WHITE PAPER ON FOOD AND DRINK WASTE MANAGEMENT

Imprint

Model2Bio
Modelling tool for giving value to agri-food residual streams in bio-based industries
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Tamara Fernández Arévalo
Centro Tecnológico CEIT
tfernandez@ceit.es

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Executive Summary

The underlying purpose of this white paper is to demonstrate the great valorisation potential of the agri-food industry's by-products, as well as the limitations or obstacles that may hinder this valorisation.

Firstly, ***the agri-food industry does not generate organic waste; it generates by-products with great value – and in large quantities***. Despite their potential, these by-products are typically used as animal feed, bio-energy production, incinerated or placed in landfills, which creates economic, social, and environmental problems. Currently, research has shown that if treated with innovative technologies these by-products could provide extremely valuable bio-components and nutrients with economic value for different industries while significantly reducing their environmental impact.

This white paper shows the potential of some of the most prominent and relevant agri-food by-products in Europe and it identifies some of the innovative treatments for their valorisation, as well as promising value chains. After an analysis of the potential of the most relevant sectors of the agri-food industry (vegetable, dairy, alcoholic beverage and meat sector), the focus has been on five key residual streams such as potato steam peels, cheese whey, brewer's spent grain, grape seeds & peels, and olive leaves. Each of these by-products presents unique challenges, yet they also offer numerous opportunities for innovative and sustainable valorisation. The case studies presented have allowed us to exemplify the potential of biorefinery approaches that could be implemented using by-products as substrate valorisation processes. Thanks to these approaches, it is possible to obtain a wide range of high-value products, from biodegradable films and bioplastics to antioxidants and biofuels. This strategic approach not only addresses the environmental concerns associated with waste disposal, but also aligns with the growing demand for sustainable solutions and the promotion of circular economies.

In parallel to technological innovation, it is necessary to develop tools for managing information, analysing solutions in an agile manner and also for making decisions. One such tool worth is the pioneering Model2Bio decision support (DSS) tool (https://www.model2bio.eu/). It is based on mathematical models to predict agri-food residual streams and to identify the best routes for valorising them. Based on current innovation, the obvious strategy to follow is to maximise the conversion and extraction processes to obtain value-added compounds. But is it the best valuation option in all cases? Considering only technical criteria, the answer would be yes. But what is the point of obtaining valuable products if the cost of their production and logistics exceeds their market value? Under this holistic perspective the problem becomes complex and it is necessary to use tools that allow all variables to be analysed as a whole. The Model2Bio-DSS tool considers technical, economic, environmental and social aspects together to make the best valuation option in each specific case, helping in decision-making with multiple factors.

In addition to the vast potential that exists, this white paper shows the key barriers and limitations that make valorisation difficult today. *The path to be followed in the valorisation of by-products is promising, but requires the commitment and involvement of all members of the value chain: from the generators of by-products to the producers of value-added products, from researchers who will try to propose new solutions and tools to the consumers of these products, and of course policy makers.*

Recommendations or Actions:

- Platforms or secure channels, together with other initiatives, should be implemented to avoid distrust and promote information-sharing among different stakeholders involved in waste valorisation.

- The creation and development of a centralised European database for residual streams, monitored by the EU, that includes detailed information about agri-food waste streams, including their origin, characterisation and use, with detailed information about by-products. The database could serve as the basis for circular economy research and innovation initiatives.

- A harmonized legislation for residual stream valorisation costs across EU states could eliminate economic barriers (i.e., taxation) arising from differing legislations, stimulating circularity and sustainability while reducing concerns about costs.

- Design and apply top-down initiatives to ensure growing acceptance and demand of products coming from a circular origin whilst pushing producers to join the demand.

- Promote the access to revalorisation of by-products through the creation of financial investments programmes which cover research, development, technological infrastructure, and operational adjustments necessary for producers, especially SMEs to enter the valorisation market.

- To ensure and boost future approaches to plant extracts valorisation it would be ideal to have a harmonised regulatory framework; financial support to scale-up technologies such as subcritical water extraction to industrial level; research and innovation on plant extraction and enrichment processes such as adsorption resin; awareness raising among stakeholders and consumers about the benefits and positive impact of using plant extracts.

1. Introduction

One third of food produced globally ends up being wasted throughout various stages of the value chain[1]. In the European Union (EU), an estimate of 58.5 million tonnes are generated annually, where more than half of it is produced by households and the second largest share of it comes from the processing and manufacturing sectors, which causes significant economic, environmental, and social impacts[2]. The economic impact rises to losses of 132 billion EUR based on the food market value, plus the costs associated with its management. 252 million tonnes of CO_2, 342 billion metric cubes of water waste and impacts on soil due to associated land use reflect on its environmental impact. 36.6 million people with difficulties to access decent meals are not fed with the surplus of food, which ends up being wasted and so this causes a social impact. We can agree that "…wasting food is not only an ethical and economic issue but it also depletes the environment of limited natural resources"[3] in a complex context of increasing climate change, resource scarcity, increasing fluctuation of food prices and globally rising population.

In line with the concern for food waste, society faces the challenge of waste management. For years, waste has gone into landfills, resulting in an economic and environmental problem. The economic model based on a high use of resources and an excessive generation of waste has become unsustainable, and that is why the concept of circular economy has become relevant. In 2020, the total waste generated in the EU-27 amounted to 2,135 million tonnes or 4,815kg per capita, of which 32.2% was landfilled and only 39.2% was recycled[4]. Considering the figures there is a long way to go.

The food and drink industry is the biggest manufacturing sector in the EU, employing more than 4.5 million people involved in producing, processing, transporting, and selling food[5]. That is why ***the agri-food industry is a major actor in the generation of organic by-products.***

There are different stages during the agri-food value chain where residual streams can be located: production, post-harvest, processing and manufacturing, retail and wholesale, consumption, and services[6]. At the production and processing stages, residual streams are generated by a lack of careful handling of the product while being transported or stored, inefficient processing, food pollution or products that do not receive proper packaging[7]. If we move further through the chain, at the market and retail level food is wasted through a lack of adequate packaging, storage, and preservation[8]. At a consumer level, among others, aesthetic reasons play a role in driving food residual streams. Due to consumers' demands for the perfect aesthetic product, different actors higher up the value chain (including farmers and markets/ retail sector) interact and strive to meet this requirement: the result is large amounts of edible products discarded for not meeting the ideal visual characteristics[9].

As observed, the current situation within the agri-food industry is far from sustainable. FAO defines sustainable agriculture and food production as the correct management of natural resources that ensures the preservation of ecosystems functionality while ensuring future human demands. As Boix-Fayos and de Vente[10] explain,

1 Spanish Agency for Food Safety and Nutrition, Desperdicio Alimentario. Available at: https://www.aesan.gob.es/AECOSAN/web/para_el_consumidor/ampliacion/desperdicios.htm
2 European Commission (2023) Reducing food waste Factsheet.
3 European Union, Food Safety – Food Waste, Available at: https://food.ec.europa.eu/safety/food-waste_en
4 Eurostat – Waste statistics. Available at: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Waste_statistics#:~:text=Hazardous%20waste%20treatment-,Total%20waste%20generation,4%20815%20kg%20per%20capita.
5 Food Drink Europe. Data & trends of the European food and drink industry 2021. Available at: https://www.fooddrinkeurope.eu/resource/data-trends-of-the-european-food-and-drink-industry-2021/
6 Teigiserova,D.A., Hamelin, L., Thomsen, M. (2020). Towards transparent valorization of food surplus, waste and loss: Clarifying definitions, food waste hierarchy, and role in the circular economy, Science of the Total Environment, 707
7 Rodrigues, J., Liberal, A., Petropoulos, S., Ferreira, I., Oliveira, M. B., Fernandes, A., Barros, L. (2022). Agri-Food Surplus, Waste and Loss as Sustainable Biobased Ingredients: A Review, Molecules, 27(16)
8 Rodrigues, J., Liberal, A., Petropoulos, S., Ferreira, I., Oliveira, M. B., Fernandes, A., Barros, L. (2022). Agri-Food Surplus, Waste and Loss as Sustainable Biobased Ingredients: A Review, Molecules, 27(16)
9 Nance,E., Vadnais, A., Hicks, C., Lawson,T. (2023) Open Case Studies: Insistence on Cosmetically Perfect Fruits & Vegetables. The University of British Columbia. Available at: https://cases.open.ubc.ca/insistence-on-cosmetically-perfect-fruits-vegetables/
10 Boix-Fayos, C. & de Vente, J. (2023) Challenges and potential pathways towards sustainable agriculture within the European Green Deal, Agricultural Systems, 207, 3 Available at: https://www.sciencedirect.com/science/article/pii/S0308521X23000392

currently "*agroecosystems interact with natural systems in the provision of services to the society. However, the current intensive agro-industrial system of food production and consumption is not sustainable since it does not consider these interactions and is largely responsible for environmental disasters and land degradation including loss of soil organic matter and soil biodiversity, soil erosion and floods, overexploitation, contamination and eutrophication of surface and groundwater resources, land levelling, and removal of vegetation*". Naturally, the agri-food industry can and should play a fundamental role in striving to incorporate different lines of action to increase its sustainability and reduce environmental, economic, and social harm.

One path to move towards sustainability is for the agri-food industry to incorporate a circular logic. This can be exemplified by transforming its current value chains from a linear to a circular model. According to the Ellen McArthur Foundation[11], a circular economy model moves away from a linear model, where products are produced and later discarded as waste. It evolves into a circular system, one where waste and pollution are eliminated through the reuse of products and materials, thus allowing nature to regenerate.

When it comes to waste management, the agri-food industry plays a fundamental role as its waste streams could be transformed into valuable products or by-products but which usually end up discarded in landfills or burned[12]. If valorised, bioactive compounds, antibiotics, pigments or subtracts for phytochemicals could be obtained[13]. Thus, "waste" will not be further used in this white paper because all the streams discussed below will have a valorisation opportunity. Instead, by-product or residual stream will be used.

Overall, these by-products still contain interesting macromolecules like proteins, fats, and carbohydrates and interesting micro-molecules like polyphenols and carotenoids. These can be extracted, purified, and characterised by existing and emerging technologies, leading to the development of new commercial applications in food and non-food (pharmaceutical, biomedical, cosmetic, etc.) sectors"[14].

If it is not clear yet, lost food is lost potential. But what are some of the main challenges the agri-food industry faces in its shift to a circular model? Five interconnected challenges have been identified[15]:

- **First, the improvement of prediction tools to provide support to policy makers and companies. Life cycle analysis (LCA) remains incomplete as its inventory data are unavailable or not accessible to assess environmental impacts of current innovation in the agricultural waste management.**
- **Second, current agricultural valorisation technologies do not allow the full potential of the residual streams to be obtained.**
- **Third, ensuring that barriers to innovation are supressed. The complexity of the waste composition, the high energy demand for its processing, among other factors, result in barriers to the innovation in valorisation processes.**
- **Fourth, specialisation of by-product valorisation. As described previously, the by-products obtained from the agri-food industry are complex in their composition. Therefore, chains are designed to meet a single product valorisation, and integrated chain valorisation processes remain scarce and challenging to establish. A biorefinery approach should be the goal.**
- **Fifth, there is insufficient expertise in managing materials and knowledge flows to improve the presence of unstable nutrients, pollutants and agri-food by-products valorisation associated with waste management processes.**

The objective of this report is to highlight how the large-scale volumes of by-products produced by the agri-food industry are a unique opportunity to obtain these rich and complex components. As a result, new scenarios can be envisioned to reduce unnecessary production and environmental footprints focusing on leading circularity in the

11 Ellen McArthur Foundation, What is a circular economy? Available at: https://ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview
12 Asian Development Bank. (2022). Unlocking the Value of Agrifood Waste Streams Available at
13 Berenguer, C., Andrade,C., Pereire, J., Perestrelo, R., Câmara, J. (2023). Current Challenges in the Sustainable Valorisation of Agri-Food Wastes: A Review. Processes, 11.
14 Galanakis, C. (2015) Food Waste Recovery-Processing Technologies and Industrial Techniques. Academic Press Elsevier
15 Gontard, N., Sonesson, U., Birkved, M., Majone, M., Bolzonella, D., Celli, A., Angellier-Coussy, H., Jang, G.W., Verniquet, A., Broeze, J., Schaer, B., Batista, A. & Sebok, A. (2018). A research challenge vision regarding management of agricultural waste in a circular bio-based economy. Critical Reviews in Environmental Science and Technology, 48 (6), 614–654.

agri-food industry. This report also highlights the importance in involving governments and investors for driving and further supporting innovation in valorisation processes.

The next chapter will explain the importance of the agri-food sector in generating by-products; it explains its diverse composition focusing on residual streams elements from the meat, vegetables, dairy and alcoholic beverages sectors. It includes notions about its characteristics, environmental problems and potential uses or applications of the by-products.

2. Generation and composition of agri-food residual streams

Among the different industries present in the EU, the food industry (including drinks production) is the biggest manufacturing industry, with nearly 300,000 companies, employing 4.6 million workers and a turnover of 1.12 billion EUR[16]. It is the leading exporting industry with a turnover of 156 billion EUR (data of 2022). However, its environmental footprint is 85 Mt CO_2 per year[17], generating 18 Mt of food loss per year[18,19].

To identify potential uses of agri-food by-products, it is necessary to understand by-products generation and analyse its physical-chemical composition. This white paper presents the by-products generated in the four sectors with the highest turnover of the agri-food sector: the vegetable sector (tomato, artichoke and potato), the dairy sector (cheese production), the alcoholic beverages sector (beer and wine production) and the meat sector.

2.1. Vegetable sector

In 2022 the value of vegetables (and fruits) produced in the EU was estimated at 73.4 billion EUR, accounting for 14% of all agricultural production[20]. A significant part of the wastes from this sector currently remains underexploited. Streams from the processing of tomatoes, artichokes and potatoes will exemplify the potential of this sector to obtain value from its by-products.

2.1.1. Tomato

Tomato is one of the vegetable crops most widely produced in the world, being either consumed directly (fresh tomato) or used to produce tomato products (processed tomato). The industrial processing of tomatoes to obtain products such as paste, juice, puree, sauce, soup, ketchup, whole dried tomatoes, and tomato powder is an industrial activity with growing importance on a global scale, with worldwide production of processing tomato reaching approximately 40 million tonnes annually[21].

By-product generation

The main by-products generated in the tomato processing industry are tomato pomace, a mixture of tomato skins and seeds and discarded tomatoes. The quantity of by-products produced can vary from one processing plant to the other, due to the raw material characteristics and processing conditions. It has been reported to range from 1.5 % up to 5 % of the initial weight of tomatoes, thus representing from 600 thousand to 2 million tonnes of disposed organic matter annually worldwide[22].

Physical-chemical characterisation of by-products

Tomato pomace is a wet by-product with a dry matter content of 30-40%, of which a large amount is fibre (40-80%). Peel and seeds are rich in dietary fibre, red pigments carotenoid and lycopene, phenols, and proteins. While tomato peel contains antioxidants because of the presence of high concentrations of lycopene, tomato seeds encompass a predominant quantity and quality of plant proteins with most essential amino acids.

Potential application of the by-products

Tomato discards have been recognised as preventing the development of degenerative diseases, as they carry a high level of lycopene, β-carotene, vitamin C, and vitamin E[23]. Due to its high content of total dietary fibre (TDF), food processors are taking steps for an investigation into the use of tomato peel in new developments. Tomato pomace is used for compost production, as it is a positive nutrient for the soil, improving its structure and reducing erosion, and also for biogas production to produce energy.

16 FoodDrinkEurope (2022) DATA & TRENDS OF THE EUROPEAN FOOD AND DRINK INDUSTRY 2022.
17 FoodDrinkEurope (2022) DATA & TRENDS OF THE EUROPEAN FOOD AND DRINK INDUSTRY 2022.
18 EU Platform on Food Losses and Food Waste.
19 European Commission (2023) Reducing food waste factsheet.
20 European Commission- Agridata food portal: Fruits and Vegetables. Available at: https://agridata.ec.europa.eu/extensions/DataPortal/fruit-and-vegetables.html
21 World Processing Tomato Council (2020) http://www.wptc.to
22 Silva, Y.P.A.; Borba, B.C.; Pereira, V.A.; Reis, M.G.; Caliari, M.; Brooks, M.S.L.; Ferreira, T.A.P.C. Characterization of Tomato Processing By-Product for Use as a Potential Functional Food Ingredient: Nutritional Composition, Antioxidant Activity and Bioactive Compounds. Int. J. Food Sci. Nutr. 2019, 70, 150–160.
23 Bilton, R., Gerber, M., Grolier, P., & Leoni, C. (2001). The White Book on antioxidants in tomatoes and tomato products and their health benefits. Final report of the Concerted Action Fair CT97-3233. https://www.wptc.to/tomato-&-health-wptc.php.

Currently, this by-product is mainly used in animal feed or is placed in the landfills[24] (the EU still landfills or incinerates agri-food residues at different rates per country), thus representing costs and environmental concerns for the tomato processing industry. Being the second largest crop, it generates an estimated volume of 50,000 tonnes tomato by-products per year in EU, representing a serious disposal problem.

2.1.2. Artichoke

The artichoke is a crop cultivated in the Mediterranean area, with Italy and Spain being the main producing countries. Spain is the world's second largest producer of artichokes (215,000 t/year) after Italy (around 474,000 t/year)[25].

By-product generation

More than 60% of the artichoke total volume is discarded from consumption purposes, making available an abundant, inexpensive, and profitable source of natural antioxidants in the discarded fractions[26]. In Spain alone, more than 150,000 t/year of artichoke by-products are generated, (60% of raw material[27]) consisting mainly of stems and bracts.

Physical-chemical characterisation of by-products

Artichoke is considered one of the vegetables with the highest antioxidant capacity and content of polyphenols. Artichoke by-products can provide phenolic compounds, proteins, pectin and polysaccharides including cellulose and dietary fibre.

Potential application of the by-product

Artichoke by-products are promising as they have shown the presence of polyphenolic compounds, which act as health protectors due to their antioxidant properties; and contain inulin, a soluble fibre present in their heart fractions. All these compounds have an application in the nutraceutical and pharmaceutical industries due to its health-benefiting properties: digestibility, fat absorption, and water and mineral binding capacities. The fibre content of artichoke stems seems relevant for the food industry for its baking application: the addition of fibre concentrates in wheat flour significantly improved dough properties inducing an increase of water absorption, stability and tenacity, and a reduction of extensibility and softening in comparison to the dough without fibre.

As in the case of tomato by-products, and in general for all plant by-products, their main use is animal feed, and at a second level the production of biogas through anaerobic digestion.

2.1.3. Potato

Potato is widely consumed as food all over the world. In several countries, potatoes are one of the most important basic crops for human consumption, together with wheat, rice, and corn. According to the Food and Agriculture Organization (FAO), China is the biggest potato producer with an output of 72,000,000 tonnes, followed by Russia (35,718,000 tonnes) and India (26,280,000 tonnes)[28]. About 15% of potatoes are mainly processed into French fries.

By-product generation

In the potato processing industry, potato peelings are the largest generating by-product, followed by discarded potatoes. Depending on the peeling method used, it ranges from 15 to 40% of the raw material mass[29]. Industrial processing generates between 70,000 to 140,000 tonnes of peels worldwide annually. In Belgium alone, five million processed potatoes generate about 449,000 tonnes per year fresh potato peels. In addition, potato

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24 Silva, Y., Pereira, V., Reis, M., Caliari, M., Brooks, M. and Ferreira, T. (2019). Characterization of tomato processing by-product for use as a potential functional food ingredient: nutritional composition, antioxidant activity and bioactive compounds. International Journal of Food Sciences and Nutrition. 70(2), 1-11. Doi: 10.1080/09637486.2018.1489530.

25 Villanueva-Su·rez, M.J., Mateos-Aparicio, I., PÈrez-CÛzar, M.L., Yokoyama, W., & Redondo Cuenca, A. (2019). Hypolipidemic effects of dietary fibre from an artichoke by-product in Syrian hamsters. Journal of Functional Foods, 56, 156-162.

26 Noriega-Rodríguez, D., Soto-Maldonado, C., Torres-Alarcón, C., Pastrana-Castro, L., Weinstein-Oppenheimer, C., Zúñiga-Hansen, M.E. (2020). Valorization of Globe Artichoke (Cynara scolymus) Agro-Industrial Discards, Obtaining an Ex- tract with a Selective Effect on Viability of Cancer Cell Lines, Processes, 8, 715; https://doi.org/10.3390/ pr8060715.

27 Noriega-Rodríguez, D., Soto-Maldonado, C., Torres-Alarcón, C., Pastrana-Castro, L., Weinstein-Oppenheimer, C., & Zúñiga-Hansen, M. E. (2020). Valorization of globe artichoke (Cynara Scolymus) agro-industrial discards, obtaining an extract with a selective eect on viability of cancer cell lines. Processes, 8(6). http://doi.org/10.3390/pr8060715

28 The Potato—International Year of the Potato. [(accessed on 27 April 2020)];2008 Available online: http://www.fao.org/potato-2008/en/potato/index.html

29 Natu, R.B., Mazze, G., &. Jadhav, S.J. (1991). Waste Utilization." In Potato: Production, Processing, and Products. Edited by D.K. Salunkhe, S.S. Kadam, and S.J. Jadhav. Boca Raton, FL: CRC Press.

residue rots very quickly if not used immediately due to considerably high moisture levels[30].

Physical-chemical characterisation of by-products

Potato peels are good sources of starch (35-70%) and fibre (21-49%) and have low levels of protein. However, the main constituent is water, with a dry matter content of less than 18%.

Potential application of the by-product

Potato starch is widely used by the pharmaceutical, textile, wood, and paper industries as an adhesive, binder, texture agent, and filler. Potato starch is a 100% biodegradable substitute for polystyrene and other plastics and used, for example, in disposable plates, dishes, and knives[31]. Fuel-grade ethanol can be obtained through fermentation of potato by-product as starch[32]. Potato protein is good at limiting amino acids. Because of the quality of potato protein, by-products from potato processing plants can be used for feed, food, and diverse products.

As in the previous cases, its main current use is animal feed and biogas production. Surplus and discarded potatoes are used as feed for livestock and as raw material for the manufacture of starch, ethyl alcohol and a few other industrial products like, dextrose and liquid glucose among others.

A more in-depth analysis of current and innovative valorisation pathways will be made in Section 5.1.

2.2. Dairy sector

More than 12,000 dairy processing sites exist in the EU. Five of the top ten global dairy companies are European, and the European milk processing industry brings more than 9.3 billion EUR to the overall EU trade balance[33]. In 2021, a total of 150.7 million tonnes of milk were processed to produce dairy products[34], and 10.4 million tonnes of cheese was produced. Here, emphasis is made on the main residual stream from cheese industry: cheese whey.

By-product generation

In general, the production of 1kg of cheese yields 9kg of whey from 10 litres of milk, although the amount obtained varies greatly depending on the type of cheese produced[35].

Physical-chemical characterisation of by-products

Although its composition varies depending on the origin of the milk and the type of cheese produced, in general the approximate water content is 90 to 95%. Whey is a nutrient-rich product; for example, 1,000 litres of whey contain more than 9kg of high biological value protein, 50kg of lactose and 3kg of milk fat. This is equivalent to the daily protein requirements of about 130 people and the daily energy requirements of more than 100 people.

Potential application of the by-product

The sugars of cheese whey can act as substrate for bioprocesses such as fermentation, in order to produce a wide spectrum of products (fatty acids, alcohols or biopolymers). Their proteins are very useful for films and coatings production due to their gas barrier properties.

A more in-depth analysis of current and innovative valorisation pathways will be made in Section 5.2.

2.3. Alcoholic beverage sector

2.3.1. Beer

Beer is one of the most popular and consumed drinks all over the world. The alcoholic beverages market in Europe is one of the largest in the world. Western Europe represented a market value of approximately 359 billion EURin 2020[36].

By-product generation

Brewer's spent grain (BSG) is the main solid by-product from the brewing industry (grain husks, parts of the pericarp and seed coat layers), representing the 85% of the total by-products generated during the beer production and it is generated at a ratio of

30 Ncobela, C.N., Kanengoni, A.T., Hlatini, V.A., Thomas, R.S., Chimonyo, M. (2017) A review of the utility of potato by-products as a feed resource for smallholder pig production. Animal Feed Science and Technology, 227,107-117. https://doi.org/10.1016/j.anifeedsci.2017.02.008.
31 FAO (2008) Potato: New light on a hidden treasure. FAO. https://www.fao.org/3/i0500e/i0500e02b.pdf
32 FAO (2008) Potato: New light on a hidden treasure. FAO. https://www.fao.org/3/i0500e/i0500e02b.pdf
33 EDA (European Dairy Association), Annual Report, 2014, 2015 and 2020
34 Eurostat, 2021.
35 Panesar, P. S., & Kennedy, J. F. (2012). Biotechnological approaches for the value addition of whey. Critical Reviews in Biotechnology, 32(4), 327–348.
36 Statista. Available at: https://www.statista.com/topics/3932/alcohol-market-in-europe/#topicOverview

around 20kg of BSG per 100L of beer[37].

Physical-chemical characterisation of by-products

BSG has a high protein (20-30%), and fibre content (45-70%), and to a lesser extent, other compounds such as starch, lipids, or phenolic compounds[38,39].

Potential application of the by-product

Currently, BSGs are handled as animal feed[40] or disposed of in landfills, although their main constituents (proteins and fibre) can be valorised in many ways, which has been analysed in Section 5.3.

2.3.2. Wine

The EU is the main wine producer and exporter in the world, and the wine industry has a great importance in the alcoholic beverages sector, producing around 15.8 billion litres in 2019[41]. During the industrial process of winemaking, the grape pulp, seeds and skins (also known as grape pomace) are obtained as the main by-product.

By-product generation

Four types of by-products from winery industries can be identified: the main stream is the mixture of seeds and peels, representing the 25% of the initial raw material[42], pomace, and two secondary streams such as the unfermented lees from white grapes and the fermented lees from black grapes, and the stems, representing the 6%[43] and 4%[44] of the raw material, respectively.

Physical-chemical characterisation of by-products

Polyphenols, such as tannins, and anthocyanins are highly present in stems, seeds and lees. The pomace or the mixture of seeds and peels has a dry matter content of between 30% and 45%, with dietary fibre being the main component (35-70%). Stems are very poor in sugars (less than 1 % in dry matter), and very rich in cellulose, lignin and hemicellulose due to their woody nature. And finally, the lees are the wine by-product with the highest percentage of proteins, and a very high concentration of ash, much higher than that of any agri-food waste, and also higher than the by-product of any fermented drink such as beer.

Potential application of the by-product

According to a multitude of studies such as those shown in the review by Troilo et al.[45] or Poveda et al.[46], winery residual streams such as grape skins, stems and wine lees, have received increasing attention for their applications in the food sector, as they are a good source of functional and bioactive compounds, in particular by exploiting antioxidant and/or antimicrobial activity or their extracts to replace the most common additives and to test activity against food pathogens.

More in-depth analysis of the grape pomace residual stream has been carried out in Section 5.4.

2.4. Meat sector

The meat sector has a great importance in the agri-food industry in the EU, accounting for one quarter of the total value of agricultural production. One of

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37 Wagner, E., Pería, M.E., Ortiz, G.E., Rojas, N.L., Ghiringhelli, P.D. (2021). Valorization of brewer's spent grain by different strategies of structural destabilization and enzymatic saccharification. Industrial Crops and Products, 163, 113-129. https://doi.org/10.1016/j.indcrop.2021.113329

38 Mussatto, S.I. (2014). Brewers spent grain: a valuable feedstock for industrial applications. Journal of Science Food & Agriculture, 94(7),1264–1275.

39 Petron, M.J., Andrés, A.I., Esteban, G., Timón, M.L. (2021). Study of antioxidant activity and phenolic compounds of extracts obtained from different craft beer by-products. Journal of Cereal Science, 98. https://doi.org/10.1016/j.jcs.2021.103162.

40 González-García, E., Marina, M.L., García, M.C. (2021). Impact of the use of pressurized liquids on the extraction and functionality of proteins and bioactives from brewer's spent grain. Food Chemistry, 359. https://doi.org/10.1016/j.foodchem.2021.129874

41 EUROSTAT. https://ec.europa.eu/eurostat/web/products-eurostat-news/-/edn-20201119-2

42 Chowdhary, P., Gupta, A., Gnansounou, E., Pandey, A., & Chaturvedi, P. (2021). Current trends and possibilities for exploitation of Grape pomace as a potential source for value addition. Environmental Pollution, 278, 116796. http://doi.org/10.1016/j.envpol.2021.1

43 Nerantzis, E. T., & Tataridis, P. (2006). Integrated Enology- Utilization of winery by-products into high added value products. E-Journal of Science and Technology, 1(3), 79–89.

44 Souquet, J. M., Labarbe, B., Le Guernevé, C., Cheynier, V., & Moutounet, M. (2000). Phenolic composition of grape stems. Journal of Agricultural and Food Chemistry, 48(4), 1076–1080. http://doi.org/10.1021/jf991171u

45 Troilo, M., Difonzo, G., Paradiso, V.M., Summo, C., Caponio, F. (2021) Bioactive Compounds from Vine Shoots, Grape Stalks, and Wine Lees: Their Potential Use in Agro-Food Chains. Foods, 10, 342. https:// doi.org/doi:10.3390/foods10020342

46 Poveda, J.M., Loarce, L., Alarcón, M., Díaz-Maroto, M.C., Alañón, M.E. (2018) Revalorization of winery by-products as source of natural preservatives obtained by means of green extraction techniques, Industrial Crops and Products, 112, 617-625, https://doi.org/10.1016/j.indcrop.2017.12.063

the great challenges of the current meat industry is the management of the by-products generated. Meat by-products are presented as difficult to manage, which leads companies to entrust them to special waste managers, representing an extra cost for the industry, as well as an environmental problem.

By-product generation

Among the activities of the meat industry, a focus on the slaughterhouses and cutting plants will be used to reflect on the waste streams of veal and pork[47]. The productive processes taking place at slaughterhouses generate common by-products from parts of the animal such as blood, offal and manure, but also other animal-specific residual streams such as pig hair or chicken feathers.

Physical-chemical characterisation of by-products

Animal blood is a protein-rich residual stream, accounting for around 90% of dry weight. Animal offal is also very rich in proteins, even though it is a thicker by-product with 30% of dry matter. Animal manure, which is the digested food found in the stomach of slaughterhouse animals, is very rich in fibres (around 36%), which come from the grass of the animal diets. On the other hand, pig hair and chicken feathers are very rich in keratin (up to 95% of dry weight[48]), the main constituent of hair, and have many applications in cosmetic industries. These residual streams also have very low water content, contributing to its stability during storage.

Potential application of the by-product

Blood contributes with a high organic load to the wastewater stream when it is discharged into water systems. However, it can be considered as a by-product, for further use as an organic soil amendment for different crops. This blood must be heat treated and coagulated before its use. Blood management is a problem in many slaughterhouses, as there are very few treatment factories for the use of this material in its liquid state. For its collection and subsequent treatment by incineration, it must be coagulated, so in medium-large slaughterhouses the blood is collected in tanks for this purpose and heat treatments are used to reduce its volume and subsequent delivery to an authorised waste manager.

Animal manure is mainly used in anaerobic digestion plants for the production of biogas or fertiliser for its nitrogen content in some crops.

47 The Project takes data from Model2bio project.

48 Pahua-Ramos, M.E., Hernández-Melchor, D.J., Camacho-Pérez, B., (2017). Degradation of Chicken Feathers: A Review. BioTechnology: An Indian Journal, 13. (6):153

3. Innovative emerging technologies for agri-food by-products valorisation

The by-products of agri-food companies constitute a significant burden for environment when handled inappropriately, while their rich nutrient content makes them a very promising source of valuable compounds. Therefore, their management is a very important, but also complicated issue with economic, social, and environmental aspects involved. The conventional pathways to manage agri-food industry waste involve landfilling, incineration, composting and animal feeding, which have been applied for many years now.

These treatments cause a loss of potential and in some cases a large economic and environmental burden. On the other hand, and promoting circular economy approaches, the emerging technologies presented in this section involve the valorisation of agri-food by-products as products with higher added value, like bioactive compounds, enzymes and products that can be used in the food industry as additives.

Emerging technologies can be understood as disruptive technologies that are not yet established at full-scale in the industry but that are promising alternatives for current technologies in terms of sustainability, productivity or both. This chapter will highlight some of the most promising technologies for valorising residual streams. However, brief clarification should be made. Most valorisation technologies need previous intermediate processes in order to prepare the residual stream for further valorisation process. The intermediate steps applied within agri-food by-product management schemes involve mostly storage, transfer and stabilisation. Thus, pre-treatments set the foundation of optimal final treatments for the recovery of components from by-products. Even though these intermediate processes are not included in this section, it is important to state their importance in the full value chain.

In Section 5 more information about these valorisation processes and its products is described.

3.1. Fermentation technology

3.1.1. Technology definition

Fermentation is a bioprocess conducted by bacteria and yeast under aerobic or anaerobic conditions. It consists of the breakdown of sugars to produce energy for the cells while producing different compounds (acids, alcohols, gases), depending on the microorganism and the biochemical route. In industrial biotechnology, two main strategies are followed; pure or mix cultures. Pure cultures are based on single microorganism species cultivation. This strategy has higher operational costs, but the product spectrum is wider and higher added-value compounds can be obtained. Mixed cultures use a balanced combination of microbial species that have the ability to work together to produce a range of products.

3.1.2. Advantages and disadvantages

The main *advantages* of this technology are the wide spectrum of products that could be obtained and its ubiquity in many sectors (food, pharmaceutical, textile…). Also, the low cost and sustainability when working with mixed cultures is a clear advantage. Furthermore, as the technology itself has been long used, research on it already has a solid base.

The *drawbacks* from the technology are that as it is a biologic process, it is very sensitive to system changes, which requires a good control system. It can also see its operating costs increased when working with pure cultures, although the products obtained with this strategy tend to have higher added-value. The complex and heterogeneity of residual streams composition is a challenge when designing specific fermentation strategies and must be looked closely for each substrate.

3.1.3. Application to residual streams

This technology is a good option for residual streams with high water content, as biological reaction occurs in water medium, and high carbohydrate content, as it is the main substrate of the process. Some of the substrates, identified during the execution of in Model2Bio project, that are good candidates for this technology are cheese whey, grape pomace, or potato peels (see chapter 5 for further information on their case studies).

3.1.4. Technology readiness level

Industrial fermentation has been applied for centuries to produce beer and wine for example, but its application to valorise by-products from food industries is nowadays at TLRs of 1-3. In contrast, fermentation of lignocellulosic biomasses to bioethanol (2nd Generation bioethanol) is at a high TRL (commercial process). Due to its potential, we think that it is worth the investment in closing the gap between research and industry for the valorisation of agri-food residual streams by fermentation. The wide spectrum of products that can be formed, the flexibility of the microbial strains to convert the sugars and other components in the biomasses and the extended current knowledge on industrial fermentations, are clear advantages in further developing fermentation processes for residual streams from food and brewery. These advantages stimulate further investments in innovation.

3.2. Adsorption resin to enrich extracts

3.2.1. Technology definition

Adsorption resin is a method used in purification processes to concentrate specific metabolites and eliminate undesired products by a simple principle. In general, this technology allows an enrichment factor between 3 and 10. The principle is based on the affinity of the targeted metabolites with a specific resin and worked in 3 main steps. First, the sample solution is added to the resins and a first fraction is recovered, the raffinate. During this step, resins trap the metabolites of interest, and the other compounds go through it and are recovered in the raffinate. The second step of the process is the washing step. Usually, water is used to remove the rest of the sample solution that was not trapped in the resins and is recovered in the "washing" fraction. The final step is the elution of the compounds of interest by an appropriate solvent, usually ethanol or methanol for phenolic compounds. Solvent is added to the resins and takes off the metabolites from the resins. The eluate fraction, enriched in compounds of interest, is recovered.

3.2.2. Advantages and disadvantages

This technology has some *advantages* over other techniques that can also enrich or purify the extract, such as membrane filtration, crystallisation, and flash chromatography. Adsorption resin can concentrate the product by a factor of 3 to 10, depending on the type of resin and the operating conditions. It can also achieve a very high specificity for the desired product, which results in a lower loss of valuable compounds and lower contamination by undesired ones. Another advantage of adsorption resin is that it can be reused many times on different batches of extract, which reduces the operational cost and the environmental impact of the process.

However, adsorption resin also has some *disadvantages* that need to be considered. For instance, adsorption resin requires a pre-treatment of the extract to remove any suspended solids, fats and oils that can block the pores of the resin and reduce its performance. It may also have a limited capacity and selectivity for some compounds. Moreover, adsorption resin may degrade over time, which affects its stability and efficiency.

3.2.3. Application to residual streams

One of the difficulties in valorising agri-food industry by-products through extraction technologies is to produce a product with high levels of interesting molecules, when the initial material is often low in bio-actives compounds. A primary extraction technology (such as subcritical water extraction, SWE or supercritical CO_2 extraction, SFE-CO_2) can be used after some development steps to extract the elements of interest from a by-product. But the levels achieved are still rather low, because of the co-extraction of molecules that have similar polarities to the ones targeted. Adsorption resin can selectively capture certain types of actives (like polyphenols for instance). In this way, it is possible to remove from a primary extract the unwanted elements that were co-extracted during the primary extraction and obtain a higher enrichment and higher levels in the final product. Combining these two technologies allows us to get a product with high levels of interesting molecules and a high added value, even from a low-active starting material, such as agri-food industry by-products.

3.2.4. Technology readiness level

Adsorption resin has a lot of potential in various fields and is widely used in labs. At a higher scale, this technology is not yet very developed even though pilot plants already exist. The main obstacle to its use is the high cost of buying the resin, but this can be reduced by cleaning and reusing the resin for multiple productions.

3.3. Microbiome determination

3.3.1. Technology definition

In Model2Bio we have determined the microbiome (community of microorganisms) present in the by-products in order to identify microorganisms that could be useful for residual stream stabilisation or valorisation. This technology consists in taking homogenic samples of the residual streams and extracting the bacterial DNA present. With advanced sequencing analysis it is possible to know which species are present in the sample.

3.3.2. Advantages and disadvantages

Taking *advantage* of beneficial microorganisms that already exist in the residual stream can be a way to develop simplified processes for storage or processing. As an example, the growth of certain microorganisms with beneficial properties could be stimulated by adapting the incubation conditions (temperature, aeration, etc.) or the process conditions in the factories.

Some *disadvantages* of the technology are that the extraction of DNA from complex samples can be challenging and may need protocol adaptions from by-product to by-product. Another drawback of the technology is the high costs associated to the microbiome analysis of the samples, as many samples need to be taken during the processing. It is possible to sequence a high number of samples together, reducing the cost of the analysis, but it is necessary to be able to gather multiple samples during the entire production and storage processes to monitor the microbiome development.

3.3.3. Application to residual streams

This approach has been applied, for example, to the storage of tomato seeds and peels, where the evolution of the microbiome in the samples was followed up and analysed during storage at different conditions. Under certain conditions, acidification was observed, as a result of growth of specific lactic acid bacteria, contributing to the stability of the material.

Knowledge on the microbiome in the wastes can be applied as well to modify the characteristics of the materials for enrichment in healthy components or for conversion of components into useful products [49].

3.3.4. Technology readiness level

The microbiome determination technology is advancing at a rapid pace and nowadays some equipment and companies can be found that perform these types of analyses. Although it is not widely applied to agri-food products. This technology has vast potential for acquiring important knowledge of the residual streams when deciding which the best option for storage and / or valorisation is.

49 Marshall, C. W., LaBelle, E. V., & May, H. D. (2013). Production of fuels and chemicals from waste by microbiomes. Current opinion in biotechnology, 24(3), 391–397. https://doi.org/10.1016/j.copbio.2013.03.016

4. Novel digital tools to maximise value from agri-food by-products

As we have observed in previous chapters, technological support is key for success in residual stream valorisation. Beyond this application to specific treatments, innovative tools underpin a wide array of initiatives to support waste management through different means. By zooming out, the objective of this chapter is to highlight some of the current development of digital tools applied in the EU context of agri-food by-product valorisation.

4.1. Model2Bio Decision Support System (DSS) tool

4.1.1. Description and objectives

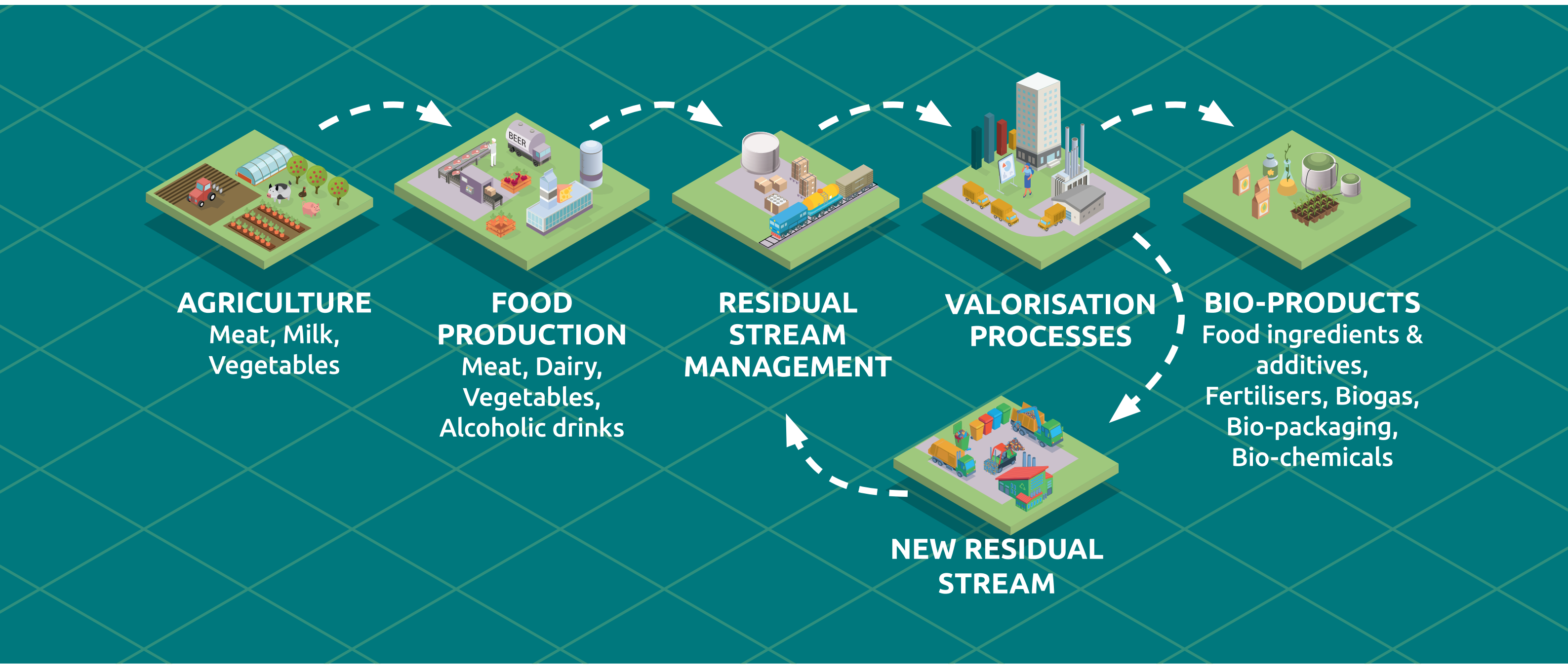
Most agri-food organic by-products present a high complexity and a heterogeneous mixture, which make the production and separation of specific compounds difficult. Furthermore, the variability in quantities and physical-chemical composition of these streams, as well as their seasonality limit the technological and economic feasibility of the conversion processes for valuable products. Therefore, a deeper knowledge of the composition, logistics, volume and valorisation potential of organic by-products could support the decision-making process to maximise the benefit of a specific raw material and select the most appropriate technologies for its optimal recovery.

The solution suggested within the Model2Bio project involves the development of an innovative decision-support (DSS) tool to help predict the physical-chemical characteristics of the by-products generated in the agri-food sector and select the best valorisation alternative.

The tool has a holistic perspective for the selection or prioritisation of the valorisation routes, taking into account technical, economic, environmental and social aspects. Firstly, the tool performs a technical/economic prioritisation to select the best valorisation options, and later, these priorities are analysed from a general environmental, social and economic perspective.

Based on general information about agri-food companies, the tool predicts the best way to valorise food by-products, estimating in turn the type and quantity of the bio-products produced, the energy generated, the net operational costs of the entire value chain, and the waste generated, among several other aspects.

The tool is based on the interconnection of

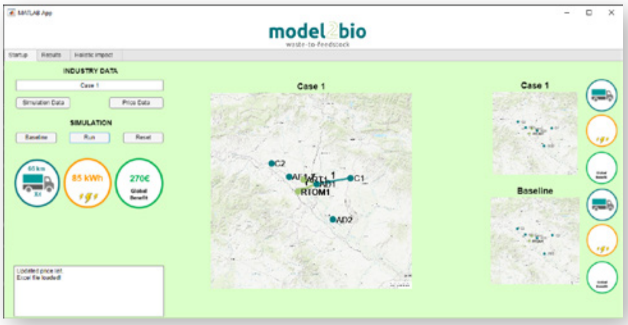


Graphical representation of the Model2Bio-DSS tool

3 elements: simulation module, optimisation algorithm and LCA module.

- **Simulation module:** able to predict the mass fluxes for any bio-based by-product alternative using a set of compatible model libraries describing the agri-food production lines, the intermediate processes (storage, mixing, separation and transport) and the final valorisation in the bioprocesses.
- **Optimisation algorithm:** will select automatically the bio-based by-products alternatives that minimise a global cost function previously defined using the mathematical models constructed.
- **LCA module:** estimates the environmental, economic and social impacts associated with any bio-based by-product alternative using an LCA methodology.

The next figure shows the layout of the M2B DSS tool.



Layout of the DSS tool

4.1.2. Expected contribution in the field of by-product management

As part of the Model2Bio project, the tool is being tested in 3 European areas (Spain, Greece, Belgium) in order to analyse different management systems, with different degrees of development of valorisation technologies.

- The tool enables an effective and innovative approach to applying circular economy models in agri-food value chains. It can offer different advantages for various groups, including agri-food companies, waste management companies and bio-industries. It can be a strong asset of the involved stakeholders in terms of knowledge increase about the potential of the examined by-products and valorisation pathways, revenue increase and business opportunities within handling and valorisation of agri-food by-products. It can also be in terms of new markets, new processes and the identification of new products. More specifically, the tool can help to:

BIO-INDUSTRIES
- increase the knowledge about the potential of its agri-food by-products.
- find new ways to value its by-products.

WASTE MANAGEMENT COMPANIES
- increase income and business opportunities by providing new ways of handling agri-food by-products.

BIO-INDUSTRIES
- identify of new markets: new processes, new by-products.
- optimise their processes through a greater knowledge of the availability of by-products and the effect of introducing new by-products.

The outcome of the project will not be a marketable product, but a demonstration of what it can actually do and predict. Even so, while the marketable tool is being finalised, the Model2Bio-DSS tool will be available to assist the entire value chain through support or consulting studies in the optimal way to manage residual streams. This is a solution adapted to the needs of the sector, since not all clients addressed by the tool are experts in the use of this type of software. If clients would like to be users, adapting the Model2Bio-DSS tool to a specific area and distributing usage licenses is also an option.

4.1.3. Expected Challenges

The development of realistic decision support tools presents numerous limitations and obstacles:

Collection of real information:
The main challenge in the development of decision-making tools is the collection of information to build the tools, since companies are reluctant to share information about their processes.

Information integration:
All information collected on traditional and emerging technologies, by-product production, composition, location of producing companies and more, must have the same level of detail, to ensure a balance of information.

Seasonality and complexity of organic by-products:
Organic by-products are very heterogeneous and have great variability in their composition; consequently obtaining good characterisation results is a great challenge.

Up-scaling of valorisation technologies:
Emerging technologies evaluated during the Model2Bio project, or technologies analysed in European pilot-scale projects, have major scientific challenges helping bring these technologies closer to large-scale application.

4.2. BRILIAN Optimisation Toolkit

4.2.1. Description and objectives

The BRILIAN[50] project aims to contribute to set long-term strategies for the adoption of cooperative business models in EU. The project will run three specific pilots that are real-environment demonstrations at high TRLs. The business models developed around BRILIAN pilots will draw on existing rural infrastructures in which current main processes and contractual agreements will be adapted in order to maximise benefits while reducing operational risks. In this regard, business model design approaches will be supported by modules dealing with organisational, logistic and sustainability factors included in the BRILIAN optimization toolkit. This toolkit aims to provide support for the design and optimisation of bio-based value chains, putting primary producers in the centre.

The modules seek to provide guidance when designing business models for new bio-based value chains. They consider organisational, logistic, environmental and social aspects. The **organisational module** aims to contribute to enable new forms of collaboration among actors of bio-based systems. Contractual agreements between primary producers and biorefinery owners will be proposed for optimised value chain planning and the management of agricultural by-products in a bio economy context.

The **logistic module** aims to provide insights on the benefits and potential implementation of the shortest possible supply chains to demonstrate low/zero-ILUC operations allowing the supply chains to adopt a twofold purpose. On one hand, improving the management of bio-based feedstock for the current industrial use and, on the other hand, enhancing the identification of cost-effective chains of custody in the bio-based feedstock supply chains for biorefineries.

The third module developed will be the **sustainability module** that will include aspects for the circularity and social framework evaluation and the environmental assessment methodology. These last two modules will be cross-checked under the digital **optimisation toolkit**, which will go across the indicators and data coming from these modules to provide ad-hoc recommendations on business cases building for the value chain under analysis. Accordingly, using as input data generated and gathered during the project, this digital toolkit will support critical decisions on business case propositions.

The BRILIAN optimisation toolkit seeks to maximise benefits of rural communities while supporting the implementation of circular and sustainable bio-economy value chains, enabling vertical integration of the primary producers to generate added value bio-products. Therefore, it will contribute to maintaining economic value locally for farmers, cooperatives and agroindustry while both increasing the circularity of the primary sector and the share at European level of bio-based products obtained through the valorisation of by-products and side streams from their processes, in turn contributing to the decarbonisation objective.

4.2.2. Expected challenges

Nevertheless, the deployment of bio-based value chains in rural areas faces several challenges. These include policy and regulatory barriers and also regional particularities such as the limitations related to the sales channels, given that these markets are new for farmers. Additionally, BRILIAN must deal with different technological barriers, including the need for TRL improvement. This covers the successful scale-up and adaptation to industrial conditions of processes and methods previously validated under laboratory conditions, and the redesign of processes that were initially designed to operate in a narrow range of parameters and must now comply with requirements associated to new stream flows and conditions.

50 The project is supported by the Circular Bio-based Europe Joint Undertaking and its members under grant agreement N° 101112436. Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or CBE JU. Neither the European Union nor the CBE JU can be held responsible for them.

4.3. MixMatters Integrated System

4.3.1. Description and objectives

The MixMatters[51] integrated system is a smart and multi-purpose solution that makes valorisation of a wide range of mixed bio-waste streams containing impurities from the agri-food industry a viable option. The system consists of a separation unit and the valorisation hub, encompassing a range of advanced technologies into an integrated system that is mobile, modular, multi-purpose and smart.

The separation unit efficiently sorts, separates, and prepares the feedstock by removing impurities like plastic, cardboard, and metals from the biological compounds found in mixed bio-waste. It is a versatile biorefinery that combines cutting-edge technologies to process and enhance the previously separated streams, resulting in high-value products. Both components are integrated with an advanced decision support tool that decides on the integrated system configuration and the logistics, to ensure the most optimal cost-benefit and best environmental performance of the entire process.

The overall objective of MixMatters is to set up the system and demonstrate the separation and valorisation of mixed agri-food biowaste containing impurities such as plastic, cardboard or metal and coming from three streams from the agri-food industry (wholesale markets, greenhouses, and the food and drink industry) into six high-value outputs: powdered ingredients, sugar concentrates, recombinant proteins, green fibres, bioactive compounds, and plastic monomers.

In relation to this, the project aims to:

a. profile the targeted waste streams and waste generation sites and plan the demonstration, laying the ground for industrial symbiosis

b. test and optimise the separation unit and valorisation hub prior to demonstration

c. validate the quality, quantity, and commercial value of the outputs with end users

d. guarantee regulatory compliance and safety of the project developments, as well as assessing the environmental and techno-economic aspects of the entire solution and social acceptance of the final products.

e. engage multiple actors in the process with a view to securing widespread, long-term deployment of the results

f. ensure wide visibility of the results, thereby increasing public awareness of bio-based solutions.

4.3.2. Expected contribution in the field of residual stream management

Thanks to the MixMatters Integrated System**, 2 types of innovative separation and 7 valorisation technologies** will be advanced from at least TL5 to TRL7. In the mid-term perspective (3-5 years after the end of the project), the MixMatters system is expected to:

- process approximately 6,240 tonnes of mixed biowaste a year, thus reducing landfill use and incineration of waste, increasing processing of biowaste, and helping to meet EU reuse and recycling targets
- process approximately 1,123 tonnes of plastic a year, preventing pollution and biodiversity loss
- avoid the emission of 2,780 tonnes of CO_2 every year
- market launch of 6 high value-added products
- engage with new agri-food producers and bio-based product industries to create at least two new value chains from the adaptation and configuration of the MixMatters waste valorisation technology
- expand opportunities for the use of biowaste at all stages of value chains and across all sectors so as to foster industrial symbiosis
- support the market uptake of innovative waste valorisation technologies with the prospect of generating 24.6 million EUR of revenue in the first 5 years of industrial exploitation of the system

4.3.3. Expected challenges

The valorisation of mixed bio-waste presents several limitations and bottlenecks in current technologies:

51 The project is supported by the Circular Bio-based Europe Joint Undertaking and its members under grant agreement N° 101112409. Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or CBE JU. Neither the European Union nor the CBE JU can be held responsible for them.

Waste homogenisation and impurities:
The process starts with residual stream homogenisation, aimed at obtaining impurity-free residual streams or particles of equal size. Mechanical homogenisation is typically employed, yet it possesses limitations as non-organic impurities in the by-products can damage equipment or diminish efficiency.

Limited applicability:
Present valorisation processes are better suited for the organic fraction of municipal bio-waste, which boasts consistent quantities and seasonality. However, this does not apply to agri-food residual streams from sources like greenhouses, wholesale markets, and food industries. Developing technically and economically feasible systems for these streams is arduous.

Separation technologies:
Leading-edge technologies for residual stream separation often rely on conventional methods with limitations in terms of the types of streams they can process (e.g., specific materials like metal particles) and cost efficiency (high labour costs). Although advanced technologies are emerging to enhance efficiency, their application is still restricted.

Focus on collection over separation:
Most leading developments in residual stream management are centred on collection (e.g., smart bins, monitoring technologies for real-time data) rather than separation. This results in a gap in addressing the challenges linked to the efficient separation of mixed bio-waste.

Valorisation suitability:
Valorisation technologies are viable for homogeneous agri-food residual streams or constant municipal mixed bio-waste. However, these technologies are not well-suited for agri-food streams that contain complex components of higher value, such as biomaterials and speciality ingredients for food and feed.

Valorisation methodology:
Different valorisation methods exist, such as thermochemical and biochemical processes, but they require by-products to be relatively non-polluted. Additionally, these methods might not always be implemented at an industrial scale or economically feasible, thus creating a barrier to widespread adoption.

Complexity of valorisation:
The valorisation of mixed bio-waste is a complex process that involves multiple steps, including homogenisation and different valorisation pathways. The complexity can lead to challenges in scaling up and effectively implementing these processes.

Lack of impurity handling:
Impurities present in mixed bio-waste can pose challenges during the valorisation process. These impurities might not be effectively managed by existing technologies, leading to decreased efficiency or undesirable outcomes.

4.4. B-Resilient Skills Hub

4.4.1. Description and objectives

The B-Resilient[52] Skills Hub, an integral element within the European B-Resilient project, serves as a structured document tool. Its core purpose is to provide European food production SMEs with access to a wide array of valuable resources. This hub primarily aims to support SMEs by imparting the necessary knowledge and expertise to optimise biomass use and minimise waste generation. It is regularly updated throughout the project to incorporate the latest insights and best practices related to biomass valorisation and zero waste strategies. The skills hub is a collaborative effort by the B-Resilient partners and functions as a centralised repository tailored to the specific needs of food production SMEs.

With ease of navigation, users can explore an assortment of resources that empower them to enhance operational resilience and work toward sustainable growth. The skills hub's fundamental goal is to enable European food production SMEs to unlock the potential of biomass, contributing to a more environmentally conscious and operationally efficient industry. You can consult the Skills Hub here: https://t.ly/xwWwQ

The B-Resilient project aims to enhance the resilience of European food production SMEs (within the agri-food ecosystem. It seeks to achieve

52 This project has received European funding under Grant Agreement 101074621 of which 1,12 million goes directly to Food Processing SME thanks to the B-Resilient Financial Support to Third Parties Scheme. Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EISMEA. Neither the European Union nor the granting authority can be held responsible for them.

this by optimising the use of biomass, a crucial component of the agri-food and bio economy sectors. The project's focus is on maximising the use of available raw materials and converting by-products into bio-based ingredients, aligning with zero-waste and circular principles.

Importantly, the challenges and opportunities in the agri-food sector align with those in other industries that work with bio-based materials. B-Resilient seeks to connect the agri-food ecosystem with sectors such as cosmetics, green chemistry, and the broader bio-based economy, promoting collaboration and the development of new products that meet consumer demand. Examples include plant-based protein snacks mimicking the sensory qualities of meat, natural cosmetics made from biomass-derived components, and sustainable bioplastics and bio-lubricants for packaging.

The project aims to create new value chains and business models for European food production SMEs, fostering continuity and resilience for themselves and other stakeholders in the value chain. Digital technologies will play a crucial role in enabling circular solutions, improving economic and ecological sustainability, and enhancing cooperation among value chain participants. These digital tools will accelerate the adoption of new products and services and support their internationalisation.

Overall, B-Resilient contributes to building resilience in the agri-food ecosystem and expedites the transition of SMEs toward a green and digital economy, aligning with the objectives of the updated EU Industrial Strategy.

4.4.2. Expected contribution in the field of residual streams management

- **Enhancing biomass management**: B-Resilient actively promotes sustainable practices in biomass management, contributing to reduced waste and increased resource efficiency in various industries.

- **Empowering SMEs for resilience**: The project equips SMEs with the knowledge and tools needed to enhance their operational resilience and sustainable growth.

- **Driving innovation**: B-Resilient fosters innovation by supporting the development and deployment of market-ready, bio-based solutions, inspiring new products, services, and business models.

- **Supporting international expansion**: SMEs receive support for international expansion, with a focus on marketing bio-economy products and solutions, enhancing their competitiveness and facilitating growth.

- **Restoring consumer trust**: The project actively works to rebuild trust in sectors such as agri-food, cosmetics, and chemistry by highlighting sustainable, bio-based solutions, encouraging healthier and more sustainable consumption habits.

- **Boosting employment**: Sustainable businesses supported by B-Resilient offer stable job opportunities, strengthening societal well-being and resilience.

- **Contributing to global sustainability**: By promoting sustainability, resource efficiency, and climate neutrality, B-Resilient contributes to a more sustainable and resilient global ecosystem.

4.4.3. Expected challenges

The agri-food value chains, encompassing production, manufacturing, and distribution of food, face significant challenges.

- The volatility in energy costs, logistic constraints, currency exchange rates, and resource scarcity is one of the main challenges of the agri-food industry.
- Unique vulnerabilities arise from food's limited shelf life and variations in raw material quality and availability, especially in organic products.
- Climate change exacerbates these issues, leading to extreme weather conditions, declining global crop yields, food waste, and environmental damage.
- The growing global population, expected to reach 9.7 billion by 2050, contributes to increased demand for resource-intensive meat, dairy, and processed foods, straining both dietary health and environmental resources.
- Changing customer preferences, especially in the West, demand greater transparency and sustainability in supply chains.
- Trade disputes and protectionist measures further complicate the agri-food ecosystem.

- Rising labour costs and limited pricing power challenge food processors.
- Low research and development investment, slow adoption of digital technologies, and workforce aging hinder innovation and digitalization in the industry.

This convergence of challenges has been termed a “perfect storm.” The agri-food ecosystem must deliver more food while enhancing resilience against disruptions, including pandemics like COVID-19.

The pandemic exposed the vulnerability of the agri-food ecosystem, emphasising the need for rapid change to ensure a stable food supply for the growing global population.

5. Case studies of promising valorisation opportunities

The following case studies highlight innovative strategies and their positive outcomes as alternatives to landfill or incineration. Each case includes data on the problems and challenges associated:

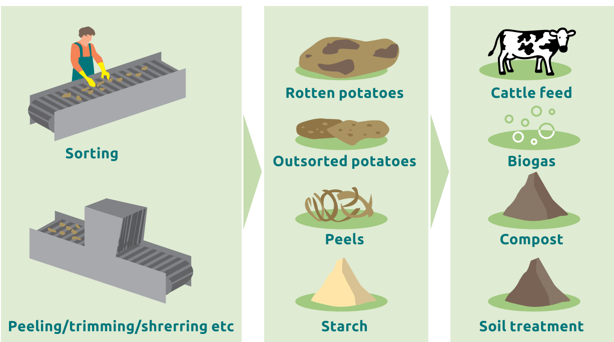
- the residual streams geographical distribution in Europe;
- their seasonality & composition;
- their current management;
- potential proposals for innovation and valorisation;
- the associated resource recovery with diverse products obtained,
- their value and potential markets;
- the current state of the art of the technology;
- to summarise with conclusions, projection and expected positive impact .

The case studies selected are potato steam peels (PSP), cheese whey (CW), brewer's spent grain (BSG), grape pomace (GSP), and olives.

5.1. Potato steam peels

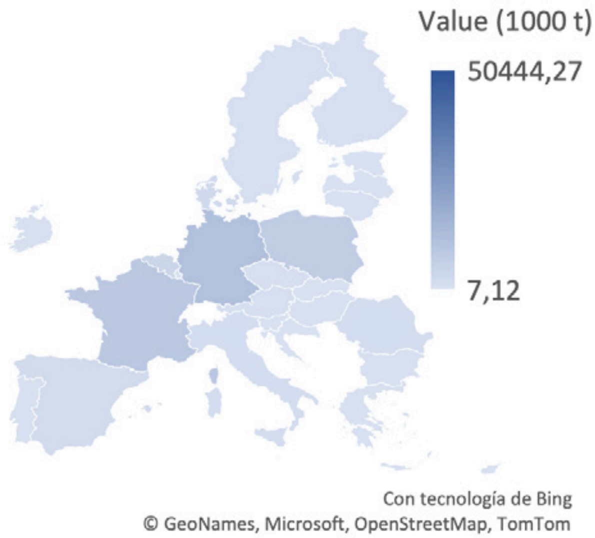
5.1.1. Problem statement & challenges

Potato is one of the most abundantly produced and consumed vegetables worldwide, with a global production of 359 million tonnes[53]. In addition to its fresh consumption, it is extensively used in many industries to produce food products such as chips, French fries, hash browns, and frozen food.



Current valorization routes of by-products from the potato processing industry

5.1.2. Geographical distribution



Map of European Union potato processing in 2020 per country (percentage), FAOSTAT.

The main potato processing countries in the EU are The Netherlands, Belgium, Germany, and Denmark, accounting for 81.5 % of the total potato processing in the EU.

5.1.3. By-product volume

During potato processing, potato peels (PP) are the main residual stream with approximately 0.16 tonnes of PP per tonne of potato processed[54].

5.1.4. Seasonality and composition

The chemical composition of potato peels can vary according to biological or industrial aspects. The variety of potato and its maturation state can affect its composition. On the other hand, the peeling method used in the industry produces a potato peel residual stream with variable amount of water and starch (if the more inner part of the potato is peeled).

As stated in Section 2.1.3, the main components of this residual stream are water and carbohydrates (mainly starch), although they are also rich in fibres and proteins.

53 FAOstat, 2020
54 Pathak, P. D., Mandavgane, S. A., Puranik, N. M., Jambhulkar, S. J., & Kulkarni, B. D. (2018). Valorization of potato peel: a biorefinery approach. Critical reviews in biotechnology, 38(2), 218–230. https://doi.org/10.1080/07388551.2017.1331337

5.1.5. Present management

Nowadays, most of the potato peels are discharged or used in animal feed, biogas production via anaerobic digestion or composting. These are low added-value products, while potato peels have the characteristics for being better valorised in other processes. Some of the processes that have been investigated in the project are glycoalkaloid extraction, anaerobic fermentation to produce volatile fatty acids (VFA), and aerobic fermentation for the production of mycoprotein.

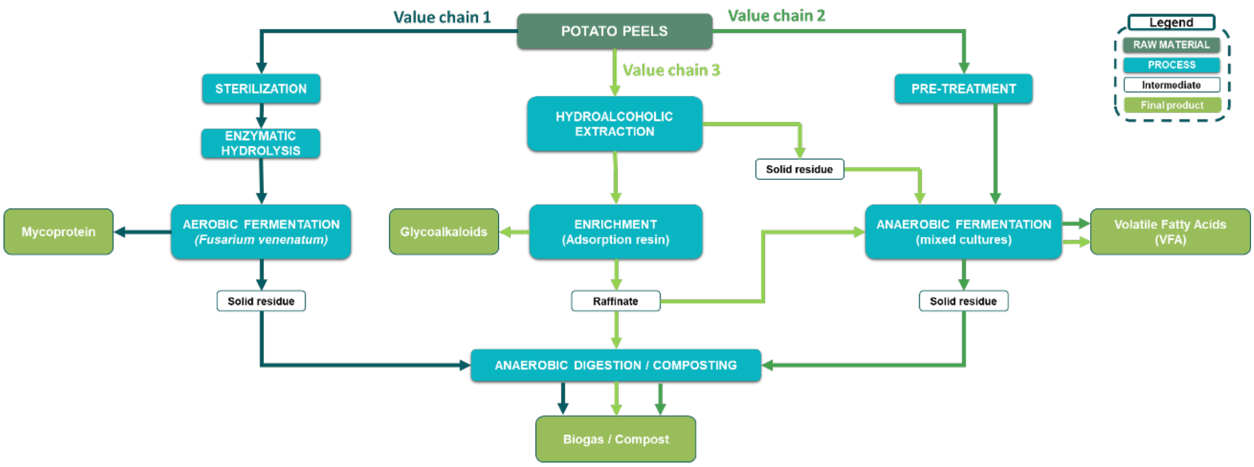
5.1.6. Innovation + valorisation

The proposed biorefinery includes three valorisation options (value chains) that include different technologies (blue boxes) and could obtain two or more products (light green boxes). These value chains cannot be applied in the same biorefinery at the same time, and the decision of which to use could depend on the readiness of the technology, legal restrictions in the area or on the money needed for the biorefinery development.

Value Chain 1 (VC1): With the aim of producing mycoprotein, a first sterilisation step is needed, followed by an enzymatic hydrolysis in order to enhance the amount of available sugars, which are otherwise stored in form of starch and fibres. Then, an aerobic fermentation with a specific yeast (*F.venenatum*) is able to produce the mycoprotein. The solid residue after mycoprotein extraction could then be send to anaerobic digestion or composting for the production of biogas or compost.

Value Chain 2 (VC2): The final product of this value chain is VFAs, produced via anaerobic fermentation after a mechanical pre-treatment of potato peels in order to homogenise the by-product. The fermentation broth after the separation of VFA could be used for anaerobic digestion to produce biogas.

Value Chain 3 (VC3): This value chain is the one with more final products, as it is an integrated approach. Potato peels would first be used for glycoalkaloid extraction via hydroalcoholic extraction and enrichment processes, obtaining an enriched extract containing 8 % of glycoalkaloids. From this, two by-products are produced, which will be used in the fermentation for VFA production as they are rich in sugars. As in VC2, the residue from fermentation process could be also used for biogas or compost production.



Potato peels valorisation scheme.

5.1.7. Products obtained, value and potential markets of impact

The agri-food industry is responsible for the production of millions of tonnes of by-products each year, which are usually thrown away or under-valorised into composting or anaerobic digestion. However, these different types of organic streams are still rich in many compounds such as proteins, sugars, secondary metabolites that could be recovered and valorised into different sectors such as nutrition, cosmetic or even pharmaceutical. Hence, there is a need to shift the current utilisation or under-utilisation of these by-products, to give them a second life and create a more circular economy.

The products obtained in the described value chains are described below:

Mycoprotein is a form of single-cell protein, also known as fungal protein, derived from fungi for human consumption. It had a market size of USD 641.5 million in the year 2022.

Volatile fatty acids (VFA) are a group of organic acids consisting of 2 to 6 carbon atoms, which have a wide range of applications, including as building blocks to produce solvents, polymers, or flavours. In the case of butyric acid, its market size during 2022 was USD 374.19 million, whereas acetic acid, a widely used VFA in the industry, had a market size of USD 20.6 billion in 2021.

Glycoalkaloids (GA) are compounds present in various plants of the Solanaceae family. This includes commonly consumed vegetables such as potatoes or tomatoes. GA can be used as biopesticides and also show interesting results in cancer treatment.

Biogas is a gas mainly composed of methane and carbon dioxide and is considered a renewable energy source as it is produced from raw materials such as agricultural, manure, municipal, or food residual streams. It is mainly used for electricity production, although it can also be compressed and used to power motor vehicles. The global biogas market size was valued at USD 62.72 billion in 2022.

Compost is a mixture of ingredients used as plant fertilizer and to improve a soil's physical, chemical, and biological properties. It is commonly prepared by decomposing plant and food waste, recycling organic materials, and manure. The resulting mixture is rich in plant nutrients and beneficial organisms, such as bacteria, protozoa, nematodes, and fungi. The market size was valued at USD 5.9 billion in 2022.

5.1.8. TRL technology readiness level

Composting and AD are available solutions at industrial scale (TRL7-9). In terms of extraction technologies, hydroalcoholic maceration is also already very widespread in different industries. Many installations at different scale already exist in Europe. Regarding the enrichment part of the process, adsorption resin is at an early stage compared to hydroalcoholic maceration (TRL1-3). There are just a few industrial installations for this technology so far. The same can be said for fermentations. Given the potential of such processes, it would be interesting to develop them.

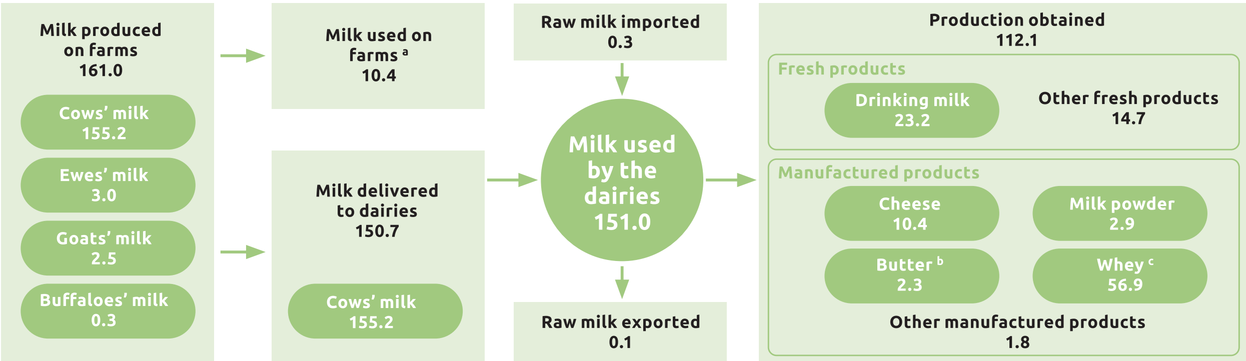
5.1.9. Conclusions and future projection and positive impact

Potato by-products, potato peels specifically, are a high potential residual stream. If more efforts were put into the development of the low TRL technologies of the proposed biorefinery, we would be advancing to close the gap to industrial development. Then, more complete biorefineries could be designed in order to manage this important residual stream while obtaining many high added-value products for the pharmaceutical, cosmetic, and food industries.

5.2. Cheese whey

5.2.1. Problem statement and challenges

The dairy industry represents a major activity in the agri-food sector for the EU. About 96% of the produced milk comes from cows, and around 66% is used to obtain dairy manufactured products. In 2021 a total of 150.7 million tonnes of milk were processed to produce dairy products[55], and 10.4 million tonnes of cheese were produced.

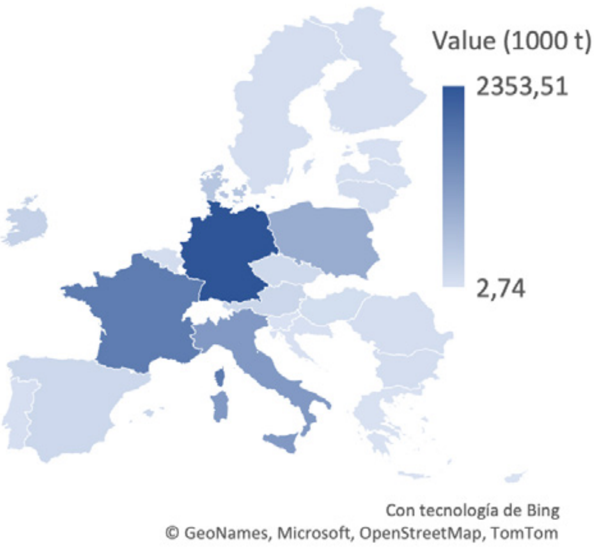


a) In whole milk equivalent
b) includes other yellow fat dairy products; expressed in butter equivalent
c) In liquid whey equivalent

Source: Eurostat (onlin e data codes: apro_mk_pobta and apro_mk_farm

Production and use of milk (million tonnes, EU, 2021).

5.2.2. Geographical distribution



Map of European Union cheese production during 2020 per country (1000 t), FAOSTAT.

The main cheese producing countries in the EU are Germany, France, Italy, The Netherlands, and Poland, accounting for 76.6% of the total cheese production in the EU.

5.2.3. By-product volume

Cheese dairies produce an average of 9-10L of cheese whey (CW) per kg of cheese produced and account for approximately 90% of the milk volume processed. Cheese whey results from the curdling of the milk in the first stages of the cheese production, thus representing an important residual stream of the process.

5.2.4. Seasonality and composition

The chemical composition of cheese whey varies depending on the animal origin of the milk (mainly quantity and specific proteins) and the curdling process applied in the industry. Sweet (enzymatic) and acidic (with acids) precipitation of casein can be applied. The cheese whey obtained characteristics

55 Eurostat (2021) Milk and milk product statistics, https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Milk_and_milk_product_statistics#:~:text=Indeed%2C%2016.4%20million%20tonnes%20of,to%20dairies%20in%20the%20EU.

may be slightly different, mainly due to pH and salt precipitates. Even though these differences, about 75% of CW is lactose (w/w on a dry basis)[56], so it has great potential as a substrate for bioprocesses such as fermentation or anaerobic digestion. In addition, it is considered a "noble" stream because it does not need any pre-treatment, thus reducing revalorisation costs. Cheese is not a seasonal product; therefore, it is able to ensure a stable production of cheese whey.

5.2.5. Present management

Most of cheese whey produced is disposed of in wastewater systems where it is a problem due to its high organic load, among others. As a result, cheese whey has to be treated. Only a small fraction of this cheese whey is revalued for animal feed or whey proteins production. Therefore, revalorisation of cheese whey could be improved in terms of biorefinery approaches.

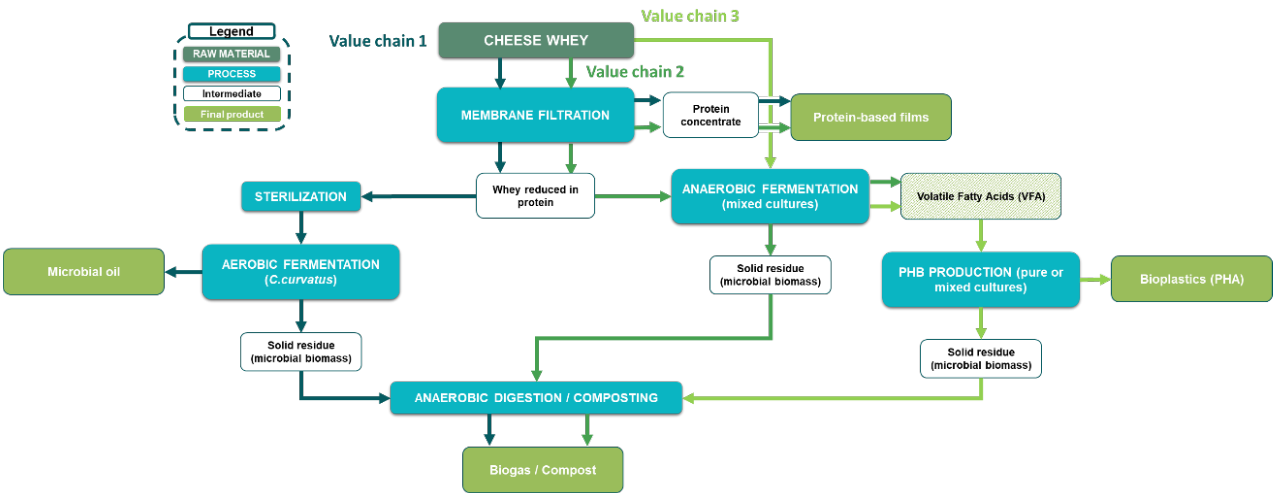
5.2.6. Innovation + valorisation

The proposed biorefinery includes three valorisation options (value chains) that include different technologies (blue boxes) and could obtain two or more products (light green boxes). These value chains cannot be applied in the same biorefinery at the same time, and the decision of which to use could depend on the readiness of the technology, legal restrictions in the area or money needed for the biorefinery development.

Value Chain 1 (VC1): the first proposed value chain starts with a protein recovery step that will be used for packaging biofilms production. The liquid by-product of the filtration step contains all the lactose of whey; therefore, it will be used for bio-oil production in a fermentation step. As in previous cases, the solid by-product of the fermentation could be used for both AD and composting.

Value Chain 2 (VC2): the second value chain has the same first (biofilms production) and last step (AD / composting), but the bio-oil fermentation is exchanged with VFA fermentation.

Value Chain 3 (VC3): the last value chain will use whole cheese whey directly for VFA fermentation, and VFA will be used as intermediates for the production of bioplastics. The by-products of both fermentations will be used for biogas or compost production.



Cheese whey biorefinery approach.

56 Fernández-Gutiérrez D., Veillete M., Giroir-Fendler A., Ramírez A.A., Faucheux N., Heitz M. (2017). Biovalorization of saccharids derived from industrial wastes such as whey: a review. Environmental Science Biotechnology, 16:147-174. DOI 10.1007/s11157-016-9417-7.

5.2.7. Products obtained, value and potential markets of impact

In the past few years, more attention has been given at EU and national level to the development of new plant-based and alternatives sources of proteins. On a health, ethical and environmental point of view, meat consumption should be reduced. In order to facilitate this societal and dietary change, however, new sources of proteins should be offered to consumers, providing the same nutritional intake. In the last few years, more and more options have been coming onto the market for meat or fish analogues, confirming the interest shown by consumers for these new types of products.

The products obtained in these value chains are described below:

Biodegradable films are thin layers of material that are often used to extend shelf life and/or improve food quality. They can be used to act as barriers to mass transfer, carriers for specific ingredients, or for the improvement of the mechanical/handling characteristics of the product. The increasing consumer demand for high quality foods, coupled with the growing environmental concerns regarding the disposal of packaging materials, has led to great interest in the development of biodegradable films Its global market size in 2021 was valued at USD 1.0 billion. In the proposed biorefinery two types of biodegradable films are obtained:

- **Protein based films:** from the protein recovery step at the beginning of the value chain.
- **Polyhydroxyalkanoates (PHA):** biocompatible and biodegradable plastics synthesized by a wide variety of microorganisms, which share very similar characteristics with plastics of petrochemical origin. These have a wider range of applicability, for example as material for 3D printing.

Microbial oil (or single cell oil) consists of the intracellular storage lipids, triacyglycerols. It is similar to vegetable oil, another biologically produced oil. This oill can be used for human nutrition as a source of polyunsaturated fatty acids. Furthermore, it is an alternative to plant or animal oils used for biodiesel as it needs far less areas of land for its production. Finally, it can also be used for oleochemicals (fatty acids, alcohols, and methyl esters) production, which are bulk chemicals for many industries. Microbial oil market size was estimated at USD 74.2 billion in 2022.

Volatile fatty acids (VFA), Biogas, Compost have been discussed in Section 5.1.7.

5.2.8. TRL technology readiness level

Current low added-value technologies such as animal feed, anaerobic digestion or composting are at high TLRs (7-9), while novel technologies proposed in the previous section are nowadays at lower TLRs. Different fermentations (for agri-food by-products) or protein extraction for biofilm production are currently at TRL 1-3, at the stage of optimising the process for further scale-up.

5.2.9. Conclusions and future projection and positive impact

Cheese whey is one of the most exploited residual streams, although its current valorisation is poor (mainly animal feed). Novel products from cheese whey could be produced by fermentation of the sugars to precursors of materials, such as lactic acid, PHA or bacterial cellulose or biofuels like bioethanol[57], which represent important themes for the EU. Working in this direction would put the EU in a better position for future sustainability development.

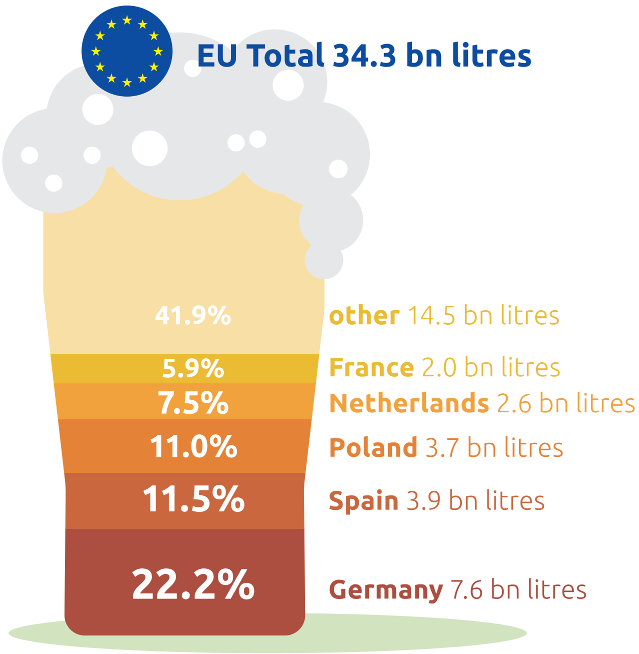
57 Zotta, T., Solieri, L., Iacumin, L., Picozzi, C., & Gullo, M. (2020). Valorization of cheese whey using microbial fermentations. Applied microbiology and biotechnology, 104(7), 2749–2764. https://doi.org/10.1007/s00253-020-10408-2

5.3. Brewer's spent grain (BSG)

5.3.1. Problem statement & challenges

Beer is the most consumed alcoholic beverage worldwide, and the third most consumed beverage after water and tea. In 2022, EU countries produced around 34.3 billion litres of beer[58].

5.3.2. Geographical distribution



European Union top beer producers during 2022, Eurostat.

Germany is the current top beer producer in Europe, followed by Spain and Poland, accounting between them for 44.7% of total European production.

5.3.3. By-product volume

During any beer production process, the grain used ends up as the main by-product, accounting for 15 to 20kg of brewer's spent grain (BSG) generated for every 100L of beer produced, which represent 85% of the brewing industry waste. Nowadays it is a seldom reused residual stream due to its high moisture content, but novel valorisation options are rising in order to give value to this important residual stream of the alcoholic beverages sector.

5.3.4. Seasonality and composition

BSG composition can vary depending on the type of grain used for the brewing process, although the differences are low, and the main constituents are the same. Although some types of beer are seasonal due to the availability of the grains and hops, beer production is stable during all the year.

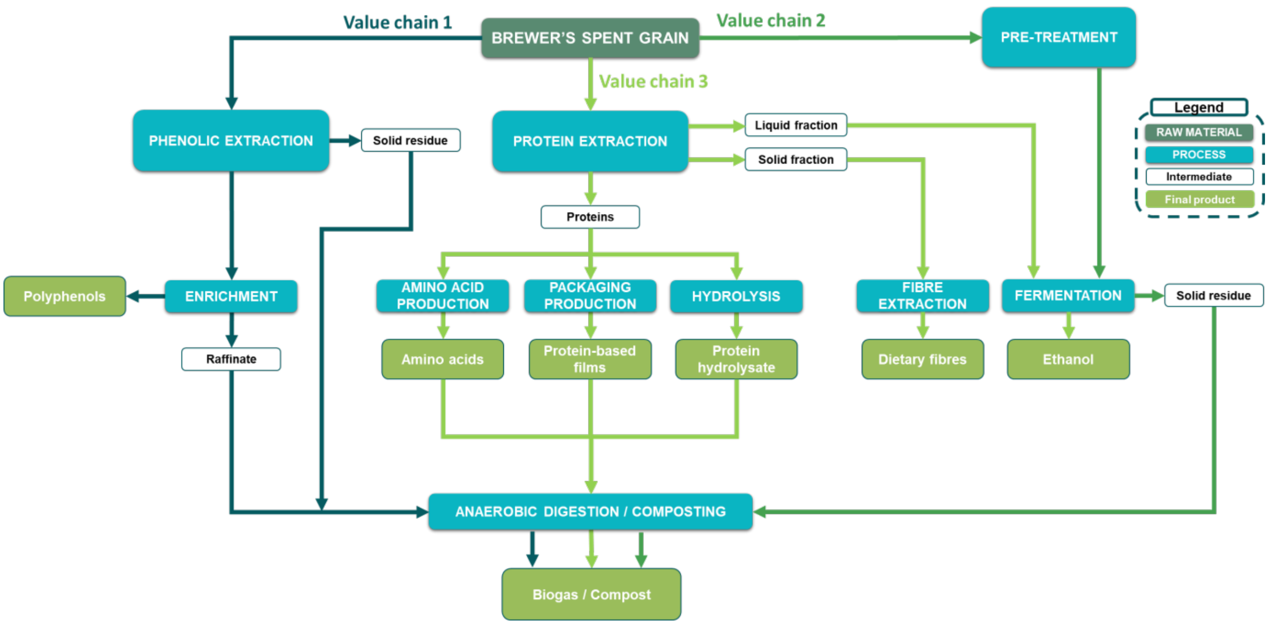
BSG has a great amount of water, which makes it difficult for storage and transport. The other main components are fibres and proteins, and a large quantity of polyphenols. BSG fibres are interesting for its sugar content, while proteins can be extracted, as well as the phenols.

5.3.5. Present management

The main use of BSG is for animal feed due to its fibre content. Another use is as food ingredients in bakery, but as stated before, if not dried, it has a short shelf life (7-10 days), which makes it difficult to reuse.

58 Eurostat 2022.

5.3.6. Innovation + valorisation



Brewer's spent grain biorefinery approach.

The proposed biorefinery includes three valorisation options (value chains) that include different technologies (blue boxes) and could obtain two or more products (light green boxes). These value chains cannot be applied in the same biorefinery at the same time, and the decision of which to use could depend on the readiness of the technology, legal restrictions in the area or money needed for the biorefinery development.

Value Chain 1 (VC1): the first proposed value chain starts with a recovery step of the phenolics in the material. The solid residue is rich in sugars, and could be further valorised. As in previous cases, the raffinate from the phenolics extraction could be used for both AD and/or composting.

Value Chain 2 (VC2): in the second value chain, the BSG is pre-treated and used as fermentation substrate for bio-ethanol production.

Value Chain 3 (VC3): the last value chain focuses on the extraction of proteins in BSG, which can be used as source of amino acids, protein-based films or protein hydrolysate. The solid and liquid fractions after protein purification will be upgraded to dietary fibres or to bioethanol.

5.3.7. Products obtained, value and potential markets of impact

In the valorisation of BSG proposed in Model2Bio two protein products could be obtained from direct extraction and fermentation, while at the same time adding value to a by-product from the brewery industry. These two products have a high potential in the food sector as they can be incorporated into food formulations for protein enrichment or the development of meat analogues for example.

Polyphenols (PPH) are natural compounds found in plants and have wide structure diversity. PPHs are traditionally used as dyes, but nowadays novel uses are being studied such as antioxidants, but they are also used as precursors in green chemistry. The global polyphenols market size was estimated at USD 1.68 billion in 2022.

Amino acids are the basic building blocks of proteins, but they can also have a wide range of applications in the industry. They can be used in fertilisers due to its chelating ability, as animal feed ingredients for their nitrogen content, in food industry as sweeteners, or in pharmaceutical and cosmetics industries, among others. Amino acids market size was valued at USD 26.39 billion in 2021 and is poised to grow to USD 53.39 billion by 2030.

Protein hydrolysate is the result of the breakdown of proteins into groups of various amino acids. The difference with amino acids is that hydrolysates are mixtures of amino acids with functional properties. They need less purification steps than single amino acids, making its production cheaper. In 2022, the global protein hydrolysate market is valued at USD 3.25 billion and is projected reach a value of USD 6.25 billion by 2030.

Dietary fibres are the fraction of plant food that cannot be digested by human digestive tract. This includes compounds such as cellulose, lignin or chitin. These can be used as mixtures as food additives, fractionated in individual and more valuable types of fibres, or used as substrates for other processes such as fermentation, where some microorganisms can use them for growth and added-value compounds production. The global dietary fibres market size was USD 6.73 billion in 2021 and it is expected to grow at a CAGR of 9.2% from 2022 to 2030.

Ethanol has a wide range of applications such as antiseptic, solvent, fuel, bulk chemical or pharmacology. The global ethanol market is valued at USD 93.78 billion in the year 2022 and is forecasted to reach a value of USD 130.33 billion by the year 2030.

Protein based films, biogas, and compost have been discussed in Section 5.1.7.

5.3.8. TRL technology readiness level

Most of the technologies proposed in the biorefinery approach are found at industrial scale (TRL 7-9), but not using agro-industrial residual streams as substrates. For this concrete application, more investment and research are needed to implement real biorefineries for the production of value-added products.

5.3.9. Conclusions and future projection and positive impact

The process developed in the Model2Bio project shows promising results and a huge potential for the valorisation of BSG. With more development to optimise the process and increase the protein content even more, this valorisation pathway could become a new source of revenue for breweries and a new market segment for the development of plant-based protein ingredients for human nutrition. This would contribute both to a more circular economy and to the shift towards healthier and more environmentally-friendly eating habits.

BSG represents a great opportunity as a new substrate for valorisation as nowadays it is only being used for animal feed. The biorefinery presented in this case study is the one with most product options. Even though some of these technologies are at low TRLs, it shows the potential of such an important residual stream and its use in future biorefineries.

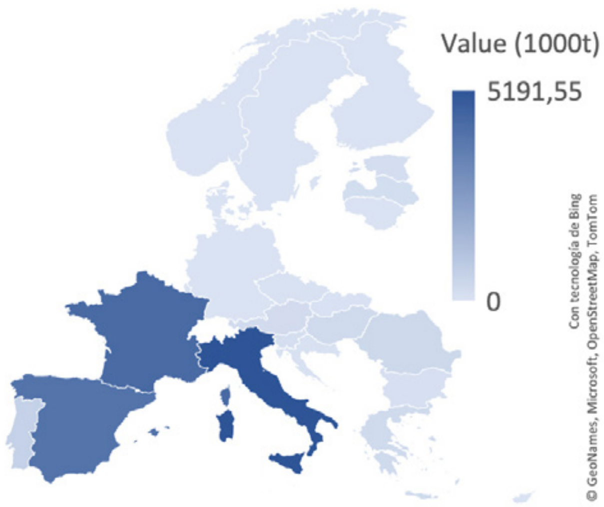
Among the novel uses of BSG, protein recovery, phenols extraction and its use as fermentation substrate are the most relevant. These technologies could be used to increase the value of this residual stream as many added-value products can be obtained.

5.4. Grape seeds & peels

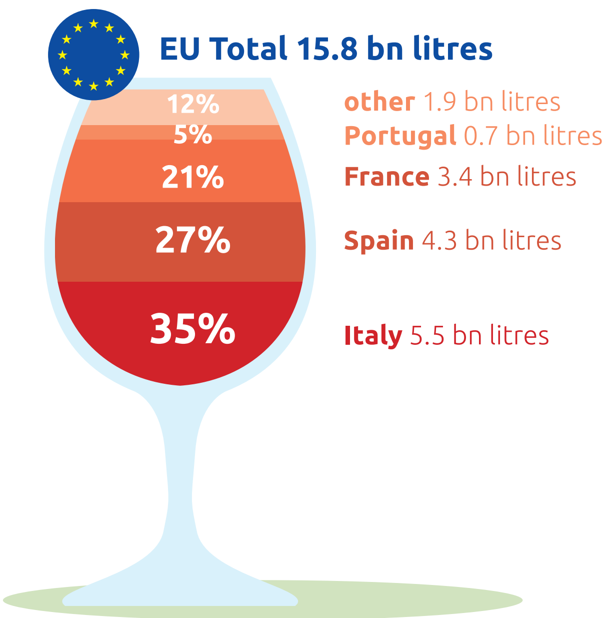
5.4.1. Problem statement & challenges

The EU is the main wine producer and exporter in the world, and the wine industry has a great importance in the alcoholic beverages sector, producing around 15.8 billion litres in 2019. During the industrial process of winemaking, the grape pulp, seeds and skins (also known as grape pomace) is obtained as the main by-product.

5.4.2. Geographical distribution



European Union top wine producers during 2020, FAOSTAT.



Top wine producers in the EU, 2019[59].

5.4.3. By-product volume

In the wine industry, 35kg of pomace and 10kg of lees are generated for every 100kg of grapes used as raw material. Therefore, the pomace fraction is 0.35 and the lees fraction is 0.1.

5.4.4. Seasonality and composition

Grape pomace is a by-product with high variability in terms of composition. This depends on the grape variety and ripening, but also on the fermentation process. Furthermore, it is a seasonal product (harvested in summer), thus it doesn't have full year availability. The main difference is between red and white grape pomaces. Red grape pomace is obtained after the grape fermentation, while white grape pomace is obtained before the fermentation process. This means that red grape pomace contains ethanol and has a specific regulation, and it must be taken to a distillery[60]. In contrast, white grape pomace can be used directly in further processes.

5.4.5. Present management

Grape seeds are a by-product of wine and grape juice production. A very common practice is to use them as compost or animal feed, which reduces waste and contributes to sustainable practices. Specifically, red grape pomace must be managed in a distillery due to its ethanol content.

Some distilleries have already created biorefinery approaches and obtain value-added products, and they can be real models for creating new biorefineries with this residual stream. However, if a distillery does not benefit from the pomace after removing the ethanol, it is only used for animal feed, fertiliser or biogas production. Its high amount of phenolic compounds and pigments has made it a great by-product for extraction processes. But it is also a carbohydrate-rich substrate, making it a good option for fermentation processes. All these technologies are to some extent compatible with cascade approaches.

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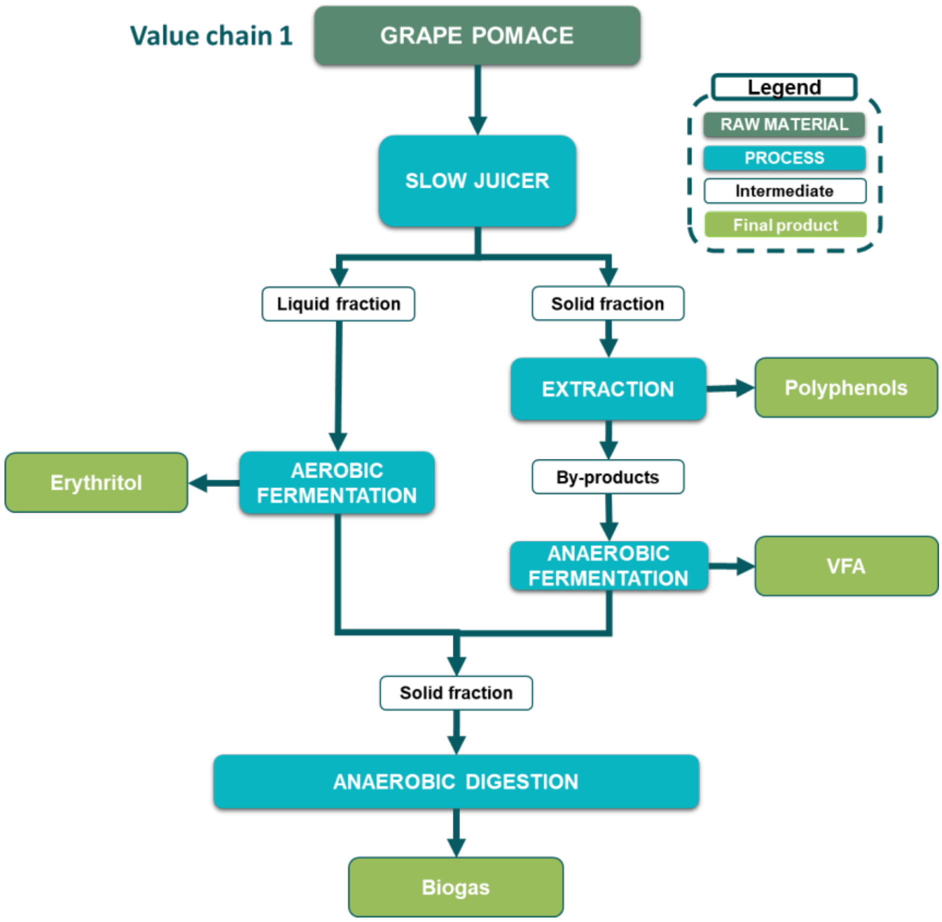
59 EUROSTAT: https://ec.europa.eu/eurostat/web/products-eurostat-news/-/edn-20201119-2

60 Commission Delegated Regulation (EU) 2019/934 of 12 March 2019 supplementing Regulation (EU) No 1308/2013 of the European Parliament and of the Council as regards wine-growing areas where the alcoholic strength may be increased, authorised oenological practices and restrictions applicable to the production and conservation of grapevine products, the minimum percentage of alcohol for by-products and their disposal, and publication of OIV files.

5.4.6. Innovation + valorisation



Grape pomace biorefinery approach.

It is technically feasible to valorise grape seeds and peels (GSP) using an integrated process, combining fermentation and bioactive compounds extraction. GSP is rich in sugars and phenolic compounds that can be extracted from this substrate. For fermentation, however, the quantity of solids in GSP needs to be reduced, which is realised by means of slow juicing. After the slow-juicing step, the juice can be used very well as a substrate for aerobic fermentation to produce the low-calorie sweetener erythritol. The erythritol production is about 0.5g/L·h. The produced fibrous fraction can be extracted by hydroalcoholic maceration and after an enrichment step with an adsorption resin; the antioxidant activity of this enriched extract was quite like commercial extracts.

5.4.7. Products obtained, value and potential markets of impact

Erythritol is a low caloric sweetener naturally found in some fruits. Commercially it is produced via yeast fermentation and although it is only 70% as sweet as sucrose, it contains almost no energy. This compound is used as a new food ingredient in low caloric diets, with the advantage of not interfering with glucose and insulin metabolism, thus being also a good option for diabetics. The market size reached USD 380.96 million in 2021 and it is expected to grow at a CAGR of 32.94% until 2030.

Polyphenols, VFA and biogas products have been discussed in previous sections.

5.4.8. TRL technology readiness level

The technologies commented in this section have been already discussed in previous sections and involve emerging technologies currently at low TRLs (1-3).

5.4.9. Conclusions and future projection and positive impact

The integrated process developed shows promising results. In terms of extraction, the extract obtained after enrichment has an interesting antioxidant activity. It would be interesting to conduct a study to determine the relevance of the enrichment step. Indeed, the unenriched extract already has high potential. At the same time, further research could detail the polyphenol composition of the product obtained. This would allow the extract to be even better positioned, mainly in terms of specific activity.

5.5. Olive leaves

5.5.1. Problem statement & challenges

Olive leaves precedent (OLP) from the olive industry represent an environmental issue for the industry. They need to be removed from the fields in order to avoid fermentation, plant diseases such as Verticillium wilt, one of the main olive diseases nowadays. Another reason is to allow soil oxygenation, so the leaves are normally eliminated by controlled burning in the field, which produces CO_2, particulates emissions and poses a potential fire risk.

5.5.2. Geographical distribution

The main olive oil producers are Spain, Italy, Greece, Tunisia, Turkey, Morocco, Portugal and Syria. All of them belong to the Mediterranean basin. The production in these countries represents approximately 80% of the world production.

Olive production map in the Mediterranean area.

5.5.3. By-product volume

4.5 million tonnes/year of olive leaves are produced nowadays in the world[61], composed of olive pruning leaves and olive mill leaves.

5.5.4. Seasonality and composition

The olive industry is most active between September and December. Therefore, the biomass of this industry is mainly generated during this period. However, the olive tree is pruned after harvesting in January and February. Therefore, the highest accumulation of olive biomass in the form of leaves occurs during the late autumn weeks, the three winter months, and the beginning of spring.

The olive leaf biomass has an enormous potential for valorisation given its composition: 35% lignin, up to 20% of polyphenols, 18% of cellulose and fermentable sugars, 9% of proteins and minerals, 8 % of hemicellulose, 5% triterpenic compounds, and 5% of non-polar fraction (essential oil, lipids, chlorophylls). However, several challenges, like the lack of an established supply chain, the variability in its composition and its diverse handling methods, have hindered its optimal valorisation.

5.5.5. Present management

This biomass is currently underexploited; it is burnt in the fields, given to cattle or, in some cases, burnt to produce energy. Only a much reduced portion of olive leaves (about 10ktonnes, which represents 0.2% of the global amount, according to an internal NATAC market study) is used as starting material for production of olive leaf extracts. This means that more than 1,000ktonnes of bioactive compounds (polyphenols, triterpenoids, nonpolar fraction, etc.), 1,000ktonnes of cellulose and 1,500ktonnes of lignin are being burnt every year.

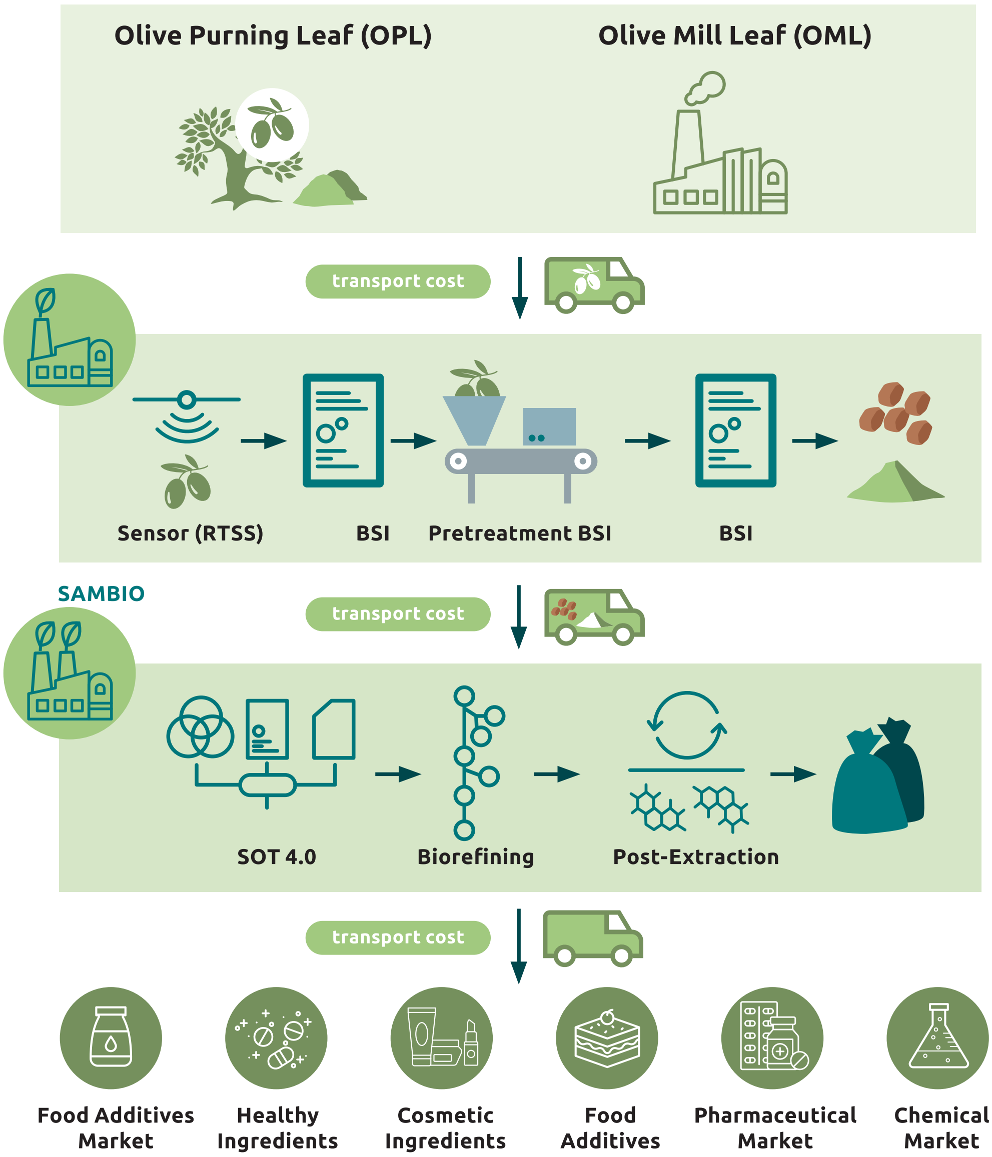
Following the cleaning process in the mills, biomass is usually sent to secondary cooperatives in charge of olive residue management, which employ it as a raw material for combustion in biomass power generation plants.

5.5.6. Innovation + valorisation

The OLEAF4VALUE project will develop an entirely new valorisation system for the olive leaf based on the assessed feedstock characteristics and its quality, projected biomass availability and well-defined industrial demand combined with state-of-the-art technical solutions available for bio-based residual pre-processing. The overall concept of the project is to set up a new smart biorefinery devoted to the full valorisation of the olive leaf.

61 Manzanares, P., Ruiz, E., Ballesteros, M., Negro, M.J., Gallego, F.J., López Linares, J.C., Castro, E., (2017) Residual biomass potential in olive tree cultivation and olive oil industry in Spain valorization proposal in a biorefinery context. Spanish Journal of Agricultural Research, 15 (3)

- The system starts with the biomass generation. Two types of biomass will be used: olive pruning leaves (OPL) and olive mill leaves (OML). Following a preliminary handling and separation in the fields (OPL) and in the mills (OML), the biomass will be transported to a biomass logistic centre.
- In the logistic centre, the biomass will be rapidly analysed with a real rime suitability index sensor (RTSIS) that will provide the biomass suitability index (BSI) of the biomass. Following this analysis, different pre-treatments will be performed to improve the BSI. The pre-treated biomass will then be re-analysed (RTSIS), to confirm the final BSI and economic value, which will be calculated accordingly (higher quality biomass -better BSI-implies higher value).
- In these conditions, the biomass will be ready to be sent to the extraction plant or stored until use. Different valorisation routes have been defined. The processing valorisation route will be determined in the biorefinery by the smart optimization tool 4.0 according to multiple parameters (BSI, sustainability, distance and market needs). All valorisation routes in the SAMBIO will be designed employing compatible industrial devises, avoiding delocalization.
- When necessary, post-extraction technologies will be applied to the extracted products and fractions prior to these reaching end-users.



OLEAF4VALUE valorisation scheme.

5.5.7. Products obtained, value and potential markets of impact

OLEAF4VALUE[62] has as an objective to increase the added value of the bio-products obtained: new molecules with new functionalities, and new market opportunities: The objective at the beginning of the project was to obtain 24 bio-based products, 16 of which are new on the market. However, more than 30 products have already been developed so far, with one year to go before the end of the project.

Furthermore, the current market price for olive leaves for energy production is 25€/tonne with an energy yield equal to 2.600kcal/ kg. In OLEAF4VALUE, for example, 1MT of olive leaves extracted in the polyphenol valorisation route will yield more than 650kg of high added value products. This added value will be shared along the supply chain and will motivate the implementation of OLEAF4VALUE's smart methodologies.

5.5.8. TRL technology readiness level

The different technologies developed in OLEAF4VALUE will end at TRL 5. The scope of the project will reach the validation of the valorisation pathways thanks to the Natac pilot plant. Once the valorisation pathways have been developed at the laboratory scale, they are taken to an industrial scale thanks to the pilot plant located at the Natac facilities, where parameters of the extractions can be evaluated, such as raw material yield, resource consumption, and their impact on sustainability and the environment. In this way, the data collected during the development phases of the pathways at the laboratory level will be consolidated.

Additionally, the development of a portable NIR sensor designed to assess the quality of the raw materials studied during the project is nearing completion. In the coming months, an in-situ test of the effectiveness of this sensor will be carried out with the aim of evaluating its performance and efficiency under real production conditions.

5.5.9. Conclusions and future projection and positive impact

Based on the results, Natac aims to take the smart biorefinery to another level, aiming to validate new routes to obtain extract, new raw materials and new market segments in the future.

62 This project has received funding from the Bio-Based Industries Joint Undertaking under the European Union's Horizon 2020 research and innovation programme under grant agreement nº 101023256.

6. Enhancing value chain collaboration and innovation for sustainable valorisation: Overcoming key challenges for circularity

This section highlights the key barriers that currently impede agri-food value chain actors and researchers in the smooth progress of sustainable valorisation initiatives in the EU. These barriers include the lack of communication and transparency among stakeholders, differing legislations in EU member states, low public awareness and acceptance of valorised products, investment barriers, and difficulties for plant extracts valorisation. For each barrier, practical recommendations are provided..

6.1. Technical barrier (I): By-product European Database

When working with computing tools such as the one developed in Model2Bio or in the other sister projects presented above, a lot of information is needed in order to create a reliable and useful tool. Important databases such as Eurostat or FAOSTAT gather information about the agri-food sector, but the by-products section is not detailed enough. Other fields of study have specific databases like the European Soil Database (ESDB).

As the EU has been focusing in the recent years on the development of the circular economy, researchers need a solid information background in order to carry out their studies. A unification of terms and description of the main by-products of the agri-food sector (characterisation, production, and destination among others), developed and maintained by the European Commission would be extremely useful. The current problem is that every project has to start from scratch, or almost. In addition, companies are often unwilling to share their data.

Recommendations

Create a solid database template: researchers would be able to fill the gaps in the by-products composition and production, supervised by the Commission.

Encourage companies to give information: through investment in European projects, companies in the sector should be asked to give information about by-product production, and that information should be fed into the database.

6.2. Technical barrier (II): Difficulties for plant extract valorisation

Extraction by hydroalcoholic maceration is a common technique to extract bioactive compounds such as flavonoids, phenolic acids, glycoalkaloids and terpenes. These compounds have various applications in food, pharmaceutical, cosmetic and nutraceutical industries, due to their antioxidant, anti-inflammatory, antimicrobial and hormonal properties. The quality and yield of the extracts depend on many factors, such as solvent composition, extraction time and temperature.

To overcome these limitations, subcritical water extraction is a good replacer for the recovery of polyphenols and other secondary metabolites from plant materials. It could substitute the more conventional hydroalcoholic maceration for the recovery of polyphenols because it provides favourable yields, avoids loss and degradation of volatile and thermolabile compounds, all that with lower cost, simplicity, and favourable environmental impact. However, this technology is currently not developed at larger scale because it requires specific equipment. This limits its application compared to conventional macerations that are widely used in the industry. Hence, more funds should be allocated for the expansion of this technology as well as other promising green technologies (UAE, MAE…) at industrial scale. Another process is the use of adsorption resin for the purification and enrichment of the extracts. Adsorption resin can be used to remove unwanted impurities, such as sugars, proteins and pigments, and to concentrate the desired bioactive compounds in the extracts.

However, despite the advantages of these innovative processes, there are still some barriers that prevent their widespread adoption in the EU. One of them is the lack of harmonised regulations and standards for the quality and safety of plant extracts and their derived products. The EU legislation on novel foods, food additives, food supplements and health claims is complex and heterogeneous in different member states, which can create confusion and uncertainty for producers and consumers. Moreover, there is a need for more scientific evidence and validation of the efficacy and toxicity of plant extracts and their bioactive compounds. Another barrier is the high cost and technical complexity of implementing these innovative processes in industrial settings. The equipment, maintenance and operation costs can be prohibitive for SMEs, which constitute a large part of the agri-food sector in the EU. Furthermore, there is a lack of awareness and acceptance among consumers and stakeholders about the benefits and risks of using plant extracts and their derived products.

Recommendations

Therefore, we recommend some actions to improve the situation:

- developing a clear and consistent regulatory framework for plant extracts and their derived products in the EU market, considering their origin, composition, quality, and safety
- supporting more research and innovation on plant extraction and enrichment processes such as adsorption resin, to optimise their efficiency and scalability
- raising awareness and education among consumers and stakeholders about the benefits and risks of using plant extracts and their derived products, as well as their environmental impact.

By implementing these actions, by-product valorisation from the agri-food industry can be enhanced in the EU, contributing to a circular economy that maximises resource efficiency. Extraction and enrichment processes such as adsorption resin can be seen as promising techniques to obtain high-value compounds from plant by-products that can improve human health and well-being.

6.3. Legal barrier (I): Differing legislations in EU Member States

The presence of varying tax regulations in the EU member states has resulted in economic disparities that are impeding the progress of sustainable production. This diversity in tax policies has led to a situation where the growth of sustainable production practices is being hampered. Specifically, the imposition of higher taxes in certain countries within the EU has emerged as a significant challenge for stakeholders actively engaged in the pursuit of sustainability. Higher taxes acts as a deterrent, discouraging stakeholders from fully realizing the potential benefits of sustainable production initiatives. This, in turn, obstructs the desired outcome of creating a coherent and integrated value chain that spans borders.

The economic impact of these divergent tax regulations cannot be underestimated. The higher tax burden placed upon stakeholders operating within specific countries curtails their ability to invest in sustainable production methods, innovative technologies, and research and development. Such limitations compromise their capacity to compete effectively on the broader market stage. Moreover, the unequal tax landscape distorts the competitive dynamics within the EU, potentially disadvantaging certain regions and sectors.

The concept of a unified value chain hinges upon seamless collaboration, streamlined processes, and synchronised efforts among stakeholders across member states. However, the presence of higher taxes creates an uneven playing field that disrupts this envisioned harmony. Stakeholders facing these economic barriers are forced to allocate resources to address tax-related challenges rather than concentrating on the advancement of sustainable production practices.

Recommendation

Harmonise tax regulations: Establishing uniform tax regulations across EU member states can level the playing field for all stakeholders. By reducing economic barriers, producers and valorisation companies can compete on a fair basis, stimulating innovation and investment.

6.4. Social barrier (I): Low public awareness and acceptance of valorised products

Public perception plays a crucial role in shaping market demand and acceptance of valorised products. The lack of awareness regarding the benefits and potential of such products has resulted in slow market growth and limited adoption, while public acceptance would encourage producers and researchers to maximise their efforts towards a more circular economy.

Recommendation

Launch public awareness campaigns: Initiating comprehensive public awareness campaigns can educate consumers about the value and sustainability of valorised products. Leveraging various media channels, these campaigns can highlight success stories, scientific evidence, and real-world applications to boost public acceptance.

6.5. Social barrier (II): Lack of knowledge about the potential of by-products

Thanks to the change in vision that the circular economy has provided, the agri-food sector has discovered a source of value in the by-products generated, which were previously considered waste. Even so, not all companies have at their disposal this knowledge about the value of their residual streams.

There are small companies, although fewer and fewer, that continue to consider their residual streams as waste due to ignorance.

Recommendation

Instruction of the agri-food sector: Continue with the instruction of the agri-food sector with the aim of making them aware of the value of their residual streams, the recovery options offered by their by-products and the recovery possibilities they have in their territory. Clusters and associations can help with these knowledge campaigns, as they can show success stories and scientific advances.

6.6. Social barrier (III): Need for communication between all members of the value chain

In order to carry out a correct valorisation of by-products, all members of the value chain should communicate well and work together. Communication is necessary between the producing companies and the valorisation companies, but also between the producing companies among themselves.

Today there are gaps in communication, especially among small producers of by-products. In addition to overcoming the barrier of knowing what potential the residual streams produced have, it is necessary to know who can valorise the residual streams. Furthermore, especially in small companies, communication between them is necessary to improve or allow valorisation through the centralisation of by-products.

Recommendation

Enable channels for communication between members of the value chain.

6.7. Social barrier (IV): Lack of communication and transparency among stakeholders

Effective communication and transparent information sharing are pivotal in driving innovation and optimising production processes. It has been observed while working on the Model2Bio project, that producers and valorisation companies often withhold information due to concerns about losing competitive advantages. This reluctance to share data limits opportunities for collaboration and prevents producers from fully realising the potential of their by-products.

Producers have stated that the lack of knowledge about other valorisation pathways, seasonality, by-product volume, storage (high water content), and logistics, are among the top barriers they have encountered on their revalorisation journey. All these barriers could be tackled if producers had better communication channels and joined-up efforts.

Recommendations

Promote information sharing: Encouraging stakeholders to share relevant information can significantly improve collaboration and innovation. Implementing secure platforms for information exchange can help stakeholders access a broader range of possibilities and combine their efforts effectively.

Foster collaborative partnerships: Organising regular workshops, seminars, and forums can bring stakeholders together, fostering an environment of trust and collaboration. Open discussions on successful valorisation pathways can inspire participants to explore novel approaches.

6.8. Economic barrier (I): Investment barriers

The investment barrier poses a significant challenge for producers aiming to valorise their by-products and embrace sustainable production practices. It slows down their entry into the market. The need for substantial capital to fund valorisation processes deters producers from fully exploiting the potential of their by-products, limiting their participation and slowing the growth of sustainable practices.

Valorisation of by-products requires substantial financial investments. These cover research, development, technological infrastructure, and operational adjustments. Many producers, especially smaller ones, find it difficult to allocate the necessary funds, thereby impeding their ability to enter the market with valorised products.

Recommendations

Financial Support: Policy makers can play a pivotal role in mitigating this investment barrier. Introducing financial incentives such as grants, subsidies, or low-interest loans dedicated to by-product valorisation can ease the financial burden on producers. This would encourage them to invest in sustainable practices without excessive financial strain. This support can help bridge the gap between pilot scale and industrial scale.

Collaborative Research: Establishing research partnerships between producers and research institutions can streamline the development process. By sharing research costs and knowledge, producers can access valuable expertise without shouldering the entire financial responsibility.

Technical Assistance: Offering technical assistance and consultancy services can guide producers through the intricacies of valorisation projects. Expert guidance can help them optimise investments, avoid unnecessary expenses, and expedite the market entry of their valorised products.

Pilot Programmes: Introducing pilot programmes (access to pilot scale test infrastructure) that demonstrate the viability and benefits of valorisation can help overcome scepticism. Producers can participate in smaller-scale initiatives, reducing initial investment risks and showcasing the potential for larger-scale operations.

6.9. Economic barrier (III): Need for tools to maximise the value of waste streams-Investment need

Based on technical criteria, the obvious strategy to follow to valorise the agri-food by-products is to maximise the conversion and extraction processes to obtain value-added compounds. But what is the point of obtaining valuable products if the cost of their production and logistics exceeds their market value? It is clear that the technical aspects are not enough, and logistics and the location of companies can shift the optimal valuation in another direction.

It is not possible to make a valuation decision considering only the technical improvements available, but rather the problem must be located in an area, and a broader perspective, a holistic perspective, must be applied: technical, economic, environmental and social perspective. The current valorisation decision takes cost minimisation as its axis, although little by little environmental and social criteria are being imposed in decision-making.

Under this holistic perspective the problem becomes complex and it is necessary to use tools that allow us to analyse all the variables as a whole.

Each region has its companies and its particular economy, so it is difficult to extrapolate solutions from one region to another intuitively.

Recommendation

The Model2Bio project has taken the first steps to overcome this challenge by, developing a decision-support tool to select the best valorisation options from a holistic perspective. But even so, it is necessary for the EU to promote research projects to continue with this line.

7. Key takeaways

The EU's food industry stands as a cornerstone of its manufacturing landscape, comprising a multitude of sectors with significant economic and employment impacts. While contributing immensely to the economy, this industry also grapples with substantial "waste" generation and environmental footprints. In light of this complex scenario, deeper interconnectedness within food value chains and across sectors emerge as pivotal pathways towards innovation and sustainable solutions.

The examined residual streams from the main agri-food sectors – meat, vegetables (tomato, artichoke, and potato), dairy (cheese), and alcoholic beverages (beer and wine) – underscore the pressing need for proactive waste management and resource use. The sheer magnitude of waste generated, such as in the meat sector where by-products are abundant yet challenging to manage, presents an opportunity for innovative approaches to harness these residual streams.

In a world increasingly focused on sustainability and circular economies, these residual streams are a treasure trove of untapped potential. However, it is imperative that efforts span sectors, academia, and industry to develop innovative and efficient methods for their valorisation. By integrating advanced characterisation techniques, we can unlock the unique composition of these residual streams, leading to tailored strategies for their transformation into high-value products. This will contribute to economic growth, environmental preservation, and a more sustainable future.

The exploration of agri-food residual streams highlights the transformative power of innovation, collaboration, and conscious resource use. As industries strive to balance economic prosperity with environmental responsibility, the integration of by-products valorisation practices emerges as a powerful means to achieve both these critical objectives, paving the way towards a more sustainable and resilient agri-food sector within the EU and beyond. This exploration into the valorisation potential of various agricultural residues has shed light on the transformative power of biorefinery approaches. Through in-depth examinations of potato steam peels (PSP), cheese whey (CW), brewer's spent grain (BSG), grape seeds & peels (GSP), and olive leaves precedent (OLP), this study has unravelled the hidden value within these by-products and the pathways towards their sustainable utilisation.

These diverse case studies converge on a common theme: the potential of biorefineries to shape a more sustainable and circular future. The journey from agri-food by-products value-added products transcends industries, offering solutions for nutrition, energy, materials, and more. The convergence of scientific innovation, technological advancement, and environmental responsibility points towards a future where residues are not discarded but celebrated as essential contributors to a greener world.

Digital tools play a key role in expanding the analysis possibilities for residual stream valorisation. As it has been seen, different European projects are being or have been carried out in order to develop these technologies. When combining the experimental and the digital worlds, tools with higher potential are obtained. For the case of the Model2Bio-DSS tool, it has allowed the construction of a demo that could be easily upgraded with sufficient data.

As we step into the future, armed with the insights from this white paper, we embark on a journey towards a circular and resource-efficient society. A society where waste is minimised, by-products are valued, and innovation drives sustainable development.

Model2Bio partners

Scan for more information

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