and quality. To prevent degradation, food by-products should be transported quickly and stored in refrigerated conditions. Preliminary treatments like irradiation and drying can increase the safety of food by-products. However, drying or grinding processes to fine particle size can be efficient





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techniques for by-products and their bioactive compounds valorization (Comunian et al., 2021).

Improved drying methods can be utilized to valorize byproducts in order to solve concerns regarding sustainability and food security. Depending on the needs of the manufacturers and the sort of drying procedures used during processing, the final products are usually in a variety of solid forms (chips, strips, or cubes) and granular goods/powders that come in a number of shapes and sizes. Additionally, the retention of bioactive components from the raw by-products may be facilitated by innovative drying technologies (Choon Hui Tan et al., 2021).

Drying can significantly alter the physical features, particularly its texture, due to the removal of moisture. Also, the visual appearance, texture, flavor, odor, and colour can be affected, and the food can become rigid, brittle, hard, and shrink significantly. Drying can cause hardening and shrinking, making the product tougher. Excessive drying of the external cell layers of tissue can lead to case hardening, which prevents moisture from being removed from the inside cell layers. In extreme drying conditions, the hardened casing may shatter while the inside cell layers remain liquid (Choon Hui Tan et al., 2021). Choosing the optimal drying technology is crucial for food valorization, as it affects both physical and nutritional qualities. Drying methods can be classified based on material type, moisture content, or drying kinetics to select the appropriate technology.

## **Drying methods**

### ***I. Conventional drying methods***

The well-known conventional drying methods are drum drying, cabinet drying, hot air oven drying, solar and vacuum drying together with spray drying, freeze drying and fluidized bed drying. During drum drying, steam is used to raise the drum's internal surface temperature,





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while, in the cabinet drying, the product is dried by spreading it out on trays or shelves and exposing it to regulated heat and airflow to eliminate moisture. On the other side, the most popular technique for creating powdered and dried fruits for use in baking, food processing, or as additives in other goods is hot air oven drying while solar drying is traditionally used for products such as vegetables, fruits, tobacco, tea, coffee, fruit, nuts, cereals, and rice and requires low-temperature energy (Khatri et al., 2024).

Vacuum drying is an effective process for creating high-quality dried concentrates and powders while retaining their natural flavor and nutritional value. The method occurs under reduced pressure conditions, which lowers the boiling point of the water and allows for the evaporation of water at a lower temperature, preventing heat damage to the generated powder. (Hasan et al., 2019). The most widely used and adaptable method for drying liquid items is spray drying while freeze-drying, also known as lyophilization, is a drying procedure that removes moisture while keeping the structure, flavor, nutritional and bioactive content of the product by sublimation (Hasan et al., 2019). Fluidized bed drying operates by continuously delivering wet particles to contact a warm surface or blowing hot air through to keep the material fluidized. Fluidized bed drying is used in the food, pharmaceutical, and chemical sectors to dry moist powders and solid capsules/particles (Fathi et al., 2022)

## ***II. Novel method of drying***

According to the literature, the most important and used novel method for drying, are: spray freeze-drying, pulsed electric fields (PEF), microwave drying, microwave (MW) vacuum drying, microwave fluidization, infrared drying (IR), infrared freeze-drying, conductive hydro-drying and supercritical fluid drying.

Spray freeze-drying is a novel and advanced drying technology that preserves the properties and quality of a variety of materials, including powders, medicines, and biomaterials. This method combines the principles of spray drying and freeze-drying to accomplish quick drying while preserving the treated materials while PEF processing involves





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applying high-voltage pulses to food held between two electrodes being an innovative drying technique that combines PEF technology with drying process (Khatri et al., 2024).

Microwave drying is a revolutionary drying process that uses microwave energy to eliminate moisture from food matrices while maintaining their quality and features. When food is exposed to microwaves, electromagnetic waves enter it and generate heat, resulting in water vaporization (Fathi et al., 2022), while MW vacuum drying processes use microwaves with radio frequencies ranging from 300 to 30,000 MHz as a heat source. MW vacuum drying might be nearly 50% faster and more efficient thanks to combined vacuum drying (high-pressure vacuum) to help eliminate moisture (Fathi et al., 2022).

Microwave fluidization replaces traditional heat producers in fluidized bed dryers. Electromagnetic radiation is the source of energy, causing an internal vibration to heat up the material and induce moisture from within to outside (Fathi et al., 2022). Another novel drying method is IR wavelengths (1-6  $\mu\text{m}$ ) which interact with the product's interior layer, leading to increased warmth and moisture evaporation. Moreover, far infrared radiation (FIR), which allows for homogeneous heating dispersion, is being used as a drying option. On the other side, infrared freeze-drying (IFD) is a specialist technique that improves the drying process by combining infrared (IR) light with freeze-drying principles. Infrared freeze-drying heats the material progressively during the drying process (Fathi et al., 2022).

Conductive hydro-drying (CHD) is a novel drying process that transmits heat directly from a heated surface to material. The material retains heat, increasing internal warmth and causing moisture to evaporate. Supercritical fluid drying is also regarded as a revolutionary drying method for manufacturing powders. It has multiple applications, including powdered fruit juice for instant beverages, food manufacture, and dietary supplements.  $\text{CO}_2$  is employed as a supercritical fluid, exhibiting liquid and gas properties at specified pressures and temperatures. The temperature and pressure are regulated to expand the supercritical fluid, resulting in the precipitation of components and separation of  $\text{CO}_2$  from dry powder.  $\text{CO}_2$  is

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naturally non-toxic, making this technique ideal for creating high-purity products. Minimal heat exposure reduces oxidation, maintaining the freshness and colour of the powder.

### **Microencapsulation**

Microencapsulation technology preserves bioactive chemicals by packing solid, liquid, and gaseous components in a continuous film and forming capsules ranging from micrometers to millimeters in size. Microencapsulation is commonly employed in the pharmaceutical and food industries for its ability (i) to reduce oxidation reactions in core materials exposed to external elements such as heat, moisture, air, and light; (ii) to reduce by-products; and to facilitate bioactive transfer (Comunian et al., 2021).

The most common encapsulation procedures for food components include spray drying, spray chilling, complex coacervation, ionic gelation, and emulsification.

- a. *Spray drying* (atomization)
- b. *Spray chilling* (spray cooling, spray congealing, or prilling).
- c. *Complex coacervation*
- d. *Ionic gelation*
- e. *Emulsification*

#### *Encapsulating agents*

Various materials have been used for encapsulation, including polysaccharides like arabic gum, maltodextrin, and modified starches; proteins like whey protein isolate and concentrate, gelatin, soy protein, casein, and milk serum; and lipids like vegetable oil and hydrogenated fats. Maltodextrin and gum arabic are commonly employed as carrier agents for spray drying due to their low cost and availability.

Regarding by-products, two directions are currently used in order to have sustainable alternatives. Thus, materials from food by-products were used as encapsulating agents, or encapsulation was used for incorporating food by-products into foods.





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For the first direction, apple pomace, banana peels, oat bran, sugar beet, avocado oil, and spent brewery yeast were used recently as carrier agents. However, studies have shown that microencapsulation of several ingredients, such as sour cherry pomace, grape seed extract, apple polyphenol skin extract, olive leaf extract, pomegranate peel extract, and pomegranate seed oil, successfully led to functional foods (Comunian et al., 2021, Borah et al., 2023).

### **Nanotechnology**

With the help of nanotechnology, agricultural waste may be redefined as a valuable resource at the forefront of sustainable innovation rather than as a burden on the environment.

Utilizing green chemistry, biocatalysts, and biodegradable nanocomposites, agricultural waste is being recycled into a wide range of goods, including biofuels, nanofertilizers, bioplastics, and sophisticated energy storage systems. In addition to reducing waste, this opens up new revenue sources and strengthens the circular economy by creating economic opportunities across industries. One of the most important steps toward sustainable growth is the potential of technology to transform waste materials into high-performing, environmentally friendly products. Nanotechnology has applications in biomass conversion, is used as a biochemical technique for waste valorization, while nanoscale catalysts is used for thermochemical processes (Balakrishnan Preethi et al., 2024).

### **Different drying techniques and hybrid drying techniques recommended for stabilization the functional and nutritional attributes**

The latest developments in drying technology aim to increase the shelf life and storage stability of food goods by finding a viable substitute for artificial preservatives. However, because phytoconstituents are sensitive to heat, the drying process may cause them to distort and degrade.

Thus, studies show that finding the right drying methods is essential to produce new products with high porous dried textures, high active ingredient retention, high drying yield,





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and high phytoconstituent preservation, as well as increased energy efficiency, low cost, and environmentally safe operations (Fathi, F. et al., 2022; Siddiqui S.A., et al., 2024).

For instance, used heat pump drying method for grape pomace and concluded that changes in air velocities increase yield and provide a cost-effective technique while causing a degradation of trans-resveratrol, catechin, and epicatechin. On the other side, changing the air velocity from 1.5 to 2.5m/s, the drying yield increase from 50% to 69%, and the energy consumption and drying time decreased significantly (Taşeri et al., 2018). Diced carrot were dried through microwave/fluidized bed drying and authors concluded that moisture content removal increase compared with conventional mechanism, a good retention of the physiochemical and biological properties compared to fluidized bed dryer was observed and initial color, flavor, and uniform quality were good conserved (Stanisławski, 2005).

Methods of drying have the potential to contribute to low drying performance, high operational costs, and strong environmental impact. Moreover, they can affect the nutritional value of macronutrients such as proteins, starches, gums, and dietary fibers present in foods, the integrity of the food structures, and their functional properties.

Stabilization the functional and nutritional attributes of macromolecules can be done by:

- understanding the correlation between the drying technique used and the functional and nutritional attributes;
- optimization of the operational parameters of the different drying methods;
- hybrid drying techniques (combination of some techniques), and pretreatment mechanisms.

Drying through conventional approaches such as sun or open-air drying found a slow process and may lead to inferior quality product due to contamination. Various advanced drying techniques (microwave, vacuum, infrared, freeze, oven drying, and different hybrid drying technologies) have been developed around the globe as successfully.





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To choose the right drying method, it is necessary to consider the following factors:

- the quality of product;
- reduction in drying time;
- energy efficiency;
- overall cost-effectiveness.

### **Strategies to increase the functionality of food products during drying and by-product**

Principal strategies to increase the functionality of food products during drying are divided by Betoret et al., 2016 into three groups:

#### **1. *Addition of ingredients that protect the degradation of bioactive compounds.***

A variety of protectants have been added to the drying media before freeze-drying or spray drying to protect the viability of probiotics during dehydration, including skimmed milk powder, whey protein, trehalose, glycerol, betaine, adonitol, sucrose, glucose, lactose and polymers, such as dextran and polyethylene glycol (Morgan et al., 2006). Betoret et al., 2016 shows that the beneficial effects of the protectants seem to be related to their protective effect on proteins and cell membranes.

#### **2. *Creation of structural elements that protect/maintain the functionality of bioactive compounds.***

*Encapsulation* - can contribute to increasing the shelf life of the product; increase functionality, promote the controlled liberation of the encapsulated bioactive compound in the target site and keep its properties protecting its bioactive compounds. Mostly, the capsule is





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mainly made up of *polysaccharides (inulin and polydextrose)*, *proteins and their combinations* for the microencapsulation of antioxidant components and probiotics.

*Edible films and coatings* - can act as carriers of functional bioactive compounds antioxidant and/or with antimicrobial properties, bacteria with probiotics effect or antimicrobial and other components which raise the value of the product by increasing the food's shelf life and protecting its physicochemical properties while maintaining its mechanical integrity and handling characteristics.

**Vacuum impregnation** - can also be used to mitigate drying effect by introducing protector compounds such as *sugars, sugar alcohols and non-reducing sugars in the food matrix*.

### ***3.Prevention of reactions causing a degradation of bioactive compounds and promotion of those that result in a functional effect.***

Vacuum drying and ultrasonic vacuum drying, microwave drying, ultrasound assisted drying, freeze-drying and low-pressure superheated steam drying contributes to:

- reduction lipid oxidation during fish and meat;
- reduction of pigments, vitamin C, phenolic compounds and other minor ingredients losses due to oxidation into fruits and vegetables;
- reduction carotenoids oxidation - by drying with hot air at temperatures below 60° C, vacuum drying and low-pressure super-heated steam drying.

These strategies can be applied regardless of bioactive compound source either being naturally present in the food matrix or derived from food waste recovery.





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## **Chapter 10- Bioactive compounds bioaccessibility and bioavailability through in vivo and in vitro digestion**

The evaluation of bioaccessibility and bioavailability of bioactive compounds has become a cornerstone in nutritional science, especially in the context of functional foods and nutraceutical development. Bioactive compounds, such as polyphenols, carotenoids, glucosinolates, and peptides, are widely recognized for their potential health benefits; however, their physiological efficacy largely depends on their release from the food matrix during digestion and their subsequent absorption and metabolism in the human body (Parada & Aguilera, 2007).

The term bioaccessibility refers to the fraction of a compound that is released from the matrix in the gastrointestinal tract and becomes available for absorption, whereas bioavailability encompasses the fraction that actually reaches systemic circulation and exerts a biological effect (Carbonell-Capella, et al, 2014). These concepts are especially important in the study of polyphenols and other phytochemicals whose health benefits are well-documented but whose absorption remains variable and often low (Dima & Dima, 2020).

To investigate these phenomena, in vitro digestion models have been increasingly standardized and widely adopted. One of the most significant milestones in this field has been the development of the INFOGEST method, an internationally validated static in vitro model that simulates the oral, gastric, and intestinal phases of human digestion. The consensus protocol initially published by Minekus et al. (2014; 2015) provided a reproducible and harmonized framework for researchers globally (Fig.1). Later, Brodkorb et al. (2019) updated and refined this method, consolidating its application for different food matrices and enabling the comparability of results across laboratories. This approach has proven instrumental in predicting the behavior of bioactives under digestive conditions, assessing their stability, transformation, and potential for absorption.



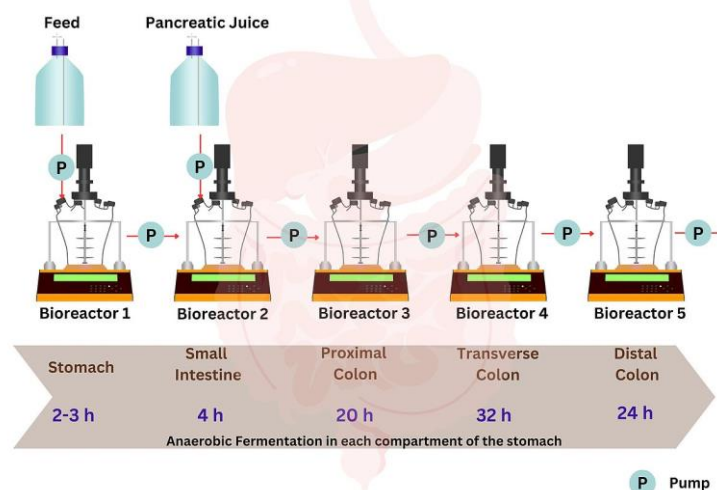


Fig. 1 Simplistic overview of the *in vitro* digestion model (Source: LAMBDA Instruments GmbH, LAMBDA Instruments GmbH)

In parallel, *in vivo* studies continue to play a critical role in understanding the complex mechanisms governing the fate of bioactive compounds. These investigations typically involve human or animal models to assess not only absorption but also metabolism, distribution, and excretion of compounds. Rein et al. (2013) and the most referenced Manach et al. (2005) provided a comprehensive review of the bioavailability of polyphenols, highlighting the controversies surrounding their absorption and metabolic transformation, and the importance of conjugation reactions in the liver and gut microbiota-mediated biotransformations. More recently, Williamson (2025), provides an updated perspective on dietary polyphenol bioavailability, highlighting the critical role of gut microbiota-mediated metabolism, hepatic conjugation reactions, and innovative delivery systems such as nanoencapsulation to enhance systemic absorption. Bié et al. (2023) further explored the interplay between polyphenols and the gut microbiota, emphasizing how microbial transformations can modulate both the bioaccessibility and the biological efficacy of these. Visvanathan et al. (2022), reviewed the

multiple factors influencing the bioaccessibility and bioavailability of citrus polyphenols, providing a roadmap for the design of *in vitro* models, animal studies, and human clinical trials. These updated contributions not only confirm the complex nature of bioactive compounds metabolism but also underscore the importance of integrative approaches—combining *in vitro* digestion, cellular absorption models, and metabolomics—to bridge the gap between ingestion and health outcomes.

A growing number of studies now combine *in vitro* digestion with cellular absorption models (e.g., Caco-2 monolayers) (fig.2) and metabolomics tools to bridge the gap between simulated digestion and systemic availability (Kalintas Caglar et al., 2024; Pinto et al., 2024; Redha et al., 2025; Serena-Romero et al., 2023; Villalba et al., 2022).

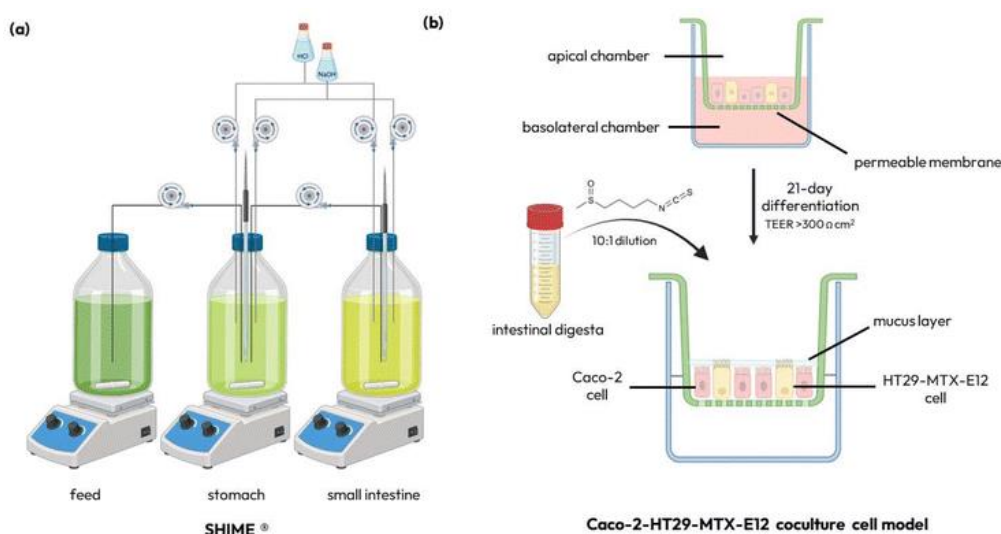


Fig.2. (a) *in vitro* dynamic gastrointestinal digestion, and (b) *in vitro* intestinal absorption based on Caco-2-HT29-MTX-E12 coculture cell model. (Image of Redha et al, 2025, with CC BY, <https://doi.org/10.1039/D4FO03446E>)

The impact of the food matrix is another key factor that modulates bioaccessibility and bioavailability (Parada & Aguilera, 2007). Encapsulation techniques, emulsification, and co-ingestion with dietary fats are among the strategies explored to enhance the delivery and



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absorption of poorly soluble compounds such as carotenoids and lipophilic vitamins. Recent research has focused on developing functional ingredients from agro-industrial by-products rich in bioactives. Some examples of these agro-industrial by-products applications can be read in Rocchetti et al. (2021), who examined how incorporating grape pomace powder into wheat bread affects phenolic compound bioaccessibility and starch digestibility during simulated digestion or Costa et al, who assessed the changes in chemical composition and bioactivity of Syrah grape pomace extract during *in vitro* digestion. The study of Hou et al. (2018) investigated how simulated digestion affects flavonoid content and antioxidant activity in aged and fresh dried tangerine peels. In orange by-product, Lu et al. (2020) compared the bioaccessibility of aged citrus peel extracts encapsulated in various lipid-based systems using different *in vitro* digestion models. Other study evaluated how *in vitro* gastrointestinal digestion affects the bioaccessibility and antioxidant capacity of bioactive compounds in tomato flours produced through different extraction methods (Coelho et al., 2021). From the point of view of the effect of technological processes such as extrusion to improve the bioaccessibility of bioactive compounds from plant-based sources, the contributions of Dr. Martínez-Monzó and colleagues, for instance, demonstrate how processing conditions can modulate the release and stability of these bioactives from by-products (Iguar et al., 2021; Iguar et al., 2022; Iguar et al., 2023; Peñaranda et al., 2025; Sarmiento-Torres, et al., 2025).

Challenges remain in correlating *in vitro* results with *in vivo* outcomes, especially considering individual variability, gut microbiota composition, and the biotransformation capacity of host enzymes. Nonetheless, the INFOGEST method continues to be refined, with versions now incorporating simulated colonic fermentation, bile salt variations, and age-specific modifications. Integration of these digestion models with omics techniques and advanced bioavailability studies will be essential for translating laboratory findings into actionable nutritional recommendations.





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The integrated application of *in vitro* and *in vivo* digestion methodologies offers a robust framework for explaining the bioaccessibility and bioavailability of bioactive compounds. This approach holds significant implications for dietary recommendations, the formulation of functional foods, and advancements in public health nutrition. As analytical techniques and experimental models continue to evolve, the field is progressing toward a more comprehensive and precise understanding of the interactions between food components and the human digestive system, subsequently informing health outcomes.

## **Chapter 11 – Sustainable product development. Obtaining of new food based on agro food chain by-products for human health and nutrition (functional food, nutraceuticals, plant-based proteins, supplements, prebiotics and probiotics)**

The agro-food industry generates a significant amount of by-products that, if properly utilized, can be transformed into functional foods, nutraceuticals, plant-based proteins, supplements, prebiotics and probiotics, contributing both to waste reduction and to human health. These by-products are rich in bioactive compounds, including antioxidants, dietary fibers, and polyphenols, which offer various health benefits, including antioxidant, anti-inflammatory, and prebiotic effects. The development of sustainable food products from these by-products aligns with a zero-waste approach, promoting the circular economy in the food industry.

### **11.1. Functional food**

The agro-food industry generates significant by-products that can be repurposed into functional foods, which are rich in bioactive compounds, offering health benefits (Galanakis, 2021).

#### **11.1.1. Probiotic Yogurt Enriched with Fruit Peel Extracts**





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By-products such as orange, pomegranate, and banana peels are rich in bioactive compounds, including polyphenols and antioxidants, which contribute to gut health and improve the viability of probiotics in fermented dairy products. Recent studies indicate that yogurt supplemented with fruit peel extracts exhibits enhanced probiotic efficacy and greater antioxidant activity (Shahidi & Ambigaipalan, 2015).

### **11.1.2. Enriched Bread with Grape Seed Flour**

The use of grape seeds, a by-product from winemaking, as a flour substitute in bread-making has shown promise in enhancing the functional properties of bread. Grape seed flour is rich in polyphenols, omega-6 fatty acids, and dietary fiber, offering potential cardiovascular health benefits and improving glycemic control (López-Caballero et al., 2022).

### **11.1.3. Pastry with Grape Pomace Powder (biscuits, cakes, rolls)**

In a recent study conducted at the Faculty of Food Engineering (ULST) (Poiana et al., 2023), three types of bakery products—biscuits, cakes, and rolls—were developed using spelt wheat flour and varying percentages of grape pomace (GP) (Figure 10.1). The aim was to evaluate the potential of grape pomace as a partial replacement for spelt wheat flour in fortified pastry formulations.

The results of this study provide compelling evidence for the feasibility of incorporating GP into bakery products. As a rich source of phenolic compounds and exhibiting high antioxidant activity, GP significantly enhanced the nutritional value of the final products. Specifically, the biscuits, cakes, and rolls enriched with GP powder displayed an improved nutritional profile compared to the control samples, particularly with regard to lipid and ash content. This suggests that GP can effectively be utilized to fortify bakery products, offering not only enhanced nutritional benefits but also contributing to the functional properties of these food products.



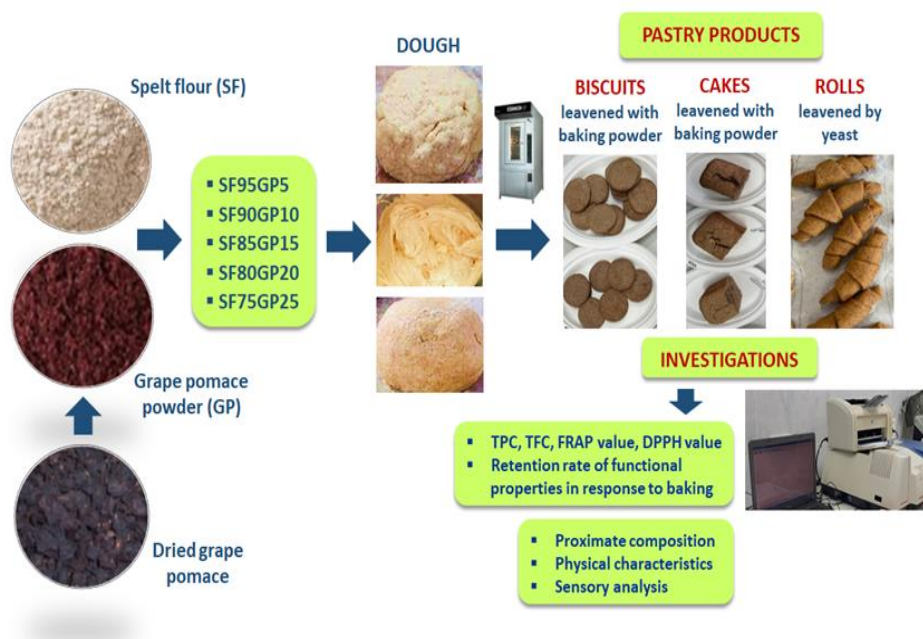


Figure 11.1. Pastry products with grape pomace (Poiana et al., 2023)

#### 11.1.4. Baguette Incorporating Brewer's Spent Grain

Brewer's spent grain (BSG), a by-product of beer production, is a potent source of protein, dietary fiber, and prebiotic compounds.

As part of the EITFOOD RIS Consumer Engagement Labs initiative, the Faculty of Food Engineering (ULS Timisoara) has collaborated with Prospero to develop a novel functional food product named **Brewer's Baguette**. This product is now available on the market in Timisoara.

Brewer's Baguette is a hypoglycemic bread enriched with fiber, achieved through the valorization of malt roots, a by-product of the beer production industry. The inclusion of malt roots not only enhances the nutritional profile of the bread but also contributes to its functional properties, such as lowering glycemic index levels.



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In addition to its health benefits, Brewer's Baguette stands out as a sustainable product. By utilizing malt roots, which would otherwise be discarded, this bread contributes to waste reduction and supports the principles of the circular economy. The development of such innovative, sustainable food products is in line with global efforts to promote resource efficiency and environmental responsibility in food systems ( <https://tim7.ro/bagheta-berarului/>).



Figure 11.2. Brewer's Baguette

#### 11.1.5. Tomato pomace-based pasta

Tomato processing results in significant by-products, including tomato skin and seeds, which are rich in lycopene, a potent antioxidant, and dietary fiber. Fortifying pasta with tomato pomace enhances its nutritional profile, contributing to both cardiovascular health and antioxidant protection, with several studies supporting the benefits of such products for consumer health (Wadhwa & Bakshi, 2013).

#### 11.1.6. Enriched Biscuits with Omega-3 from fish by-products

Fish processing generates by-products such as skin, bones, and trimmings, which are rich in omega-3 fatty acids and bioactive peptides. These by-products can be incorporated into bakery products, such as biscuits, which, when consumed regularly, may provide significant cardiovascular and cognitive health benefits (López-Caballero et al., 2022).

#### 11.1.7. Sausages with tomato and bell pepper seeds

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Recent studies have demonstrated the significant potential of vegetable processing by-products, particularly seeds, in the development of value-added meat products. These by-products have proven to be especially effective due to their antioxidant capacity (Cocan et al. (2022); Cadariu et al. (2022)).

Bell pepper and tomato processing by-products enhance meat formulations, specifically in the creation of nitrite-free sausages. Tomato and bell pepper by-products can effectively replace sodium nitrite in pork sausages, offering comparable antioxidant potential. This replacement not only improves the antioxidant profile of the sausages but also promotes the use of these by-products as natural additives to prevent or delay oxidative degradation in nitrite-free sausage formulations. Furthermore, the research emphasized the suitability of these vegetable processing by-products across various technological processes, including smoking, drying, and scalding, confirming their effectiveness in improving the quality and shelf life of meat products (Cocan et al. (2022); Cadariu et al. (2022)).

## **11.2. Nutraceuticals**

Nutraceuticals refer to food products that provide health benefits beyond basic nutrition. These can be derived from fruits, vegetables, grains, or other agricultural processes, and are enriched with bioactive compounds that offer specific health benefits, such as improving digestion, boosting immunity, or reducing the risk of chronic diseases.

### **11.2.1. Fruit-based Nutraceuticals.**

Apple pomace, is by-product from apple juice production, is being used to create nutraceutical products. Apple pomace contains dietary fibers, antioxidants, and polyphenols, which are beneficial for digestive health and provide anti-inflammatory effects. Companies in Europe are working on developing these by-products into functional foods or supplements that promote heart health and gut function (Kołodziejczyk K, et al., 2007)

Rosehip is widely used to create nutraceutical products, particularly from the by-products of rosehip processing. The seeds and skins of rosehips, often discarded, are rich in

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vitamin C, antioxidants, and essential fatty acids, which are used in supplements and functional foods that support immune health, reduce inflammation, and improve skin health (Vlaicu PA, et al., 2022).

### 11.2.2. Grain based byproducts nutraceuticals

• **Corn Gluten Meal, a nutraceutical** enzymatically hydrolyzed, which produces peptides with antioxidant properties that can reduce lipid oxidation and may have cancer-fighting potential.

(<https://agris.fao.org/search/en/providers/122535/records/65deeb9f0f3e94b9e5d2bfc4>)

- **Corn Germ** is rich in phytosterols, which can help lower cholesterol levels, and tocopherols (vitamin E) that act as antioxidants (Deepak TS, 2022).
- **Corn Silk** contains maysin, a phenolic compound with anti-inflammatory effects and potential benefits for weight management (Sarepoua, E.; 2013).
- **Wheat Bran** is a rich source of dietary fiber and has been shown to help with digestion, regulate blood sugar, and lower the risk of heart disease.

(<https://www.healthline.com/nutrition/wheat-bran>)

- **Bulgur Wheat** made from cracked whole-grain durum wheat, is rich in fiber and nutrients that aid digestion and support heart health.
- **Rice Bran** contains oryzanol, a compound that may help reduce cholesterol levels, as well as antioxidants that support overall health (Myrdal Miller, A.; 2014)
- **Barley Bran** is a good source of beta-glucan fiber, which has cholesterol-lowering effects and is beneficial for heart health (Ousager LB, 2012).

### 11.3. Plant-based proteins

The utilization of agro-food chain by-products as sources of plant-based proteins is gaining significant attention in the food industry. These by-products, derived from oilseeds,





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cereals, legumes, and fruit and vegetable processing, offer sustainable protein alternatives with functional and nutritional benefits.

- **Soy and Pea Protein Burgers** is a plant-based meat alternative. Meat analogs enriched with protein extracted from soybean meal and pea processing waste. These proteins improve texture and nutritional quality while reducing reliance on animal protein sources (Sharma et al., 2023).

- **Faba Bean and Lupin-Based Sausages:** Incorporating protein from legume by-products enhances protein digestibility and bioavailability in plant-based sausage formulations (Galanakis, 2021).
- **Bread Enriched with Oilseed Meals:** Incorporating sunflower, rapeseed, or hemp seed meal as a protein and fiber source in fortified bread formulations (Poiana et al., 2023).
- **Gluten-Free Protein Cookies:** Using chickpea and lentil protein from milling by-products to enhance protein content in gluten-free bakery products (López-Caballero et al., 2022).
- **Plant-Based Yogurts:** Utilizing protein isolates from oat, rice, and almond processing by-products to develop dairy-free yogurt with enhanced protein content and bioactive properties (Wadhwa & Bakshi, 2013).
- **Protein-Enriched Plant Milks:** Fortified almond and coconut milks incorporating pea and hemp protein from agro-industrial residues to enhance nutritional value (Shahidi & Ambigaipalan, 2015).
- **Protein Bars from Cereal By-products:** Wheat bran, rice bran, and fruit pomace proteins incorporated into protein bars for enhanced satiety and nutritional benefits (Myrdal Miller et al., 2014).

#### 11.4. Supplements





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The development of nutritional supplements from agro-food chain by-products is a sustainable and innovative strategy that enhances both environmental and human health. These supplements utilize bioactive compounds, dietary fiber, proteins, and antioxidants derived from plant-based and food industry residues to improve nutrition. Numerous studies have emphasized the significant potential of these by-products in creating functional supplements that support overall well-being.

- Pea and Soy Protein Isolates – Extracted from legume processing by-products, these proteins support muscle growth and satiety (Galanakis, 2021).
- Hemp and Flaxseed Protein Powders – Rich in essential amino acids and omega-3s, beneficial for cardiovascular and metabolic health (Shahidi & Ambigaipalan, 2015).
- Rice Bran Protein Supplements – A by-product of rice milling, rice bran protein offers hypoallergenic plant-based nutrition (López-Caballero et al., 2022).
- Oat and Wheat Bran Fiber Capsules – Contain  $\beta$ -glucans, supporting gut health, cholesterol reduction, and blood sugar regulation (Wadhwa & Bakshi, 2013).
- Fruit Pomace Powder (Apple, Grape, Citrus) – A natural source of pectin and polyphenols, promoting digestive health and prebiotic activity (Poiana et al., 2023).
- Grape Seed Extract Capsules – A rich source of proanthocyanidins, known for anti-aging, cardiovascular, and cognitive health benefits (Shahidi & Ambigaipalan, 2015).
- Pomegranate Peel Extract – Contains ellagic acid and polyphenols, effective for inflammation reduction and skin health (López-Caballero et al., 2022).

### **11.5. Prebiotics and probiotics**

The development of prebiotic and probiotic supplements from agro-food chain by-products aligns with sustainability principles while enhancing human health. These by-products, rich in dietary fiber, oligosaccharides, and fermentation-friendly compounds, serve as excellent substrates for gut microbiota support.

#### **11.5.1. Prebiotics from Agro-Food By-products**





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Prebiotics are non-digestible food components that promote the growth of beneficial gut bacteria, improving digestion and immune function.

- Inulin and Fructooligosaccharides (FOS) – Extracted from chicory root, Jerusalem artichoke, and onion peels, these compounds enhance gut microbiota diversity (Galanakis, 2021).
- Pectin from Fruit Pomace – Found in apple, citrus, and grape pomace, pectin acts as a prebiotic that improves gut health and cholesterol metabolism (Shahidi & Ambigaipalan, 2015).
- Arabinoxylans from Cereal Bran – Derived from wheat, rye, and oat bran, these fibers support short-chain fatty acid (SCFA) production, which benefits gut health (Wadhwa & Bakshi, 2013).
- Resistant Starch from Banana and Potato Peels – A fermentable fiber that feeds beneficial gut bacteria and supports blood sugar regulation (López-Caballero et al., 2022).

### **11.5.2. Probiotics from Agro-Food By-products**

Probiotics are live microorganisms that contribute to gut health by improving digestion and immune function.

- Fermented Dairy By-products (Whey, Buttermilk) – Provide Lactobacillus and Bifidobacterium strains, which enhance gut microbiota balance (Galanakis, 2021).
- Fermented Rice Bran and Cereal By-products – Contain Lactic Acid Bacteria (LAB) that improve digestive health and immune function (Myrdal Miller et al., 2014).
- Kombucha and Fermented Fruit Residues – Utilizing tea, apple peels, and pineapple cores, these contain yeast and probiotics that aid digestion and metabolism (Cocan et al., 2022).





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## **Chapter 12 – Sustainable packaging development. Obtaining of biodegradable and edible packaging based on agro food chain by-products P3 (TM)**

In the current global context, characterized by a growing concern for sustainability and efficient resource management, the recovery of by-products from the agri-food chain is a key direction to promote a circular economy and significantly reduce waste.

Agro-food by-products are defined as materials resulting from food production processes, which are not intended for direct human consumption, but which can be transformed by appropriate technologies. They include a wide range of raw materials such as husks, stems, kernels, whey, whey, bran, as well as plant or animal remains. Making efficient use of these materials is crucial to reduce food waste and negative environmental impacts, while contributing to the development of more sustainable agri-food systems. Food packaging is an essential part of the food industry sector. However, the food packaging sector is now in pursuit of lightweight biodegradable packaging for reducing materials use, waste, and transportation costs.

The main by-products that can be obtained from agro-food sector, are:

- Cereals: bran, starch, germs, processing residue, etc.
- Fruits and vegetables: hulls, seeds, peels, skin, pomace, etc.
- Milk industry: whey, skimmed milk, buttermilk, etc.
- Meat industry: bones, fats, organs, etc.
- Oil industry: sunflower oilseed cakes, rapeseed oilseed cakes, etc

Within the cereal products chain, the processing of wheat, corn and other cereals leads to the generation of bran, germs and various other residues that are rich in fiber and other bioactive compounds, and can be used as raw material for the production of biodegradable packaging.





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Starch is a good source of biodegradable material for food packaging, originating from wheat, corn, rice, and potatoes. It is widely viewed as a sustainable substitute to plastics for food packaging. Moreover, various foods, such as fruits, vegetables, snacks, and dry products, can be packaged using starch as a biodegradable film (Kolybaba, M.; et al., 2016)

The fruit and vegetable industry generates by-products such as peels, seeds, and pomace resulting from the processing of apples, pears, grapes, tomatoes, and other fruits and vegetables. They are valuable sources of cellulose, pectin and other biopolymers with potential in packaging applications. Eco-friendly packaging material based on alginic acid and grape pomace extract from *Vitis vinifera* L. (winemaking by-products) for storing red meat in the refrigerator. Specifically, biogenic amines are considered “sentinels” of the putrefactive processes (Aresta, A.M.; et al., 2023).

Bioplastics are eco-friendly alternatives to conventional plastics. They can be biobased, biodegradable, or both—made from biomass and/or broken down by microorganisms into water and CO<sub>2</sub>.

Classification and examples of plastic (Zhao, X.; et al., 2023):

→ **Petroleum-based and non-biodegradable:**

1. **PA** – polyamide
2. **PTT** – polytrimethylene terephthalate
3. **PE** – polyethylene
4. **PET** – polyethylene terephthalate
5. **PP** – polypropylene

⇒ **Bioplastics**

Can be **bio-based**, **biodegradable**, or both:

- **PLA** – poly-lactic acid
- **PHA** – polyhydroxyalkanoates





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- **PBS** – polybutylene succinate
- **PBAT** – polybutylene adipate terephthalate (*biodegradable but petroleum-based*)
- **PCL** – polycaprolactone (*biodegradable but petroleum-based*)

The dairy industry produces large amounts of whey, a by-product resulting from the manufacture of cheese. Whey contains protein, lactose, and other components that can be used to create biodegradable films and coatings. According to European commission regulation (EC) No 450/2009 “active materials and articles means materials and articles that are intended to extend the shelf-life or to maintain or improve the condition of packaged food.

The dairy industry generates large volumes of liquid waste as a by-product during the casein coagulation process. This liquid, termed as dairy whey is a yellowish green colored, water-soluble protein by-product derived after casein extraction in cheese processing. One possible way to recycle DW is to exploit its protein content as a biopolymer source to create edible films/coatings in food (Yadav, J.S.S.; et al., 2015)..

From the meat industry, the skins of pigs and cows are the main sources of gelatin as they are easily available. The commonly used gelatin sources reported are pigs’ skin and cartilage (46%), and bovine hides (29.4%), bones (23.1%), and other sources (1.5%). The gelatins extracted from porcine, poultry, and fish skins and untanned bovine hide wastes, or by-products are used for the production of packaging films or edible coatings (Nilsen-Nygaard, J., et al., 2021).

The vegetable oil industry, which includes the processing of sunflower, rapeseed and soybean seeds, produces groats and other residues rich in protein and fiber.

Properties of edible coatings obtained from groats:

- allows the shelf life of food products to be extended;
- provide physical resistance, reduce the moisture exchange of the product;
- reduce oxygen permeability, avoiding chemical changes such as nutrient oxidation (Serrapica, F.; et al., 2019).





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Oilcakes are the principal by-products obtained after the extraction of oil from the seeds. Then they are air-dried to remove the water before storage. Edible films obtained from oil cakes are suitable for packaging if they possess strong structural, biological, optical, and barrier properties. They effectively block scents, vapor, oil, water, oxygen, and light to prevent lipid oxidation, moisture loss, and discoloration, thereby preserving product quality and appearance (Petrașu, A.; et al., 2021).

### **Protein-Based Biopolymers**

- ❖ Soybean cake contains soy protein and is used to produce biodegradable films with good mechanical and barrier properties.
- ❖ Sunflower cake is rich in sunflower protein and is suitable for film formation with moderate water resistance.
- ❖ Rapeseed (canola) cake contains rapeseed protein and is utilized in creating edible films that exhibit antioxidant and antimicrobial activity.
- ❖ Peanut cake is high in protein and is used for making biodegradable films with good flexibility.

### **Composite Biopolymer**

**Mixed Oilseed Cakes** (e.g., blends of soybean and sunflower): Used to formulate composite biopolymer films by combining proteins and fibers for improved mechanical and barrier performance (Popović Senka, et al., 2020).





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## **Chapter 13- Circular economy and resource management. Application of circular economy principles in agro-food. Optimization of the value chain of sub-production. Evaluation of the economic feasibility of reuse processes**

### **12.1. Circular economy and resource management**

The agri-food sector has always been one of the main generators of waste, especially when considering the transformation and processing of raw materials at an industrial level (Chiaraluce et al., 2023). This currently has a huge impact on food systems. This production has environmental, economic and social impacts, affecting the sustainability of agri-food supply chains. Food systems are strongly involved in global sustainability trajectories, with trends in both production and consumption practices generating increasing private and social costs, the latter often being externalized to other sectors, including health, water and the global environment. The transition towards a circular and sustainable economy has attracted significant attention in recent years, especially in the food industry. The food industry is an ideal sector to initiate this transition due to its high resource consumption and significant contribution to global waste generation. However, food waste, resource scarcity, and environmental degradation are some of the global challenges that have a significant impact on the global food production system (Fazle Rabbi and Bin Amin, 2024).

The circular economy is part of the broader concept of a green economy, which involves fully reusable and recyclable material resources (Tarhini et al., 2022). The idea of a circular economy has been prominent in the modern era of industrial evolution as a revolutionary strategy for sustainable growth. Reuse of products are key tactics in this strategy, as they increase resource efficiency, reduce waste, and extend product life cycles (Psarommatis and May, 2025).

The circular economy is a concept based on changes in consumer behavior, technologies, and business models that prioritize the longevity, reuse, repair, refurbish, share, rent, and recycle





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of products and materials to achieve more efficient use of resources by closing, redesigning, expanding, and narrowing the loops of material flows. Similarly, the concept of sustainable materials management is a systemic approach to using and reusing materials in a more productive way throughout their entire life cycle (Paulo de Sa and Korinek, 2021).

The circular economy is an economic model that aims to minimize waste and maximize resource utilization. This contrasts with the traditional linear economy, which follows a “take, make, dispose” model (Cahyadi et al., 2024).

Implementing a circular economy allows for more efficient use of resources and less waste throughout a product's entire life cycle, from manufacturing to consumption. An integrated approach to food production, agriculture, and food trade contributes to the expansion of rural areas and can promote the adoption of environmentally friendly practices (Fazle Rabbi and Bin Amin, 2024).

Supply chain management involves the coordination and integration of all activities involved in the production and delivery of a product, from the procurement of raw materials to the final delivery to the consumer. Effective supply chain management aims to increase efficiency, reduce costs, and improve customer satisfaction. Key components include sourcing, purchasing, production, logistics, and distribution, which must be managed coherently to ensure smooth operation (Cahyadi et al., 2024).

Integrating the circular economy into supply chain management involves incorporating circular principles into supply chain processes. This integration requires redesigning supply chain activities to prioritize resource efficiency, reduce waste, and extend product life. Practices include closed-loop supply chains, where products are returned for reuse, remanufacturing, or recycling, and sustainable sourcing to ensure that materials are environmentally friendly (Cahyadi et al., 2024).

## 12.2. Applying circular economy principles in the agri-food sector





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In the context of agricultural and food systems, circular agriculture tends to be referred to as circular bioeconomy to distinguish it from circularity in manufacturing, which tends to rely more on extracted non-renewable resources (Duncan et al., 2023).

Circular agriculture is often confused with the rhetoric of farm-to-fork and supply chain responsibility, which encompasses elements of life cycle and traceability before and beyond the farm gate and which usually refers implicitly to agricultural and food systems in high-income countries. Because of its biological complexity and as an adjunct to natural ecosystem processes, agriculture provides some of the clearest examples of circular resource use, many of which have evolved over centuries of practice and formal and informal knowledge exchange in transitional low-input and extensive agricultural systems. Examples include respecting seasonality in production to match cropping schedules to peak growing conditions, using crop residues in animal feed, increasing soil nutrients from animal and human waste, and optimizing the use of other biological products of animal origin, including for renewable energy production (Duncan et al., 2023).

The European Union, through its Green Deal and Farm to Fork strategies, is placing the circular economy at the heart of future green industrial growth. While the circular economy has emerged as a potential win-win solution in the agri-food industry, much remains to be done in terms of the regulatory framework and technical aspects (Chiaraluce et al., 2023).

In the context of agricultural and food systems, the circular economy tends to be referred to as the circular bioeconomy to distinguish it from circularity in production, which tends to rely more on extracted non-renewable resources. The circular economy is often confused with the rhetoric of farm-to-fork responsibility and supply chain responsibility, which encompasses elements of the life cycle and traceability before and after the farm gate and which usually implicitly refers to agricultural and food systems in high-income countries. Due to its biological complexity and as an adjunct to natural ecosystem processes, agriculture offers some of the clearest examples of circular resource use, many of which have evolved over centuries of

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practice and formal and informal knowledge exchange in transitional low-input and extensive agricultural systems (Duncan et al., 2023). Integrating circular economy principles into agri-food supply chain management offers a promising approach to increasing sustainability and efficiency. This integration involves several key strategies (Cahyadi et al., 2024).

The implementation of circular economy principles can affect the 3Ps (planet-people-profit) of sustainability. It reduces the pressure on natural resources, by reusing discarded products and contributes to reducing greenhouse gas emissions. The circular economy involves productive activities developed with respect for society and the environment, in order to promote decent working conditions and equitable social development. Finally, it promotes prospects for fair remuneration and job creation, based on the reuse and valorization of waste (Chiaraluce et al., 2023).

Resource efficiency can be achieved through practices such as precision agriculture and sustainable agricultural methods, which optimize the use of inputs such as water, energy, and raw materials, improving efficiency and reducing environmental impact (Cahyadi et al., 2024). Circular economy principles include designing for waste elimination, keeping products and materials in use, and regenerating natural systems. Circular economy principles are often integral to these niches and have a longer history in engineering principles that aim to improve the efficiency of material resource use in production. In agriculture, circular bioeconomy principles are integrated into government and sectoral strategies and plans. This approach enhances sustainability by promoting resource efficiency, reducing environmental impact, and stimulating economic growth through innovative business models. The main goal of the circular economy is to fully utilize and recycle materials to combat climate change and reduce the consumption of natural resources. Waste recovery transforms agricultural by-products and food waste into valuable products, such as bioenergy, fertilizers, and animal feed, reducing waste and creating economic opportunities (Cahyadi et al., 2024).





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Technological challenges represent a significant barrier to integrating circular economy principles into the agri-food supply chain. The need for advanced infrastructure and expertise is essential for the effective implementation of circular economy practices. For example, precision agriculture uses advanced technologies to optimize field-level management of agriculture, significantly reducing resource use and environmental impact (Cahyadi et al.,2024).

Sustainable production practices, including crop rotation and agroforestry, improve soil health, increase biodiversity, and enhance resilience to climate change. Studies such as provide frameworks and case studies that demonstrate the practical applications and benefits of these strategies in diverse contexts. However, the high costs associated with these technologies can be prohibitive for many stakeholders, especially in developing regions. In addition, there is a need for innovative technologies that facilitate the effective implementation of the circular economy, such as advanced recycling techniques, waste-to-energy solutions, and precision agriculture tools (Cahyadi et al.,2024).

Another important aspect is the consumer. The circular economy is a model of production and consumption and cannot be implemented effectively if the consumer is not prepared to engage in this process. The consumer could be involved in the circular process without being directly involved in the industrial food transformation process. Collaboration between companies and regional government can promote initiatives and workshops to spread circular thinking, starting with the new generations in schools, promoting sustainable economic transition (Chiaraluce et al., 2023).

Regulatory and policy issues also represent significant obstacles to integrating circular economy principles into the agri-food supply chain. Inconsistent regulations and policies across regions can hinder the widespread adoption of circular economy practices. For example, the lack of supportive policies in some regions can hinder the implementation of waste reduction and resource efficiency strategies. Standardized policies are needed to encourage the global





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adoption of circular economy principles and create an enabling environment for the transition to a circular economy. Comparative studies on how different regulatory and policy frameworks influence the implementation of the circular economy in different regions can provide valuable insights and help adapt strategies to local needs and conditions (Cahyadi et al.,2024).

### 12.3. Optimizing the by-product value chain

The global agri-food value chain faces unprecedented challenges, including an estimated 50% increase in demand by 2050, biodiversity loss caused by climate change, and significant environmental impacts, such as 35% of global greenhouse gas emissions and 70% of freshwater use (Saladi, 2025). The value chain refers to the stages that food goes through from producers to end users. It includes farming, processing, distribution and retail. Each stage adds value, ensuring quality and accessibility for consumers (Saladi, 2025). The importance of reuse and recovery as a means of improving sustainable production practices, by reducing waste streams by recovering resources in the chain, is increasingly recognized. Faced with new challenges in the context of climate change, the food and agricultural sector could benefit in particular from the recovery of secondary (edible) flows, such as unharvested crop parts and vegetable peels, which are often overlooked by consumers. Focusing on strategies for valorizing secondary streams within food processing units, this research develops a mixed-integer optimization model to support decision makers in determining an optimal product portfolio and processing configuration (Remijnse et al., 2025).

A vital aspect of the circular economy is understanding how value is created and identifying the factors that enable value creation. The circular economy is driven by innovations that enable value creation. These innovations underpin the increase in environmental, economic and social performance of companies. In fact, there is a strong interconnection between sustainability and innovation. Several authors attribute innovations that impact value creation in a circular economy approach to four main areas: process, product,





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service and business model. These are prerequisites for achieving forms of eco-innovation or strategies that favor the transition from a linear to a circular economy. Given the types of innovations reported, their function can be traced to the circular economy through the following ways discussed below (Poponi et al., 2023).

Product innovations lead to value generation through actions aimed at extending its life cycle. Such behaviors include product reuse or reconditioning, component reuse, or the use of eco-design, which involves reducing the product's impact throughout its life cycle and optimizing production, lifespan, and recovery through the use of multiple methodologies (Poponi et al., 2023).

Process innovations create value by optimizing work steps, manifested in the reduction and recovery of waste through closed-loop or open-loop logic and in optimizing the use of energy and resources in general (Poponi et al., 2023).

#### **12.4. Evaluation of the economic feasibility of reuse processes**

During the last decade, the circular economy has received increasing consideration around the world as a method to overcome the present model of production and consumption, which is characterized by increased use and depletion of resources (Hamam M. et al., 2021).

The circular economy in the context of food supply chains emphasizes the importance of reducing food waste, promoting waste recovery and reuse, adopting new circular business models, and addressing socio-economic and political implications. Adopting circular principles can contribute to improving the efficiency, sustainability, and resilience of the food system, while creating new economic opportunities (Bigliardiab, 2024).

In the current context of resource scarcity, global climate change, environmental degradation, and increasing food demand, organic farming represents a promising strategy to support sustainable, restorative, and regenerative agriculture. The problem created by agri-food





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industry by-products and waste generation has attracted the attention of academics, regulators, industry, and consumers (Hamam M. et al., 2021).

Reducing environmental impact, improving resource efficiency and increasing profitability are just a few of the benefits that the food sector has seen by adopting circular economy perspectives. This approach promotes collaborative thinking and innovation throughout the food value chain. However, there are specific obstacles that need to be overcome to put these concepts into practice. These include changing consumer perceptions, overcoming legislative obstacles, improving logistics and supply chains, and finding creative solutions to the problem of food waste. Despite these obstacles, there is a lot of opportunity to solve pressing problems such as food insecurity and accessibility using circular economy concepts. The food sector can significantly improve sustainability by adhering to these principles, reducing food waste and encouraging sustainable practices throughout the supply chain. In addition, this approach has the potential to open up new markets for valuable products made from food waste (Fazle Rabbi and Bin Amin, 2024).

The circular economy, like all other sustainable models, requires not only innovative concepts but also innovative actors; its implementation often needs to be supported by stakeholders who enable changes in policies and decision-making tools. The adoption of strategies by companies to improve the circularity of the production system also requires collaboration with other companies along the entire supply chain to achieve the most efficient circular model possible. Implementing a circular economy is not always easy to achieve, as it often faces biophysical limits, including the high energy requirements for resource recovery and the loss of resource quality (Hamam M. et al., 2021).





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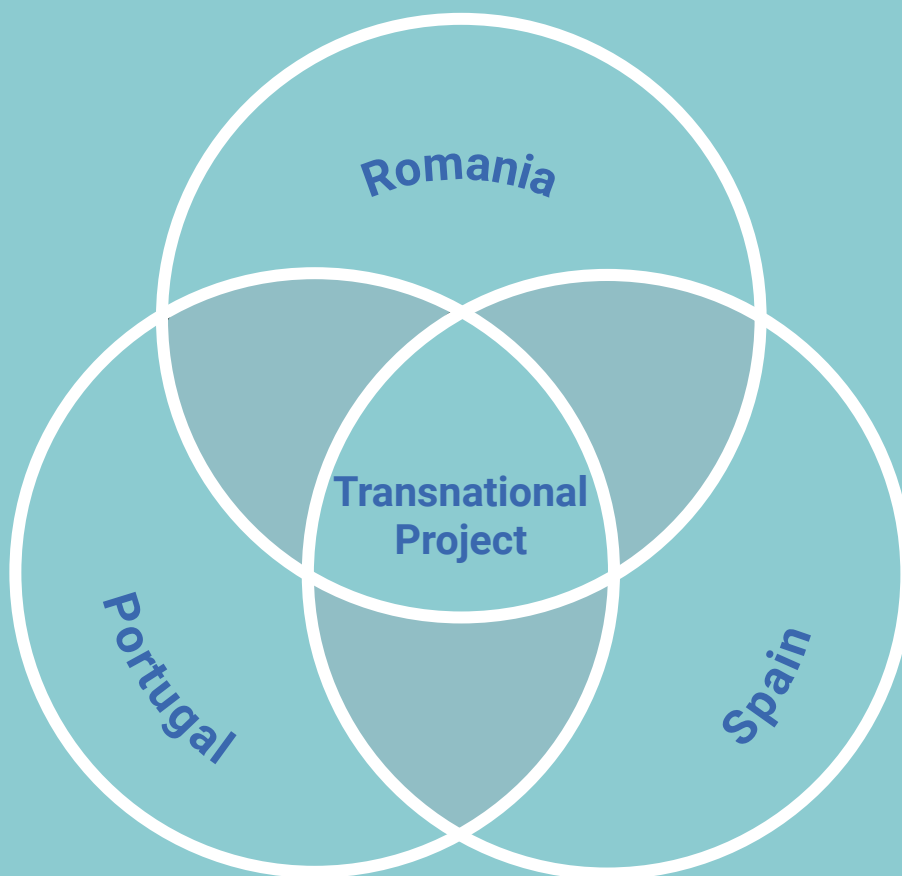
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