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high-value products from agricultural residues through sustainable chains

Deliverable D1.1

First annual reports on stakeholders' consultations, SSbD elements, BtoB market readiness

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Type

R	Document, Report	x
DEM	Demonstrator, Pilot, Prototype	☐
DEC	Websites, Patent Fillings, Videos, etc	☐
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Summary

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WP Leader (name and organisation): Jan Broeze, Stichting Wageningen Research **(**WR)

Person in charge of the deliverable (name and organisation): Burkhard Schaer, Ecozept

Author(s): Jan Linck, Alice Charpigny, Burkhard Schaer

Contributor(s): (contributors to Task 1.1 according to DOA:) INRAE, FCAC, SDU, BTBU, DSS+

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Executive Summary

The main objective of Task 1.1 within WP 1 is to conduct an analysis of the current management of agri-residues and examine preferences and expectations of different stakeholders in the value chain with regard to innovative circular agri-residues based value chains. Targeted objectives are to identify promising residue streams, regional focus areas, relevant applications and BtB markets as well as SSbD criteria and prioritized pathways. To achieve this, 17 expert interviews were conducted based on qualitative research methods. A second round of data collection will be carried out end of 2024. In this Deliverable Report, intermediate results are presented.

In preparation of the stakeholders consultation, promising residue streams have been identified through a desktop study to get an overall understanding of each feedstock's market potential. Thereafter, the main processing countries for each feedstock had been identified, further processing per country was estimated from the main production made of that feedstock and then multiplied it with the product-to-residue ratio. This means that, for instance, for potatoes residues from frozen potatoes production are considered representative for the whole sector, which overlooks that residue factors for e.g. potato starch industry is quite different from the frozen potatoes industries. More detailed estimates are generated in AgriLoop Task 1.2.

The research on residue streams showed that the volumes of agri-residues targeted within the project are promising.

By the first round of expert interviews, valuable insights from experts of the EUG and the main value-chains were collected. The implementation of the methods was successful and the intermediate results confirm the research strategy. The expert interviews showed that the challenges addressed by the project are well known, such as the need for promising valorisation pathways. They also provided some inspiration on possible valorisation pathways and opportunities. PHA, PHA applications and extracted/microbial proteins have been confirmed as promising target end products within the AgriLoop project. The market potential of these products is generally considered to be very high. However, several limitations and potential barriers need to be considered.

Abbreviations

Abbreviation	
AWCB	Agricultural wastes, co-products and by-products
B2B	Business to Business
B2C	Business to Consumer
BSG	Brewer's spent grains
CO_2	Carbon dioxide
D	Deliverable (report)
DOA	Description of Action
EFSA	European Food Safety Authority
EU	European Union
EUG	End-User Group
MP	Extracted/ microbial proteins
Mt	Mega ton
PE	Polyethylene
PHA	Polyhydroxyalkanoate
PHB	Polyhydroxybutyric acid
PLA	Polylactide
PP	Polypropylene
PPO	Polyphenylenoxid
RQ	Research question
SDGs	Sustainable development goals
SMEs	Small and medium sized enterprises
SSbD	SWRafe-andsustainable-by-design
WP	Work Package
WR	Stichting Wageningen Research

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1. Introduction

1.1 Description of Work Package 1

The tasks and results of this Deliverable Report are embedded in Work Package 1 “Foundational circular & strategic flows” that is led by **WR**. In the framework of this Work Package, the following objectives will be achieved:

(1) Estimate the potential + set up SSbD criteria + analyse stakeholders' preferences + assess B2B market of valorisation pathways,
(2) Estimate EU agri-residues volumes and potential yields for extraction and microbial fermentation chains based on compositional characteristics and processing yields heuristics,
(3) Identify, quantify potential circularised hazards
(4) Develop a framework for assessing sustainability impacts of the cascading pathways.

In order to achieve these goals, Task 1.1 led by Ecozept, provides a market analysis and research on stakeholders' expectations. This progress report describes the methodology that we applied, provides first results as well as an outlook (roadmap and agenda) for the next steps.

1.2 Background of the deliverable and description of the associated task

The objectives of task 1.1 are to conduct a market analysis and to identify experts' preferences, acceptances and expectations. In this regard we refer to “experts, this includes stakeholders and business deciders (B2B domain).

According to the DOA, Ecozept will identify potential market opportunities for the AgriLoop innovations by investigating the B2B demand building on the dialogue with stakeholders together with the partners of the consortium. We identified two innovations that we focus our research on: PHA and extracted/ microbial proteins from agri-residues. We conducted interviews with experts and will continue with this process throughout the project. We will iteratively include stakeholders' feedback in the development of the projects' innovations. Furthermore, dss+ will identify promising residue streams, regional focus areas, relevant applications.

Ecozept carries out the tasks and analyses the results, but input of all project partners is necessary at several stages of the work. The results of the market analysis will, for instance, be incorporated in exploitation plans and business modelling, thus data exchange with other tasks and work packages is necessary and takes place. SMEs and industry partners should also provide technical input on the project innovations in preparation for the interviews.

Major experts of the EUG and the main targeted value-chains were interviewed using qualitative research methods to investigate the market potential. The preliminary results lead to this progress report (D1.1). Final results on stakeholder's assessment of the market and business potential will be included in the report (D1.2) of Task 1.1.

2. Applied methods

In the course of the AgriLoop project, Ecozept's task is to conduct several multi-stage surveys with experts at the beginning, half and after two thirds of the project.

More detailed information about the methods for data collection are described in the following chapters. We describe methods that were already applied, and give a short overview about the steps that will be carried out next.

2.1 Desk research

As the conduction of the first stage survey is aspired at beginning of the project, the research is based on the project description and was extracted from the grant agreement and the description of action.

The first step was the identification of key challenges that would be the focus of the project. From the challenges, key words were derived. These were the following:

- "Cascading agri-residues biorefineries"
- "valorisation"
- "Agricultural by-products"
- "Polyhydroxyalkanoate (PHA) from renewable sources"
- "extracted/ microbial proteins (MP)"

Based on these key words we identified information that was useful for the expert interviews like descriptions of the market for agri-residues, challenges of promising end-products PHA and microbial proteins, current structure of valorisation.

2.2 Identification of practical opportunities: promising residue streams, regional focus areas, relevant applications and BtB markets assessment

The EU-28 community presents a group of countries sharing the unique market of goods in Europe. Favourable climate conditions of some European countries and available land area lead to possibilities of high production of vegetables, fruits and cereals. Agricultural production in the European Union is spread over a large area and includes diverse types of climates. On the other hand, the processing of agricultural production tends to be concentrated either in very specific regions within a country (e.g. Andalusia for Spain), or certain countries have made it their specialty and concentrate a large part of European or even world production (e.g., canned tomatoes in Italy or chips in Belgium).

Food value chain generate a significant amount of different agricultural wastes, co-products and by-products (AWCB). The results of a study showed that from 2010 to 2016 in the EU28 the estimated quantity of the AWCB appeared to be around 18.4 billion tons, with the sector percentages as follows: Animal ~31%, Vegetable ~44%, Cereal ~22% and Fruit ~2%. In the Animal sector, the most dominant were developed countries, with high population density and high level of industrialization. The Cereal, Fruit and Vegetable sectors have shown to generate higher AWCB quantities in the countries with more available land area and appropriate climate conditions (Bedoić et al., 2019).

Even though preventive measures have already been taken, food waste generation from some industrial sectors is still unavoidable. And although there are process engineers and breeders of vegetable varieties working to reduce the amount of residues at the time of processing, this reduction is offset in parallel by the increase in agricultural production.

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At the same time, increasing environmental concerns necessitate the production of fuels and chemicals from renewable resources.

Agri-residues, which overall account for about 50% of the fresh weight of harvested crops, represent a huge pool of untapped biomass resources (dry matter). Moreover, food industry waste and by-product streams are rich in carbohydrates (e.g., starch, cellulose), proteins, and minerals, that, after appropriate pretreatment, can be utilized for microbial production of bio-based chemicals and polymers. Various bio-based platform chemicals can be produced at high yields using industrial waste and by-product streams (Pleissner et al., 2016). The fractionation of industrial side streams into value-added coproducts (e.g., pectin, antioxidants, proteins, lipids) will improve the profitability margin required for the cost-competitive production of bio-based chemicals and polymers (Koutinas et al., 2014).

The aim of this chapter is to present the availability and composition of major food industry and agriculture side streams including their utilization as feedstocks for biorefinery development with emphasis on the production of platform chemicals via fermentation. Therefore, the focus lies on industrial food processes producing side streams which contain proteins, peptides, cutin and suberin (bio polyesters), polyphenols and carotenoid that could be separated in a biorefinery concept and used for the production of value-added bio-based coproducts. The food industry sectors covered in this chapter are **wineries, breweries, tomato, apple and potato processing.** Each of them will be presented in a specific chapter. However, primary agri-residues, generated close to the fields, in dispersed small quantity, that may be used on site as fertilizers, animals care or mulching are not considered.

2.2.1 Examination of feedstock

For estimating the quantity of these side streams issued from industrial food processes, a literature review was done in order to get an overall understanding of each feedstock's market: main producing countries, main processing countries, main processing production, major import/export flows. Indeed, a country may be a major producer of a feedstock that is mainly destined for "fresh" consumption and not for processing. Similarly, a country may have a low production of a feedstock but large processing units, so that with the interplay of importations, it may have a high potential for side streams issued from industrial food processes.

Having identified the main processing countries for each raw material (apples, tomatoes, grapes, potatoes, brewer's grains), it was analysed how much of the raw material was processed in each country in order to multiply it by the product-to-residue ratio. When not found directly in the literature the total volume destined for processing, then the key assumption was to consider the volume of the main processed product from this feedstock (e.g. apple juice for apples). The transformation ratio was found in the literature. The respective source will be given in each chapter dedicated to one of the 5 raw materials considered. Thus, the quantities of these side streams issued from industrial food processes are estimation issued from the processed quantity of that feedstock multiplied by the transformation ratio. Occasionally, it was possible to find directly in the literature the quantity of these side streams issued from industrial food processes.

A consistent methodology was used and either only estimates from a calculation based on the quantity processed or only figures from the literature within the same raw material were taken, in order to compare same types of data. However, it should be noted that the figures for the quantity of residues found in the literature - which could be either for a feedstock of a particular country, or for the entire European processing chain for that feedstock - enabled us to confirm our estimated figures and the robustness of our methodology.

2.2.2 Examined feedstocks and promising residue streams, regional focus areas, relevant applications

In the following, the examined feedstocks, promising residue streams, and regional focus areas are discussed. First, the potentials of the agri-residues per European country were summarised.

Table 1: Summary of agri-residues potential per big European country (own compilation).

By Country						
Country	**Total Residues [tn/yr]**	**% BSG**	**% grape pomace**	**% potato residues**	**% apple pomace**	**% tomato residues**
Germany	2 666 333	64%	12%	12%	12%	0%
Italy	2 379 836	15%	75%	0%	1%	9%
France	2 232 924	20%	73%	5%	3%	0%
Spain	2 200 720	35%	58%	0%	2%	6%
Poland	943 527	81%	0%	0%	18%	0%
UK	969 192	79%	0%	14%	7%	0%
Netherlands	804 385	55%	0%	44%	1%	0%
Belgium	571 367	0%	0%	98%	2%	0%
Romania	467 230	70%	30%	0%	0%	0%
Portugal	440 636	30%	55%	0%	0%	14%
Czech Republic	391 180	100%	0%	0%	0%	0%
Austria	217 858	86%	0%	0%	14%	0%
Denmark	137 238	91%	0%	0%	9%	0%
Greece	87 506	0%	86%	0%	0%	14%
Switzerland	35 700	0%	100%	0%	0%	0%
Hungary	31 148	0%	0%	0%	100%	0%

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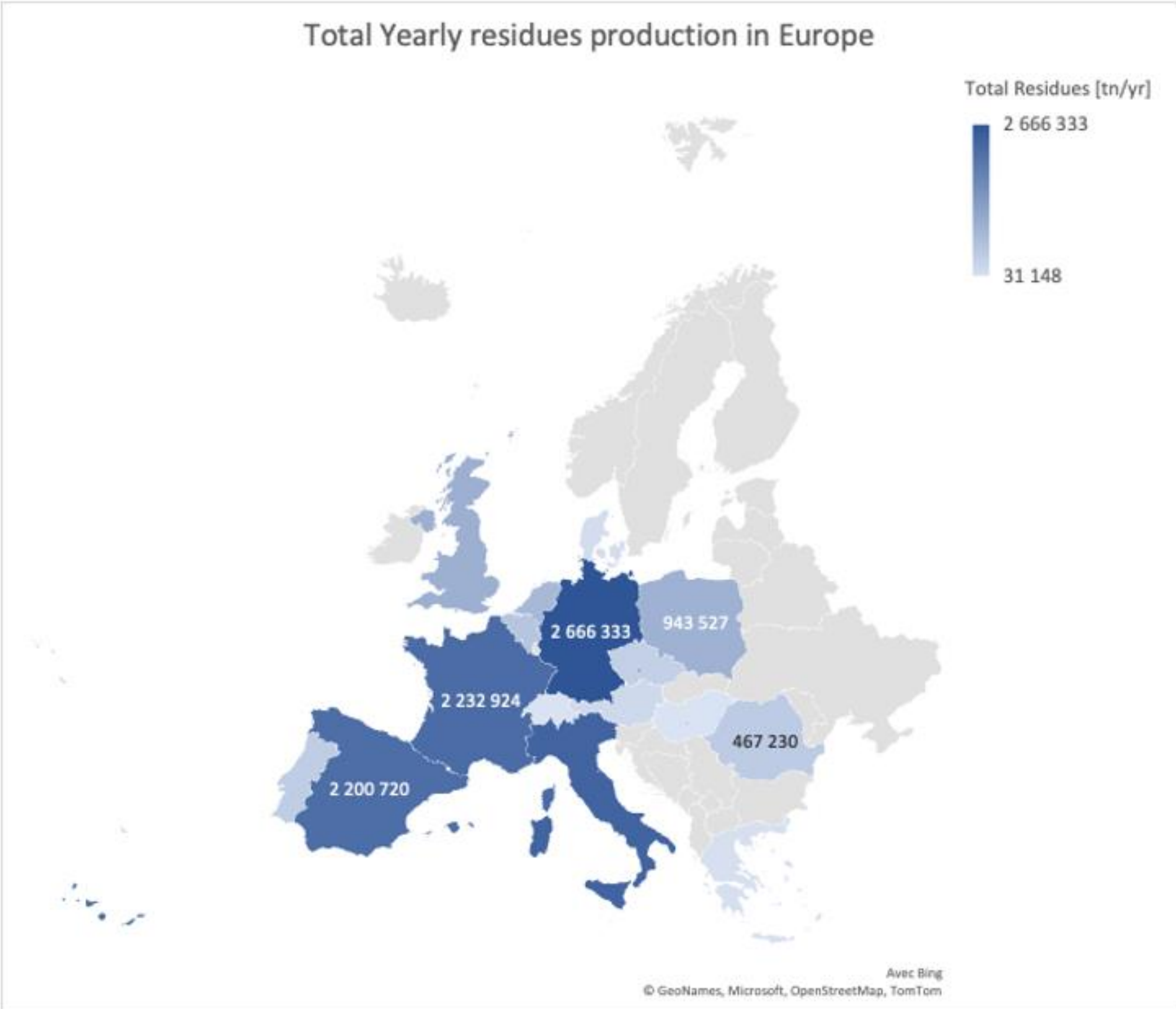

Figure 1: Estimated yearly production of residues related to processing in Europe (own compilation).

Potential tomato industry side streams

Tomatoes are grown in many countries around the world (170 according to the FAO) and in a variety of climates, including relatively cold regions thanks to the development of indoor cultivation. In terms of production volume, it is one of the world's leading vegetables, ahead of watermelon and cabbage, but behind potatoes and sweet potatoes.

Tomatoes are produced in two main sectors: tomatoes for fresh consumption (market tomatoes), tomatoes for processing, and preserving (industrial tomatoes). The latter accounts for around half of production in the European Union.

According to the statistics of the United Nations Food and Agriculture Organization, the production of the European Union (27) of tomatoes amounted in 2021 to 17.9 million tons for a surface of 0.232 million hectares, that is to say an average yield of 77 t/ha (FAOSTAT, 2021).

Almost two thirds of EU tomato production in 2021 was harvested in Italy (6.6 million tons) and Spain (4.8 million tons). In both countries, production levels in 2021 were sharply higher than in 2020 (+6.4 % and +10.2 % respectively).

In Europe, nearly 10 million tons of tomato fruit were processed in 2020, generating half a million tons of tomato pomace (residues of peels, stems and seeds) (Escórcio et al., 2022).

Fresh tomatoes for industrial processing are grown mainly in regions close to the 40th parallel, mainly in the northern hemisphere (90% of the total). It is an open field crop, increasingly mechanized. The three main production areas are California, the Mediterranean basin and China. Production in the Mediterranean basin (eleven countries, including five in the European Union) amounts to 10.5 million tons.

The Mediterranean countries are grouped together in the International Mediterranean Tomato Association (Amitom), founded in 1979 and based in Avignon. This organization brings together trade associations from five European countries (Spain, France, Greece, Italy and Portugal), five countries outside the European Union (Israel, Egypt, Morocco, Tunisia and Turkey) and nine associate members from Algeria, the United Arab Emirates, Malta, Ukraine, Iran and Syria.

According to the latest figures published by the National Association of the Canned Vegetable Industry (Anicav), Italy is a major player in the world of processed tomato production. The country is the world's third largest producer, accounting for around 14.8% of global production and 56.5% of European production, generating sales of almost 5.4 billion dollars by 2022. Italy imports large quantities of tomatoes from China (dominated by two conglomerates, Xinjiang Chalkis and COFCO Tunhe), California and Spain.

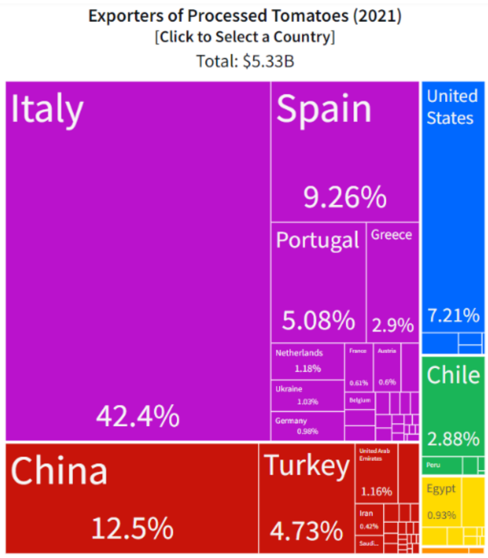

Figure 2: Exporters of Processed Tomatoes (2021)(OEC, 2023).

Although Italian production of processed tomatoes was down 10% on the previous year, at 5.5 million tons, the industry is still thriving, with a planted area of 65,180 hectares, mainly concentrated in the central-southern provinces of Foggia, Caserta and Potenza, as well as the northern districts of Piacenza, Ferrara, Parma, Mantova, Alessandria, Cremona, Verona, Reggio Emilia and Modena (OEC, 2023).

Tomato growers for processing in Italy work closely with processors, often through cooperatives that negotiate contracts on their behalf. These contracts cover the supply of tomatoes, their quality, quantity, delivery schedule and price. The tomato processing industry in Italy is distinct from the fresh tomato industry, with tomato varieties intended for processing being grown specifically for this process, with different characteristics to those intended for fresh sale. They contain higher percentages of solids, are vine-ripened and have thicker skins, which are necessary to produce processed products such as passata, sauces and pasta, which require a higher concentration of tomato pulp. The main Italian actors are AIPA, ANICAV (for the processors) and COLDIRETTI (for the agricultural cooperatives) (Colvine and Branthôme, 2021).

After two spectacularly large crops in 2005 and 2009, the Spanish industry returned to its highest levels after 2014, with volumes that have grown regularly to the point of reaching approximately 3 million mega tons (Mt) in 2015 and 2016 and took the processed total to 3.1 million Mt in 2021. Such levels of processing operations have turned Spain into the second biggest European processor, in direct and intentional competition with Italy, with 19% of the tonnage processed by the AMITOM and 29% of the volumes processed within the EU5. To date, Spain accounts for approximately 8% of worldwide tonnage and ranks fourth among the world's biggest processing countries (Branthôme, 2017).

The Portuguese sector includes a fairly small number of companies. In 2020, eight companies operated in the processing sector. Two operators – Sugal (the leader) and Italagro – share a little less than two thirds of the activity, i.e., a little more than 920 000 tons per year on average over the last five seasons (Branthôme, 2020).

For this feedstock, we collected the quantity of processed tomatoes for the whole of Europe as well as per country. In the table below we have summarized these data found in the literature. In the last column, we have estimated the potential tomato industry side streams for each major processor country according to the product-to-residue ratio we have found in the literature for this feedstock.

We consider the whole tomato pomace, the skin fraction and also the seeds fraction. According to the literature found tomato-processing by-product, also known as tomato pomace, consists of peel and seeds and represents around 4% of the fruit weight (Del Valle et al., 2006).

Table 2: Summary of tomato processing potential per big European country (own compilation).

Country	Year	Volume of processing output	Unit	% of total trans-formation in EU	product-to-residue ratio	Volume of residues generated [tn/yr]	Source
Italy	2021	5 595 000	tn/yr	51%	0,04	223 800,00	(EU FRUIT AND VEGETABLES MARKET OBSERVATORY, 2022)
Spain	2021	3 066 500	tn/yr	28%	0,04	122 660,00	
Portugal	2021	1 591 400	tn/yr	15%	0,04	63 656,00	
Greece	2021	313 400	tn/yr	3%	0,04	12 536,00	
France	2021	155 400	tn/yr	1%	0,04	6 216,00	
Poland	2021	89 000	tn/yr	1%	0,04	3 560,00	
EU	2021	10 939 000	tn/yr	99%	0,04	437 560,00	

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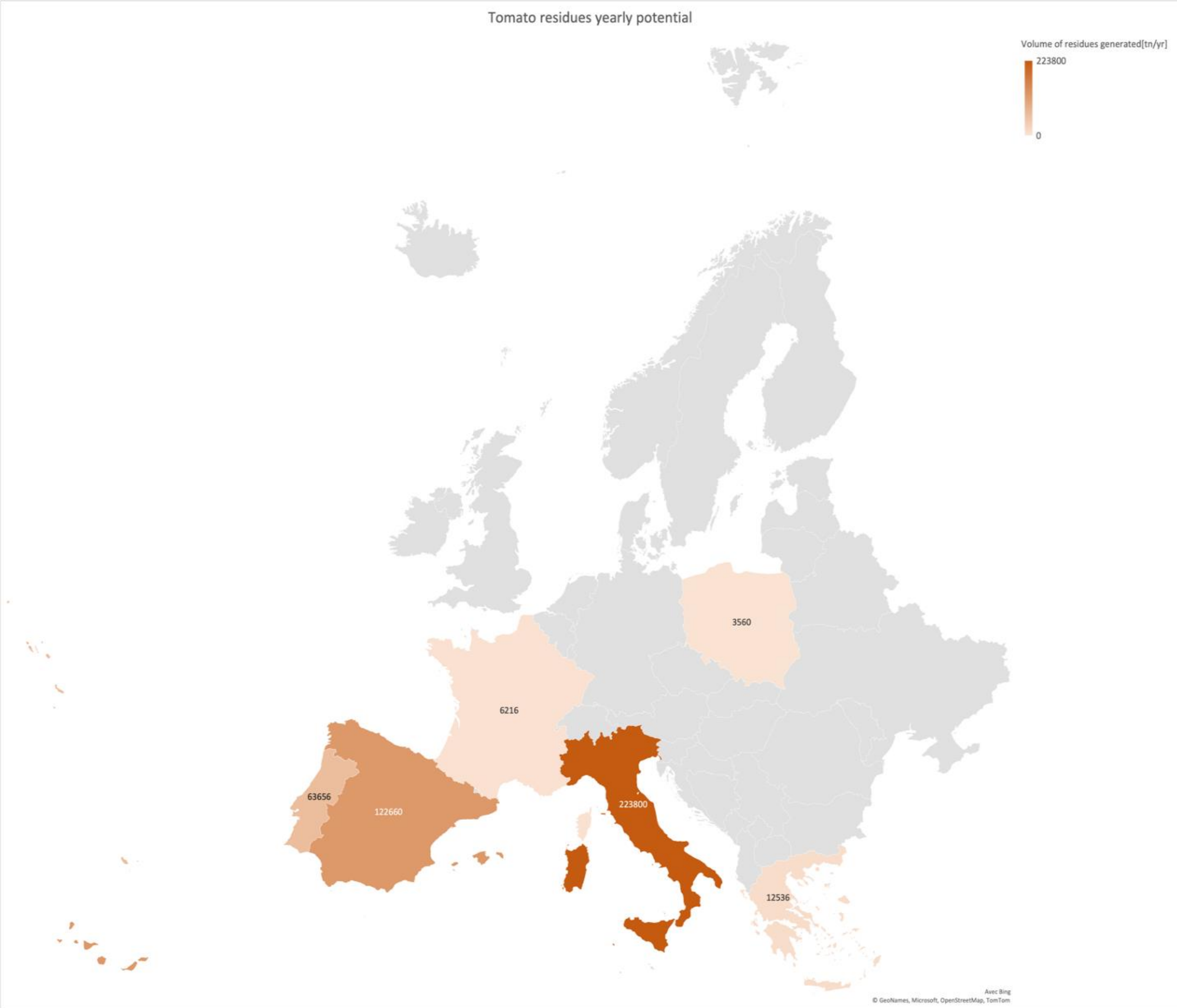

Figure 3: Estimated yearly production of residues related to tomato processing in Europe (own compilation).

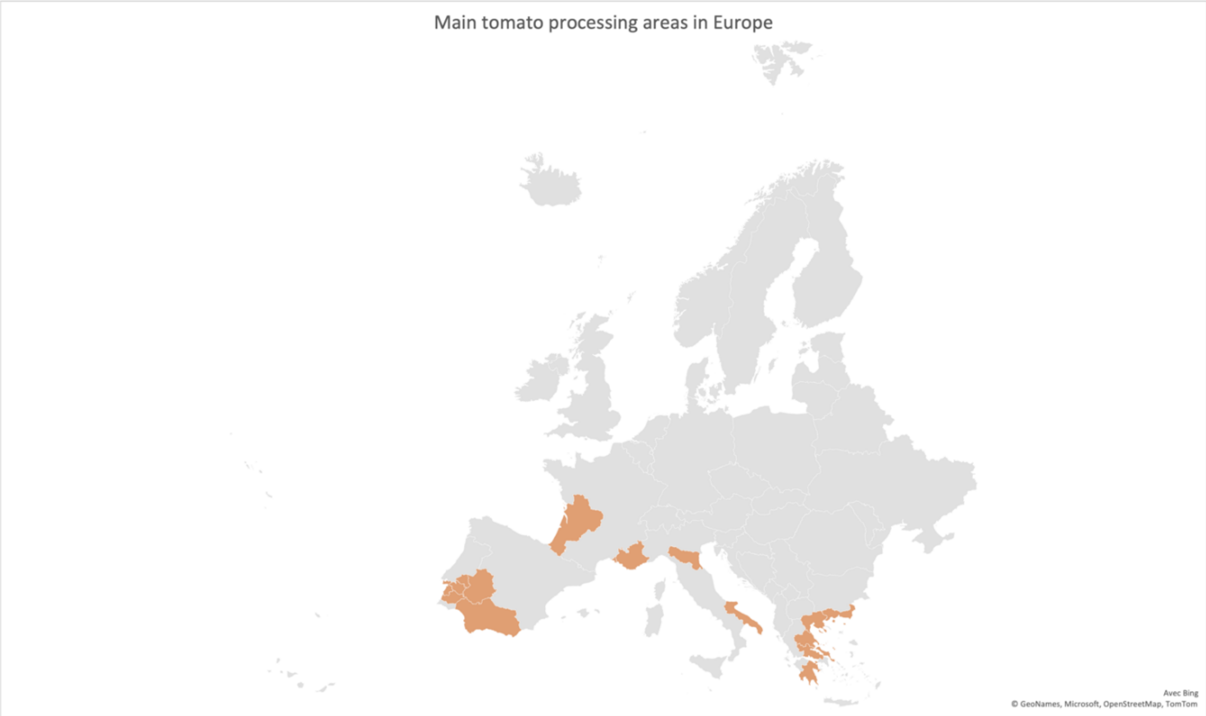

Figure 4: Estimation for the main tomato processing regions within the top processing countries (own compilation).

Following our methodology, we estimated a potential residue from the tomato industry in Europe of 432,000 tons, which is very close to the figure of 500,000 tons found in the literature and therefore confirms that our methodology is consistent.

Tomato industry, that is one of the most important sectors of the world food industry, can display an enormous potential since it produces huge amounts of residues. Such residues negatively impact on the sustainability of food industry when managed as waste, since their disposal represents one main issue in terms of environmental and economic impact. For instance, in Italy the tomato industry pays for the collection and transport of tomato residues (about 100 euros per tons). For now, it is more convenient for the food industry to pay the biogas companies for the collection of the tomato residues. Nevertheless, these residues represent a cheap and renewable biomass that, in the frame of the biorefinery model, could be exploited for the production of chemicals thus contributing to the sustainability of this production chain.

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Potential potato industry side streams

Potato (Solanum tuberosum L.) is the most important food crop after wheat, maize and rice, being a staple for 1.3 billion people, with a global production of more than 368 million tons in 2018 (FAOSTAT, 2021). Approximately 5000 potato varieties are known, hence potato is considered the most genetically diverse crop among cultivated species. Besides being one of the most commonly consumed vegetables, potato crop is also associated with one of the largest food processing sectors throughout the world (Sampaio et al., 2020).

Europe is the second largest grower of potatoes worldwide. The Union production of potatoes amounts to approximately 52 million tons (Eurostat, 2021). Germany was the largest producer of potatoes in the EU in 2020 (at 11.7 million tons, 21.2 % of the EU total), ahead of Poland (a provisional 16.4 %), France (15.7 %) and the Netherlands (12.7 %) (Eurostat, 2021).

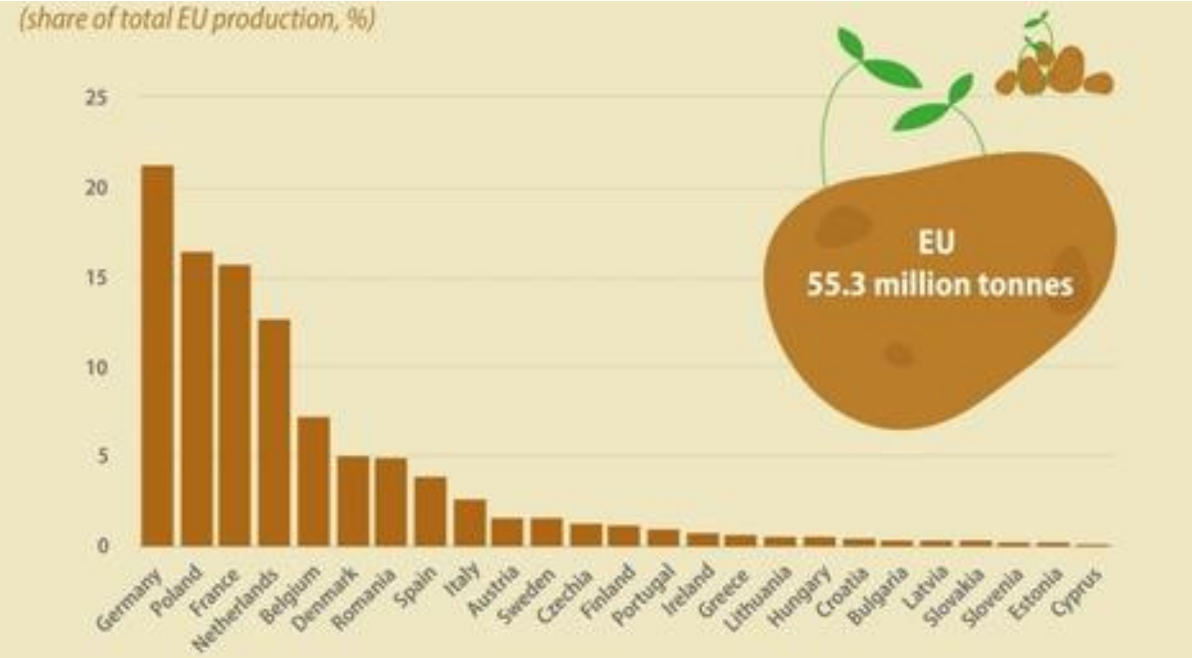

Figure 5: Production of potatoes, including seed potatoes, by producing Member State in 2020(Eurostat, 2021).

Of the 52 million tons 19 million tons correspond to potatoes for processing (EUPPA, 2021). In the European Union, processed potatoes worthed EUR 10 billion in 2017, which corresponds to 1.5% of the whole European food industry production value. More than 90% of potatoes used for processing in Europe are grown in its North-West corner. The biggest Union producers of potatoes for processing are Belgium, the Netherlands, Germany, France, and Italy. These countries have an overwhelming share in the processing capacity and exports of processed potato products (Eurostat, 2021).

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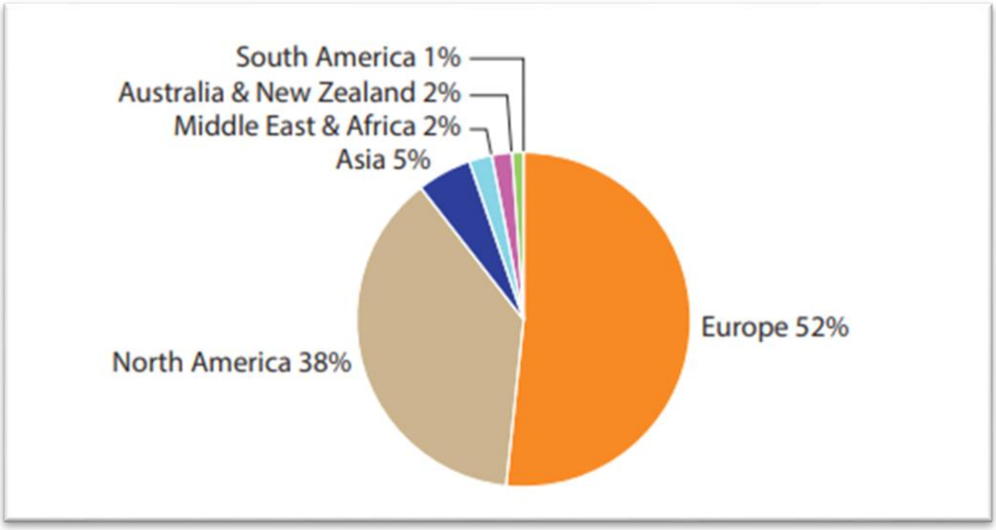

Figure 6: Share of frozen processed-potato processing capacity per region in 2018 (rabobank, 2019).

The potatoes sector can be divided into fresh potatoes, which are mainly purchased for home consumption, and potatoes for processing, such as frozen potatoes (including frozen chips), dried potatoes, prepared or preserved potatoes. It is estimated that more than fifty percent of the total global potato production is consumed after processing (Sampaio et al., 2020).

The potato industry's main money-makers are Chips and crisps. The production of frozen chips is estimated to cover approximately 41 % of the production of potatoes for processing. The frozen potato industry alone is worth €3.8 billion. The crisps industry is worth €3.6 billion. The total value generated by the potato industry in Europe reached €9.1 billion in 2019. This represents 1.6% of the total production value of the entire European agri-food industry.

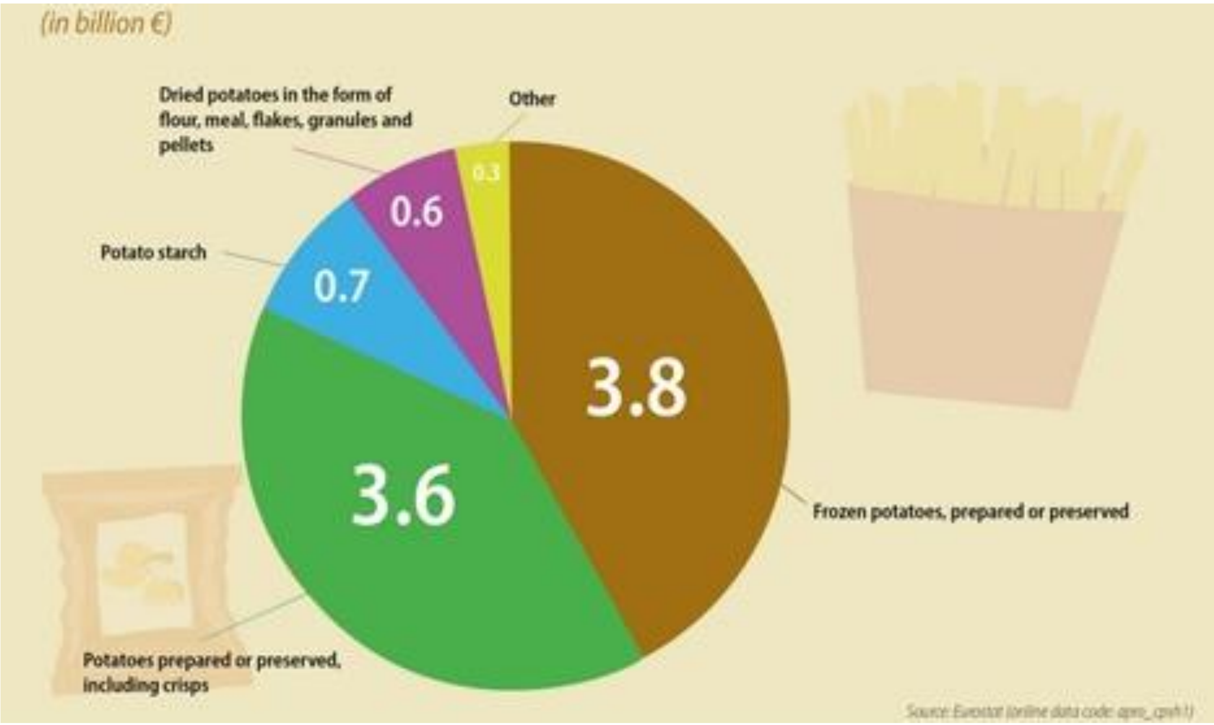

Figure 7: Production value of processed potatoes, UE in 2019 (Eurostat, 2021).

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In 2011, Belgium became the world's leading exporter of frozen potato products, ahead of the Netherlands, Canada and the United States. Belgium and the Netherlands produce more than half of the total European frozen potato products (CBS, 2016). In these two countries, the potato processing industry has grown significantly in the past decade.

In Belgium, the amount of processed potatoes increased from 3.3 million tons in 2010, to 5.3 million tons in 2019 (+38%). In the Covid-19 year 2020, this amount fell to 5.1 million tons, a decrease of 4% compared to the previous year. The Belgian potato processing industry increased the amount of processed potatoes to more than 6.2 million in 2022. The sector thus sharpens its own record from 2019 by no less than 18% (Belgapom, 2023).

In the Netherlands, the growth of the processing industry was from 3.4 million tons processed potatoes in 2010 to 3.9 million tons in 2019 (+15%). In 2020, the volume of potatoes processed by Dutch processors fell to 3.4 million tons (-13% compared to 2019). In Germany, the amount of processed potatoes has remained fairly stable at 3.6 million tons per year since 2011, which is processed into various products (e.g. dried, chips, salads, fries); 1.1 million tons of these potatoes are processed yearly into 0,54 million tons of frozen fries. The French frozen processed potatoes production is estimated at 0.48 million tons of frozen product for which 1 million tons of potatoes are needed. Due to their extensive raw material requirements, Belgian and Dutch processors import potatoes from neighbouring countries. Germany exports between 1.5 and 1.75 million tons of ware potatoes for processing to Belgium and the Netherlands and France exports 1.7 million tons potatoes to these countries (Janssens et al., 2021).

Generally, potato processing begins with tubers peeling, for which methods such as steam peeling, lye peeling and abrasion have been reported, with the latter being the most used by the crisps industry. Added value processed products such as French fries, chips, hash browns, puree and frozen food account for a waste generation caused by potato peeling ranging from 15% to 40% of the original fresh weight, depending on the peeling process (Sampaio et al., 2020). Plants peel the potatoes as part of the production of crisps, instant potatoes and similar products. The produced residue is 90 kg per ton of influent potatoes and is apportioned to 50 kg of potato skins, 30 kg starch and 10 kg inert material (Arapoglou et al., 2010). The downstream processing in the potato crisp industry is illustrated in the following general flowchart of Figure 8.

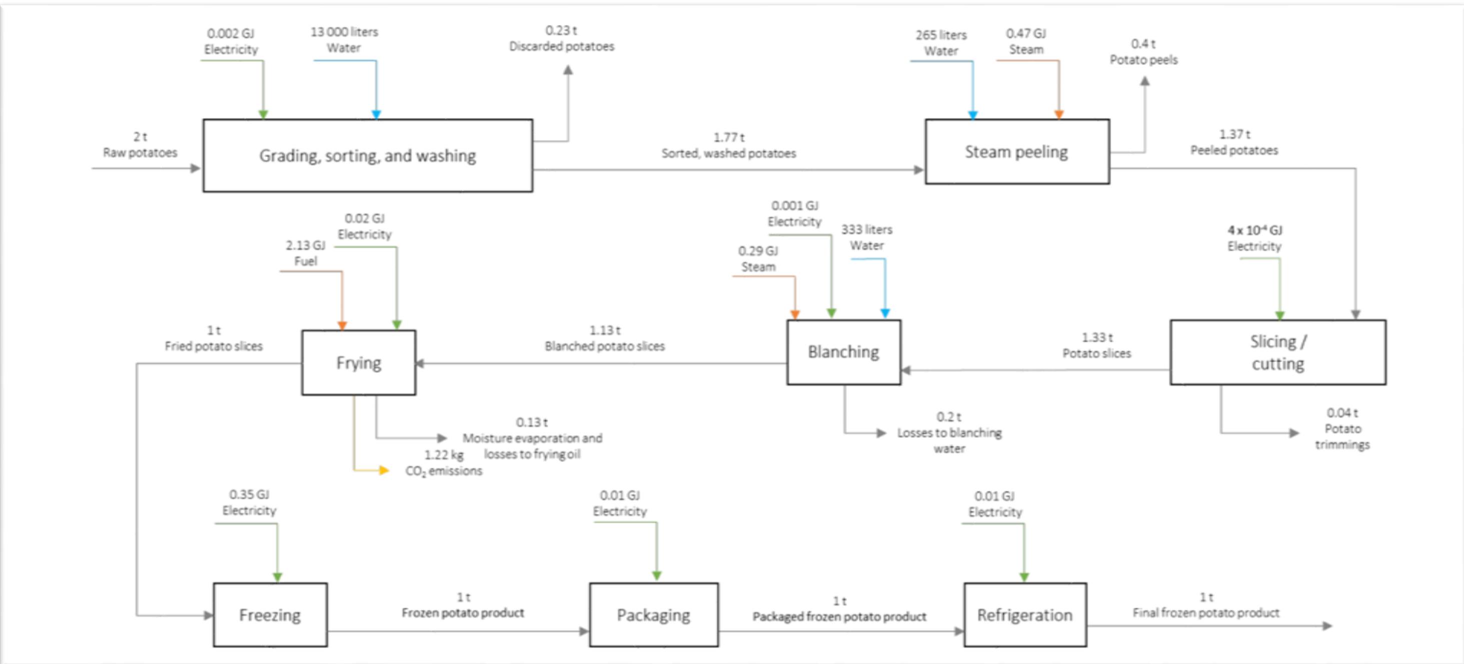

Figure 8: Process flow diagram for 1 ton frozen potato product (Van Hout et al., 2020).

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The extraction of plant bioactive molecules has been largely explored and well established by many authors as an efficient route for the reutilization of food processing waste, especially when considering the recent technological advances in molecular separations and identifications. Potato peels can be a rich source of bioactive compounds due to their high contents in phenolic compounds with recognized health-promoting properties, such as antioxidant activity, that can also be employed in food systems to extend the shelf-life of food products (Sampaio et al., 2020).

Because potato processing is an energy intensive sector, it is an area in which the sector invests much of its efforts in order to reduce its CO2 emissions. For example, the Italian potato specialist Pizzoli, the market leader in frozen potato products McCain or the Austrain company 11er Nahrungsmittel GmbH convert potato peel and other production waste into biogas in a biomass plant and used to generate sustainable electricity. This allows the company to create an environmentally virtuous production cycle, reduce the impact of its waste and receive clean energy in return (EUPPA, 2021).

For this feedstock, we easily found the value of processed potatoes for the whole of Europe and for the 4 largest processors: Belgium, the Netherlands, France and Germany. On the other hand, it was much more difficult for Italy, Spain and Poland.

In the table below we have summarized the data found in the literature: quantity of potatoes processed for Europe and for the largest potato producers; in order to get first estimates of volumes the product-to-residue ratio was assumed fixed for the different processing pathways. In the last column, we have estimated the quantity of residues for each country. Potato production areas correspond to processing areas.

Table 3: Summary of potato processing potential per big European country (own compilation). Here it is assumed that the residues factors are equal for the different potato processing pathways.

Country	Year	Volume of processing output	Unit	% of total trans-formation in EU	product-to-residue ratio	Volume of residues generated [tn/yr]	Source
Belgium	2022	6 200 000	tn/yr	33%	0,09	558 000,00	(Belgapom, 2023)
France	2022	1 166 000	tn/yr	6%	0,09	104 940,00	(FranceAgriMer, 2022)
United Kingdom	2019	1 470 000	tn/yr	8%	0,09	132 300,00	(PPA, 2022)
Germany	2019	3 600 000	tn/yr	19%	0,09	324 000,00	(Janssens et al., 2021)
Netherlands	2019	3 900 000	tn/yr	21%	0,09	351 000,00	(Janssens et al., 2021)
EU	2021	19 000 000,00	tn/yr	0,93	0,09	1 710 000,00	(EUPPA, 2021)

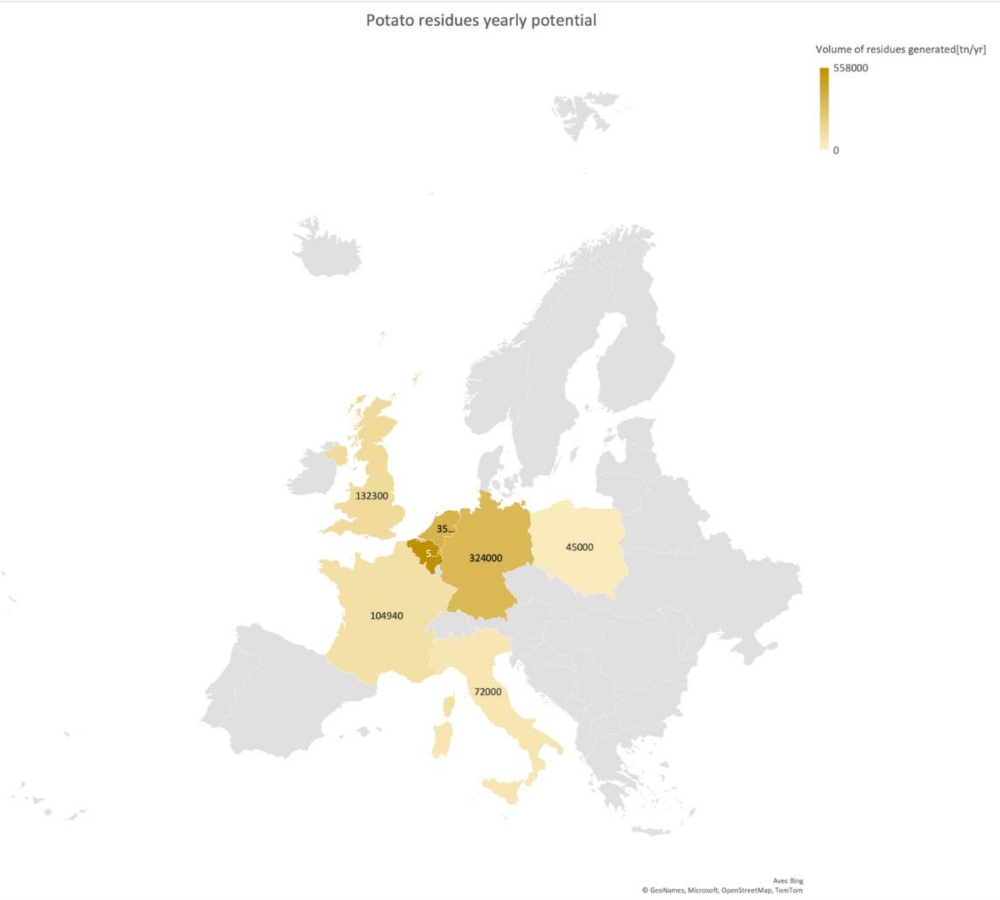

Figure 9: Estimated yearly production of residues related to potato processing in Europe (own compilation).

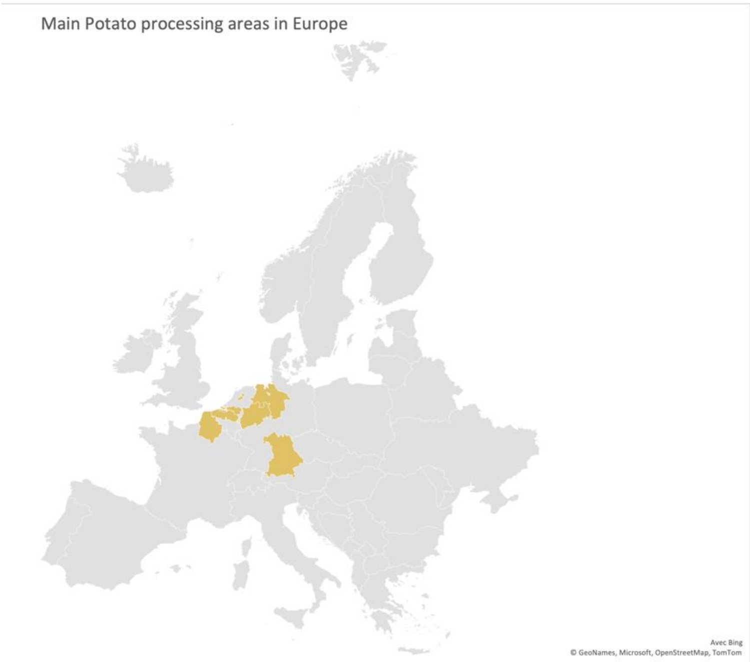

Figure 10: Estimation for the main potato processing regions within the top processing countries (own compilation).

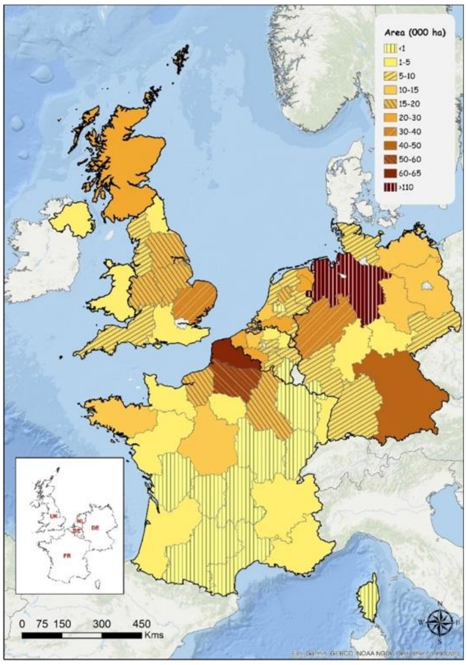

Figure 11: Potato producing regions in Europe(Goffart et al., 2022).

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Potential apple industry side streams

Apples are one of the most consumed fruits in Europe. Apples are mainly cultivated for the fresh fruit market (more than 80% of the fresh apples are destined for fresh consumption) with the rest being processed into apple juice, apple cider, applesauce, apple butter, cider vinegar, dried apples and canned apples (CBI, 2021).

It is the most widely grown fruit in temperate zones. Europe is a major fruit-growing continent, with production of around 12.2 million tonnes in 2022, driven by 3 main producer countries: Poland, Italy and France (including 4 million tonnes in Poland, i.e. a third of total European production). Between them, the 3 countries account for 2/3 of European production (FAOSTAT, 2021). In 2013, Poland was the world's leading apple exporter (Klepacka and Florkowski, 2016).

Although the global apple production continues to grow, the share of its consumption is relatively stable. Apples used for fresh consumption account for 70%–75% while the rest (25%–30%) of world total production is processed to various value-added products including juice, wine, jams and dried product (Bhushan et al., 2008; Lyu et al., 2020; Shalini and Gupta, 2010). However, apple juice is still the most demanded apple product, accounting for 65% of the total amount of processed apple (Kammerer et al., 2014).

To estimate the potential apple industry side streams, we had two options:

- either we took 25% of the quantity of apples produced in each country, which gave us an estimate of the volume of apples processed for each country, then we multiplied this volume by the product-to-residue ratio. As the volume of apples produced was readily available, this estimate was easy to make. However, the assumption of 25% of processed apples per country was a very rough approximation, as this is a world average.
- or we took the production volumes of apple juice, which represents 65% of processed apples in Europe, and multiplied it by the product-to-residue ratio. We found the second hypothesis to be a better approximation because it takes into account the internal European dynamics of raw material imports and exports, which are not captured if we do not focus on the processing volumes of an industry (apple juice in our case). We can see, for example, that Germany, which is only in 4th place with 1 million apples produced (FAOSTAT, 2021), is the undisputed leader in European apple juice production. The latter imports apples from its Polish neighbor, a major apple exporter (CBI, 2021). What's more, we easily found the volumes of apple juice produced by European country and the total for the whole of Europe, whereas we were unable to find the volumes of apples processed, either by country or for the whole of Europe.

There is, however, a correction to be made to the second hypothesis: a lot of apple juice is produced from concentrates, and Poland is one of the biggest producers of apple concentrates. Furthermore, 1 tonne of apple juice concentrate equals to roughly 5'300 L of apple juice (Heitlinger, 2016). Taking this into account, the potential for residues from apple processing in Poland is almost equivalent to that in Germany.

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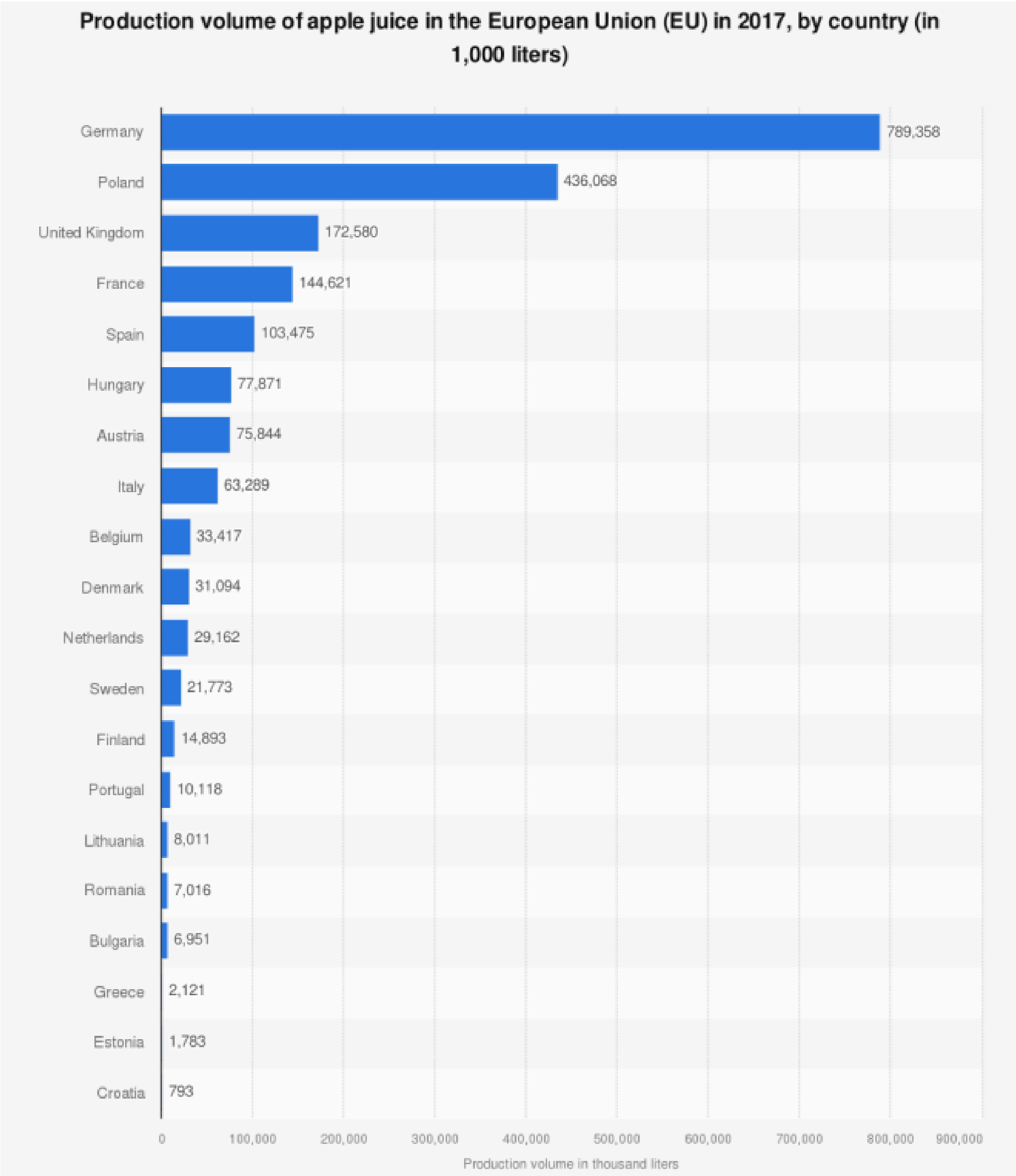

Figure 12: Production volume of apple juice in the European Union (EU), by producing Member State in 2017 (Statista, 2018).

In large scale apple juice processing industries, two types of waste are generated. The first is the unprocessed discarded apple fruit (culls), and the second is the pomace (pulp, peels, seeds, and cores) which is left after juice extraction. Generally, nearly 75% of apple fresh weight is supposed to be extracted as juice during juice production, and the left-over is collected as a food waste, the so-called pomace (Vendruscolo et al., 2008). About 250 to 350 kg of wet pomace can be obtained from a tonne of apples processed for juice (DairyFarmGuide, 2023; Gołębiewska et al., 2022). Once we had the volume of apple juice produced per country, and the product-to-residue ratio for this industry, we were able to estimate the residue potential for the major apple-processing countries as shown in the table below:

Table 4: Summary of apple processing potential per big European country (own compilation).

Country	Year	Volume of processing output	Unit	% of total trans-formation in EU	product-to-residue ratio	Volume of residues generated [tn/yr]	Source
Germany	2017	7 893 580	hL/yr	39%	0,04	315 743,20	(Statista, 2018)
Poland	2017	4 360 680	hL/yr	21%	0,04	174 427,20	
United Kingdom	2017	1 725 800	hL/yr	8%	0,04	69 032,00	
France	2017	1 446 210	hL/yr	7%	0,04	57 848,40	
Spain	2017	1 034 750	hL/yr	5%	0,04	41 390,00	
Hungary	2017	778 710	hL/yr	4%	0,04	31 148,40	
Austria	2017	758 440	hL/yr	4%	0,04	30 337,60	
Italy	2017	632 890	hL/yr	3%	0,04	25 315,60	
Belgium	2017	334 170	hL/yr	2%	0,04	13 366,80	
Denmark	2017	310 940	hL/yr	2%	0,04	12 437,60	
Netherlands	2017	291 620	hL/yr	1%	0,04	11 664,80	
EU	2017	20 500 000,00	hL/yr	0,95	0,04	820 000,00	

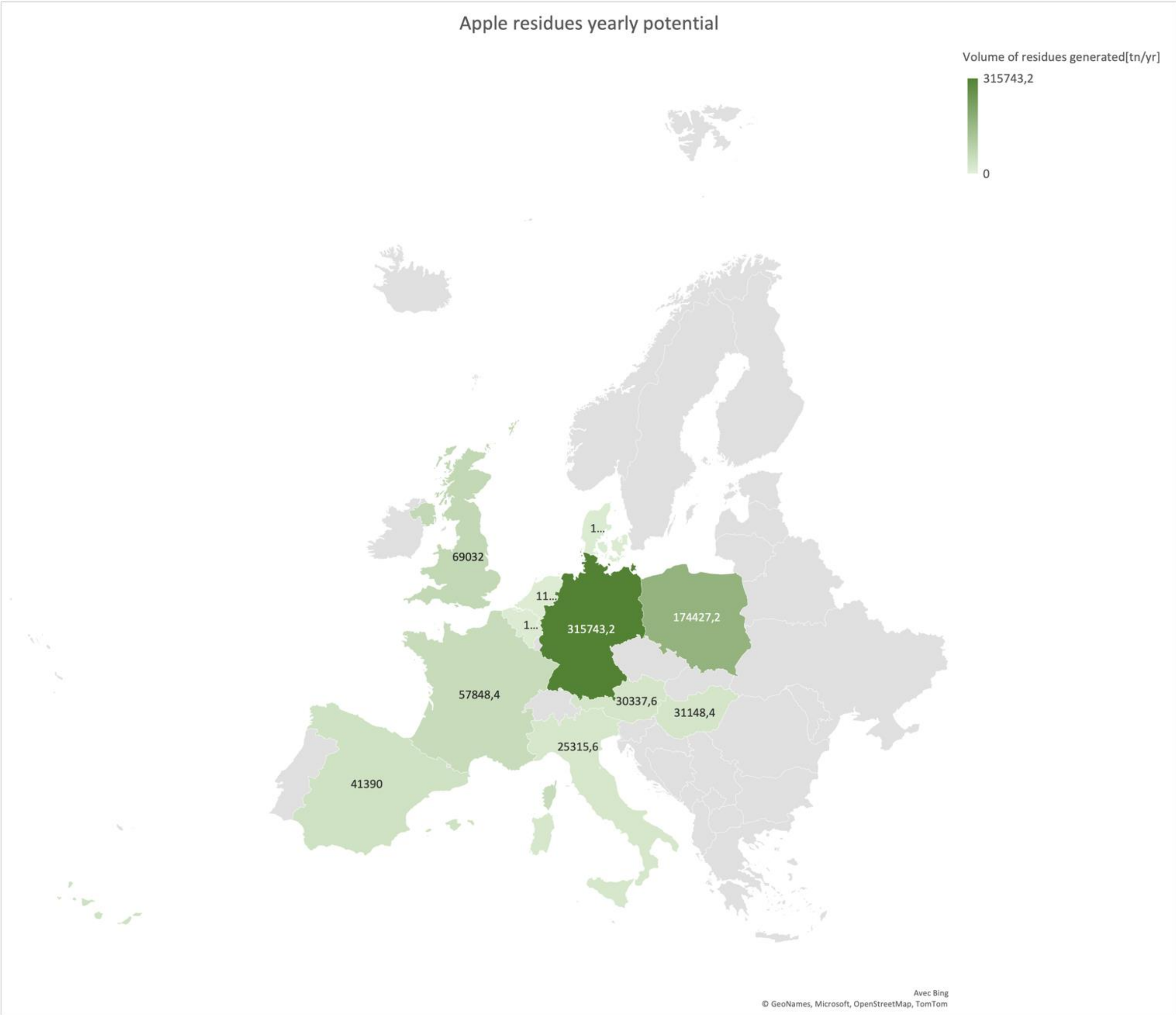

Figure 13: Estimated yearly production of residues related to apple processing in Europe (own compilation).

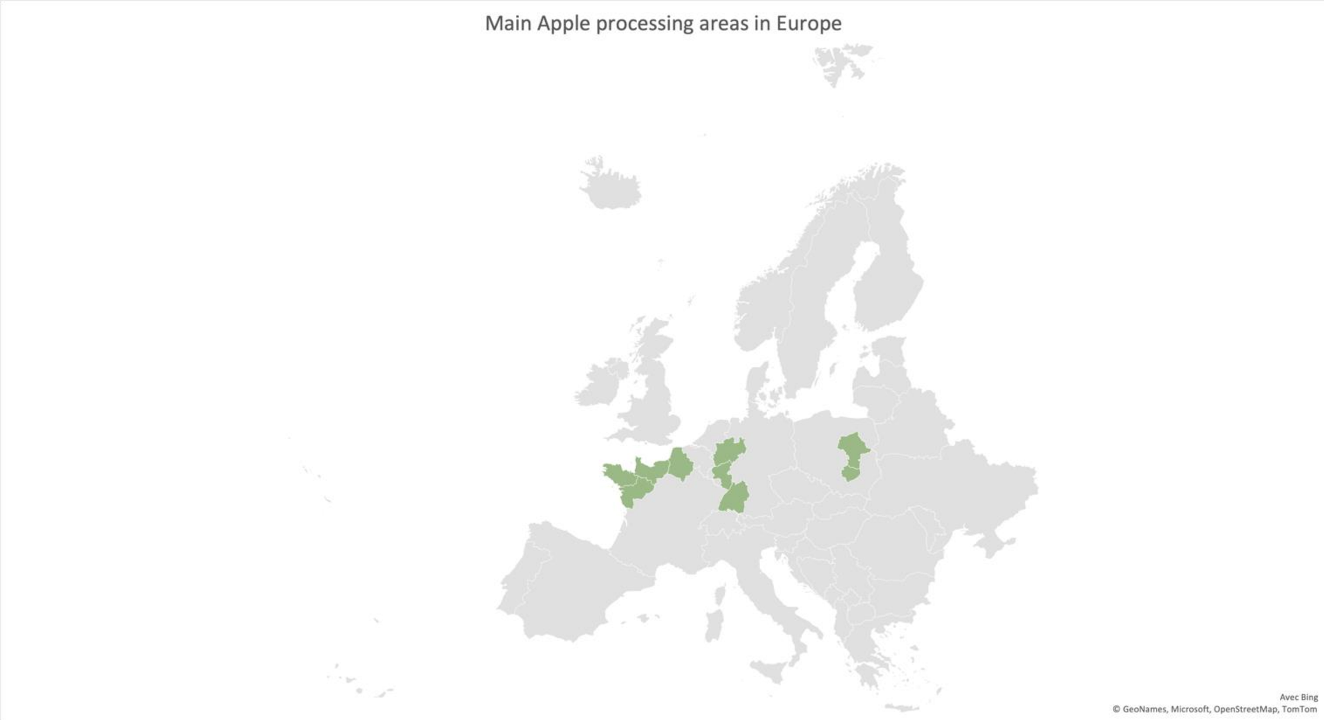

Figure 14: Estimation for the main apple processing regions within the top processing countries (own compilation).

Apple pomace from juice extraction often contains rice hulls or husks that are added by commercial juice manufacturers to aid filtration and recovery of the juice. The residual material from canning, drying and freezing of apples is also known as pomace and consists of the peels, cores and culled apples or pieces. Leftover by-products of apple processing, such as pomace containing peel, seeds, core and stem tissues may be fed to livestock (National Research Council, 1983).

Currently, due to poor waste management and a lack of environmental awareness in many countries, a large amount of apple pomace is treated as waste with no economic value. Besides, there are some technical limitations affiliated with the effective utilization of apple waste, such as the requirement of immediate treatment after obtaining it (e.g., by drying); this is important to prevent the excessive growth of microorganisms (microbiological contamination), and hence, the loss of overall economic value. To foster sustainability, AP should be treated as a valuable raw material that can be reused or processed. The sustainable management of AP is based on the recovery and utilization of apple waste, which creates a possibility to reuse it and put it back into the supply chain. Green extraction techniques allow the obtaining of AP extracts that are rich in active compounds in an eco-friendly manner. The solid residues generated during extraction can be stabilised and further transformed into, e.g., alternative energy sources or biopolymers with zero waste. Therefore, sustainable AP management gives the opportunities for reducing environmental pollution and increasing integration into a circular economy by using AP as a source of active compounds and biopolymers, a feedstock for the production of biofuels, and as a source of raw materials that can be utilised in different industrial sectors including the construction and building industry sector, the energy sector, and food or material industries (Gołębiewska et al., 2022). But considering the large volume of this by-product generated from production and processing of juice, the commercial applications of pomace can create great economic impact (Shalini and Gupta, 2010). Some success has been achieved in transforming a variety of agricultural and food processing waste into commercially viable products including bio-fuels, nutrients and multifunctional ingredients (Laufenberg et al., 2003). Similarly, in recent years, various applications of apple pomace have been considered in order to raise its recovery rate.

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Potential wine industry side streams

The EU is big player on the world's wine market; in 2020, it accounted for 64 % of global production, 48 % of consumption and 45 % of the wine-growing areas in the world.

Harvested production in many of the main grape-producing countries fell in 2021. Thus, the total harvested production of grapes for wine in the EU was an estimated 22.7 million tons in 2021. This was 1.4 million tons less than in 2020 and markedly less than the 25.7 million tons in 2018. Italy, Spain and France account for the vast majority of grape production for wine in the EU (see Figure 7.1 below). Whereas 2021 production levels in Italy remained similar to 2020 levels, they were much lower in Spain (down 11.5 %) and France (down 13.7 %) (Eurostat, 2022a).

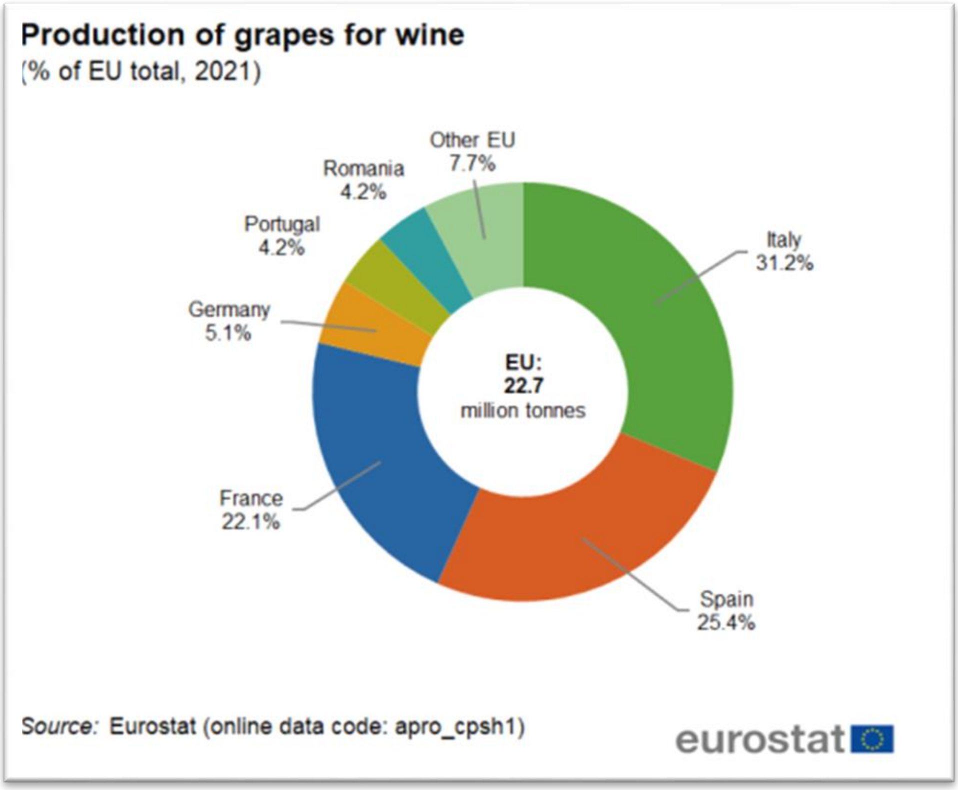

Figure 15: Production of grapes for wine (% of EU total in 2021) (Eurostat, 2022a).

To estimate the wine industry's potential secondary flows, we needed the following 3 key parameters:

- the wine production volumes per country (Volume of processing output),
- the wine production yield to obtain the quantity of grapes entering the winery,
- the transformation ratio to estimate the volume of residues obtained from a quantity of grapes entering the winery (R).

According to Eurostat, the amount of wine sold in EU-28 in 2017 was estimated at more than 179,5 million hectoliters. The main producers are Spain, Italy, and France producing more than 75% of the wine in EU-28.

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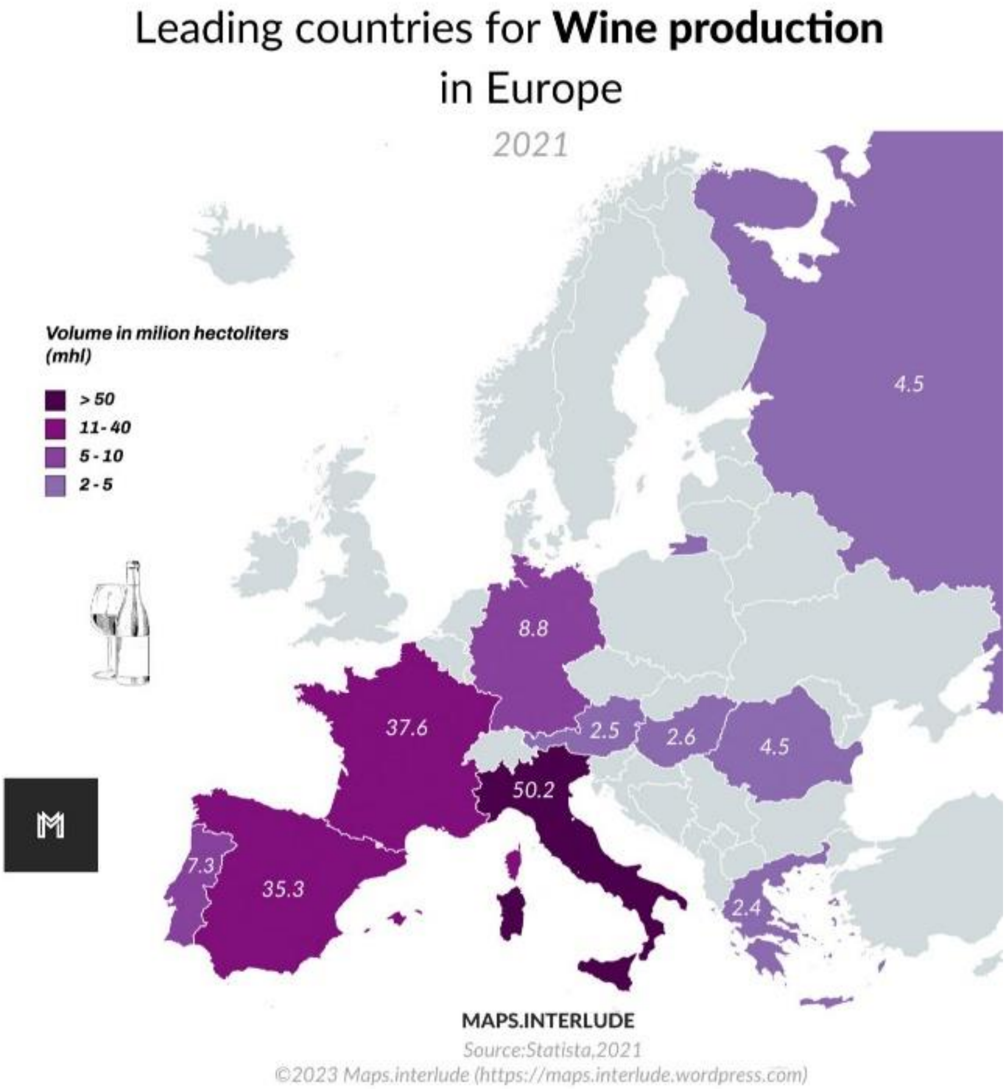

Figure 16: Leading countries for wine production in Europe in 2021 (mapsinterlude, 2023).

The main waste/by-product streams from wineries are:

- grape stems obtained after the crushing and destemming of grapes,
- grape pomace including skins and grape seeds separated from the must after pressing,
- wine lees consisting of yeast cells, tartrate salts and precipitated tannins, and pigments.

According to the literature(Ladakis et al., 2020)

- 1 kg of entering grape is necessary to produce 0.7 liters of wine (Y) (or 1 T to produce 7 hL)
- The total solid wastes/by-products of wine production processes (red or white) make up 20%-30% (w/w) of incoming grapes.
- The quantity of pomace, stalks, and seeds produced from grape processing can be calculated considering that each stream corresponds to 15%, 2.5%-7.5%, and 3%-6% of grape weight respectively.

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To simplify the calculation, we considered that the total solid wastes/by-products of wine production processes make up 25 % of incoming grapes (R). An example of the calculation of the wine residue quantities for Germany in 2022 is given below:

Volume of processing output = 8 900 000 hL / yr = 890 000 000 L / yr

Quantity of grapes entering the winery = Volume of processing output / Y = (890 000 000 / 0.7) = 1 271 428 571 kg / yr = 1 271 429 tn / yr

Volume of residues generated = Quantity of grapes entering the winery x R = 1 271 429 x 0.25 = 317 857 tn / yr

To calculate directly the volume of residues from the produced wine volumes, we used the residues factor = 0.25 / 7 = 0.0357

Table 5: Summary of wine grapes processing potential per big European country (own compilation).

Country	Year	Volume of processing output	Unit	% of total trans-formation in EU	product-to-residue ratio	Volume of residues generated [tn/yr]	Source
Germany	2022	8 900 000	hL/yr	5%	0,0357	317 730,00	(Statista, 2023)
Spain	2022	35 700 000	hL/yr	22%	0,0357	1 274 490,00	
France	2022	45 600 000	hL/yr	28%	0,0357	1 627 920,00	
Greece	2022	2 100 000	hL/yr	1%	0,0357	74 970,00	
Italy	2022	49 800 000	hL/yr	30%	0,0357	1 777 860,00	
Portugal	2022	6 800 000	hL/yr	4%	0,0357	242 760,00	
Romania	2022	3 900 000	hL/yr	2%	0,0357	139 230,00	
Switzerland	2022	1 000 000	hL/yr	1%	0,0357	35 700,00	
EU	2020	165000000	hL/yr	93%	0,0357	5 890 500,00	

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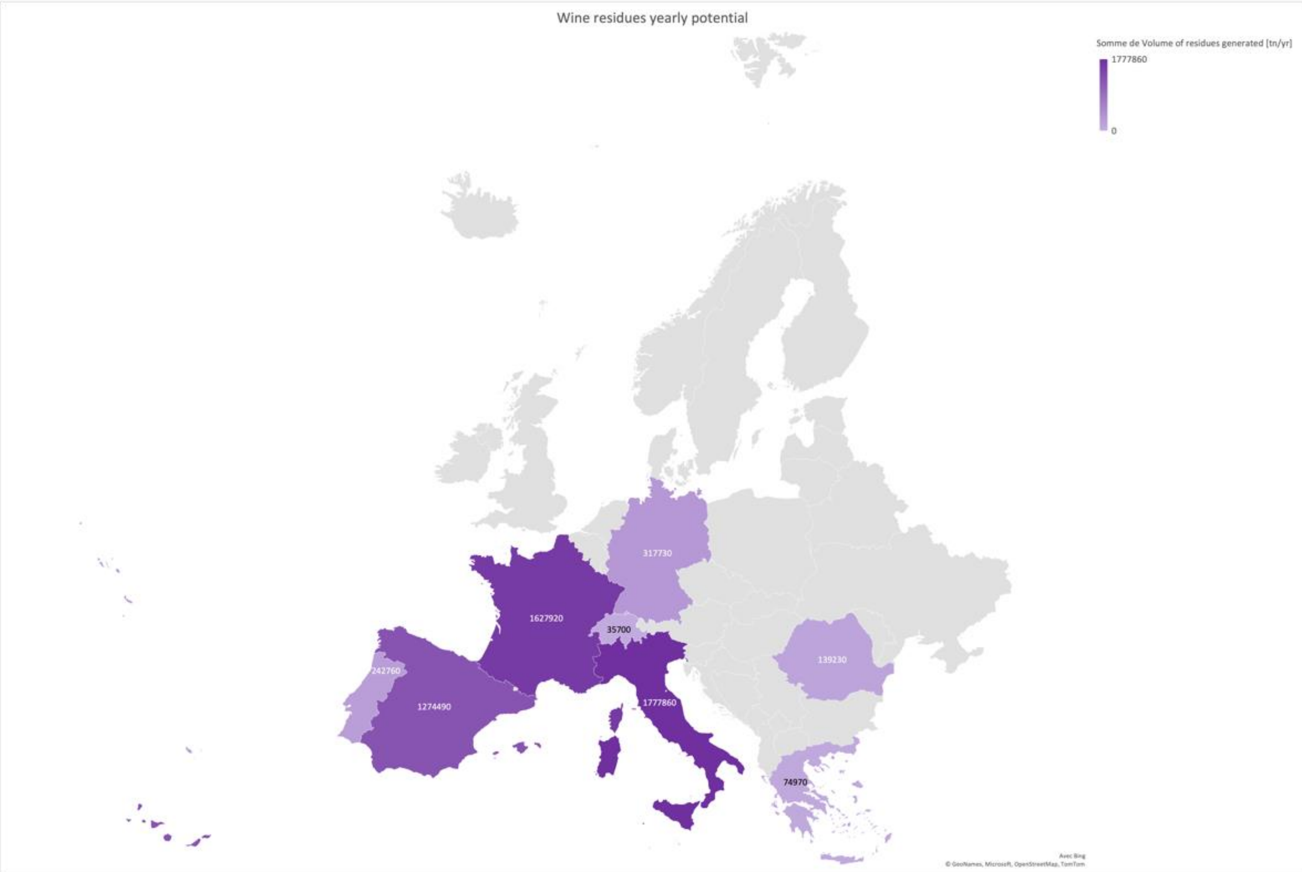

Figure 17: Estimated yearly production of residues related to wine production in Europe (own compilation).

Here are the main wine production regions of the 3 biggest wine producing countries in Europe and thus the main regions in Europe with grape pomace potential:

Figure 18: Italy's main wine production regions (Winefolly, 2023a)

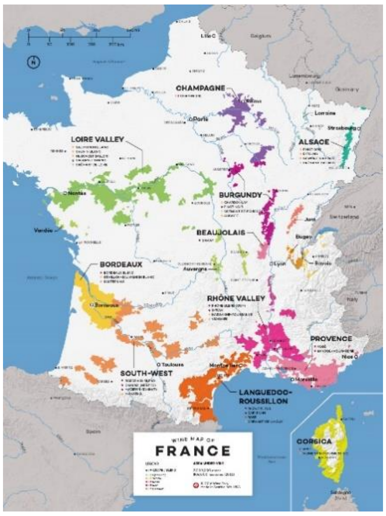

Figure 19: France's main wine production regions (Winefolly, 2023b)

Figure 20: Spain's main wine production regions (Winefolly, 2023c)

In a previous European Union's Horizon 2020 project (NoAW), a study was carried out to estimate the potential of grape marc in Europe. In the figure hereafter are the results of that study. The quantities of residues estimated are very close to the values we estimated using our methodology. This confirmed that our methodology was consistent.

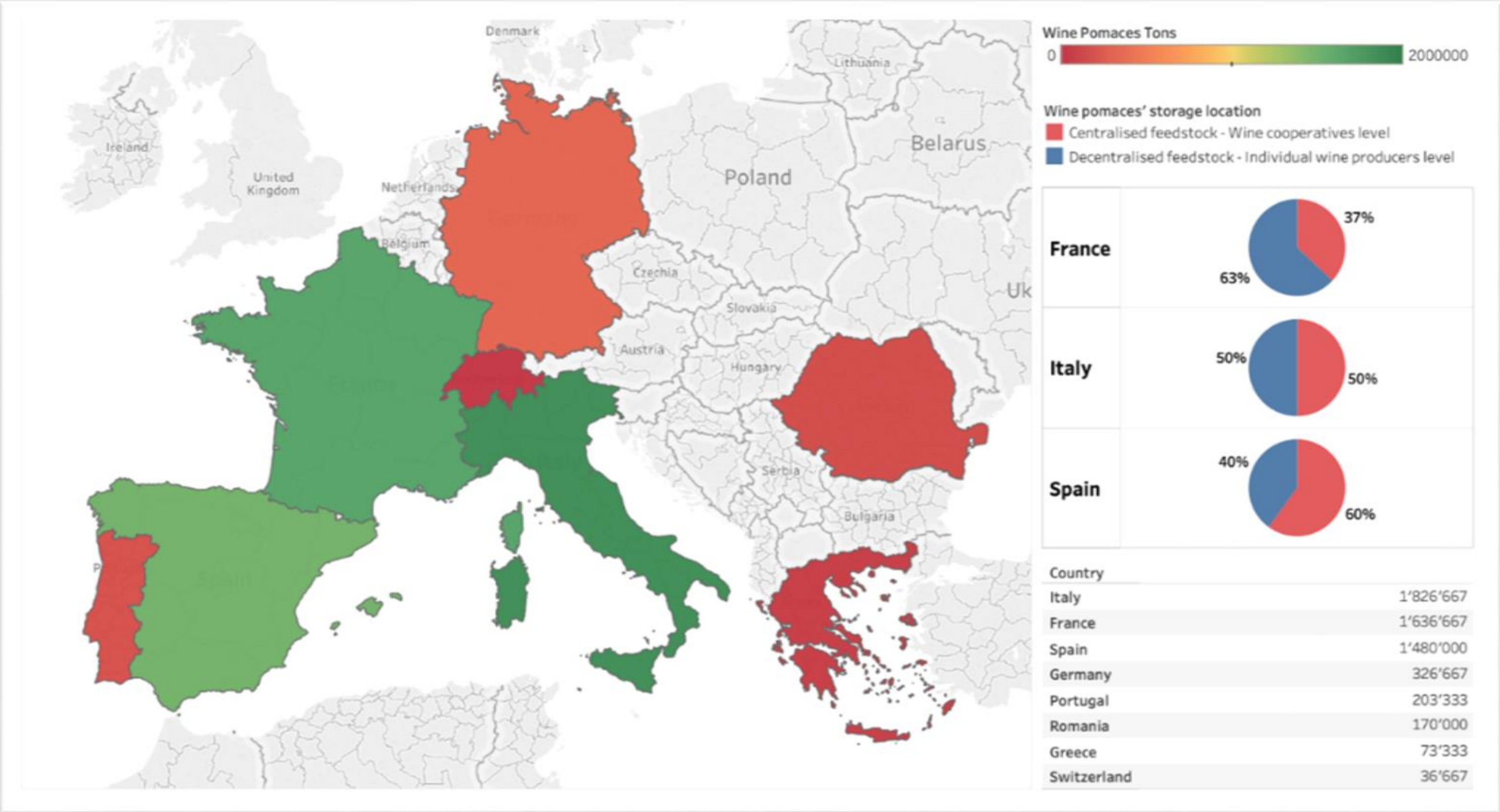

Figure 21: Estimated Wine pomace production in Europe (noaw2020, 2020).

As Europe's largest wine producers, Italy, France and Spain are the countries presenting the highest potential for wine pomaces. From an organizational perspective, Spain and Italy are very relevant as 60% and 50% respectively of the feedstock (pomace) is centralized in wine cooperatives.

Potential brewery industry side streams

In 2021, EU Member States produced 33.1 billion liters of beer containing alcohol and almost 1.7 billion liters of beer, which contained less than 0.5% alcohol or had no alcohol content at all. Compared with 2020, there was a boost in the EU's production of beer with and without alcohol. Production of non-alcoholic beer increased the most, almost by 20%, while beer containing alcohol increased by almost 3% (Eurostat, 2022b).

Among the EU Member States with data available, in 2021 just like in 2020, Germany was the top producer with 7.5 billion liters (23% of the total EU production). This means that about one in every four beers containing alcohol produced in the EU originated in Germany. Germany was followed by Poland and Spain, both with 3.7 billion liters produced, or 11% of total EU production and the Netherlands with 2.5 billion liters or 7% of the total EU production. The production of these four countries amounts to 52% of the total EU beer production(Eurostat, 2022b).

The main side streams produced by breweries are:

- brewer's spent grains (BSG) derived after the malt mashing process,
- trub from the wort tanks,
- and spent yeast separated from the fermented liquor.

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BSG accounts for approximately 85% of the total mass of solid by-products in the brewing industry and represents an important secondary raw material of future biorefineries. The mass of wet BSG obtained per 1 hl of beer produced is about 20 kg. Thus, the wet BSG quantity produced in the European Union is estimated at approximately 7 million tons (Amelinckx, 2015; Zeko-Pivač et al., 2022).

Table 6: Summary of brewery grains processing potential per big European country (own compilation).

Country	Year	Volume of processing output	Unit	% of total trans-formation in EU	product-to-residue ratio	Volume of BSG generated [tn/yr]	Source
Germany	2021	85 443 000	hL/yr	25%	0,02	1 708 860,00	(Eurostat, 2022b; Statista, 2022)
United Kingdom	2021	38 393 000	hL/yr	11%	0,02	767 860,00	
Poland	2021	38 277 000	hL/yr	11%	0,02	765 540,00	
Spain	2021	38 109 000	hL/yr	11%	0,02	762 180,00	
Netherlands	2021	22 086 000	hL/yr	6%	0,02	441 720,00	
France	2021	21 800 000	hL/yr	6%	0,02	436 000,00	
Czech Republic	2021	19 559 000	hL/yr	6%	0,02	391 180,00	
Italy	2021	17 643 000	hL/yr	5%	0,02	352 860,00	
Romania	2021	16 400 000	hL/yr	5%	0,02	328 000,00	
Austria	2021	9 376 000	hL/yr	3%	0,02	187 520,00	
Portugal	2021	6 711 000	hL/yr	2%	0,02	134 220,00	
Denmark	2021	6 240 000	hL/yr	2%	0,02	124 800,00	
EU		348 000 000	hL/yr	92%	0,02	6 960 000	

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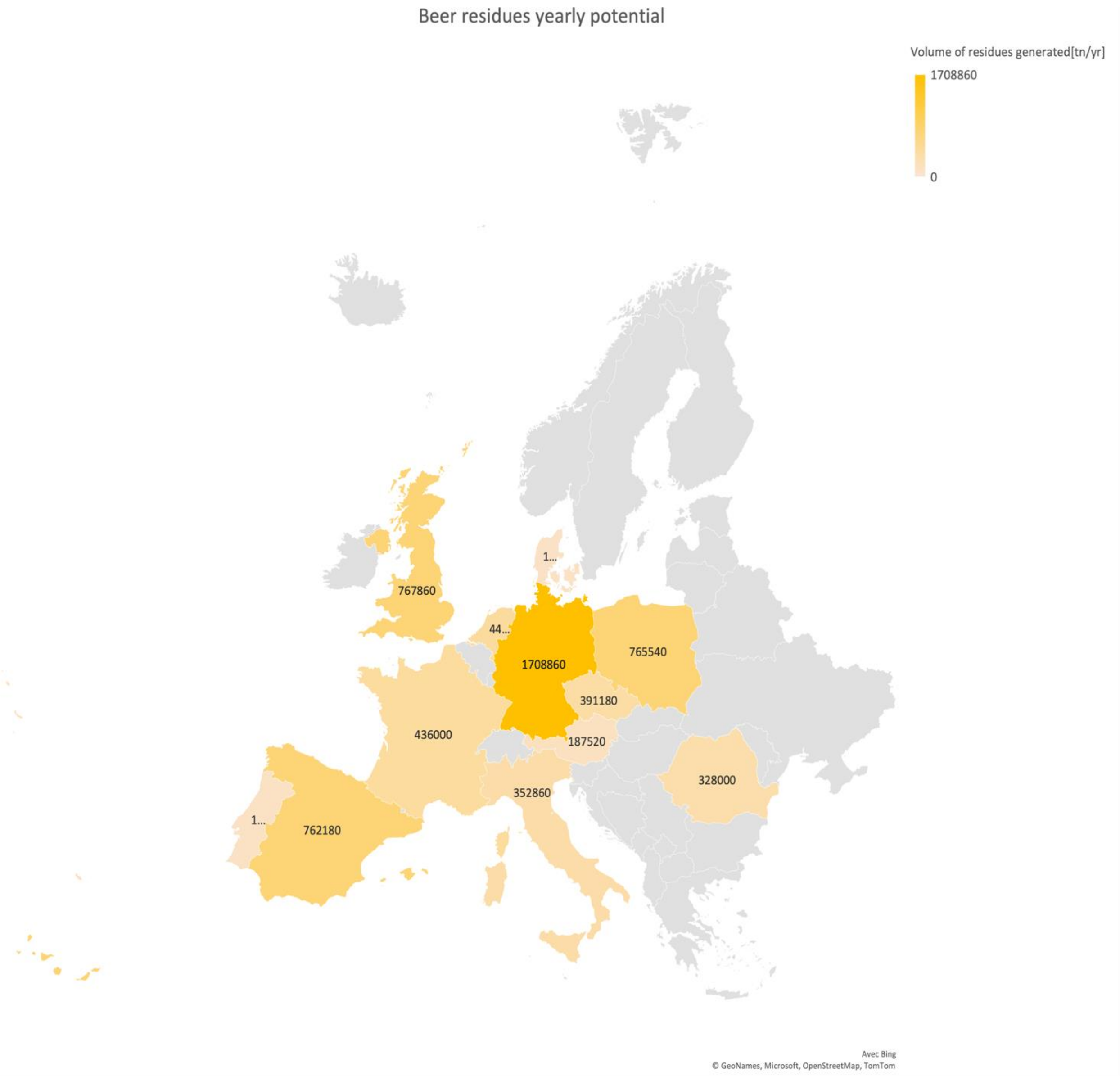

Figure 22: Estimated yearly production of residues related to beer production in Europe (own compilation).

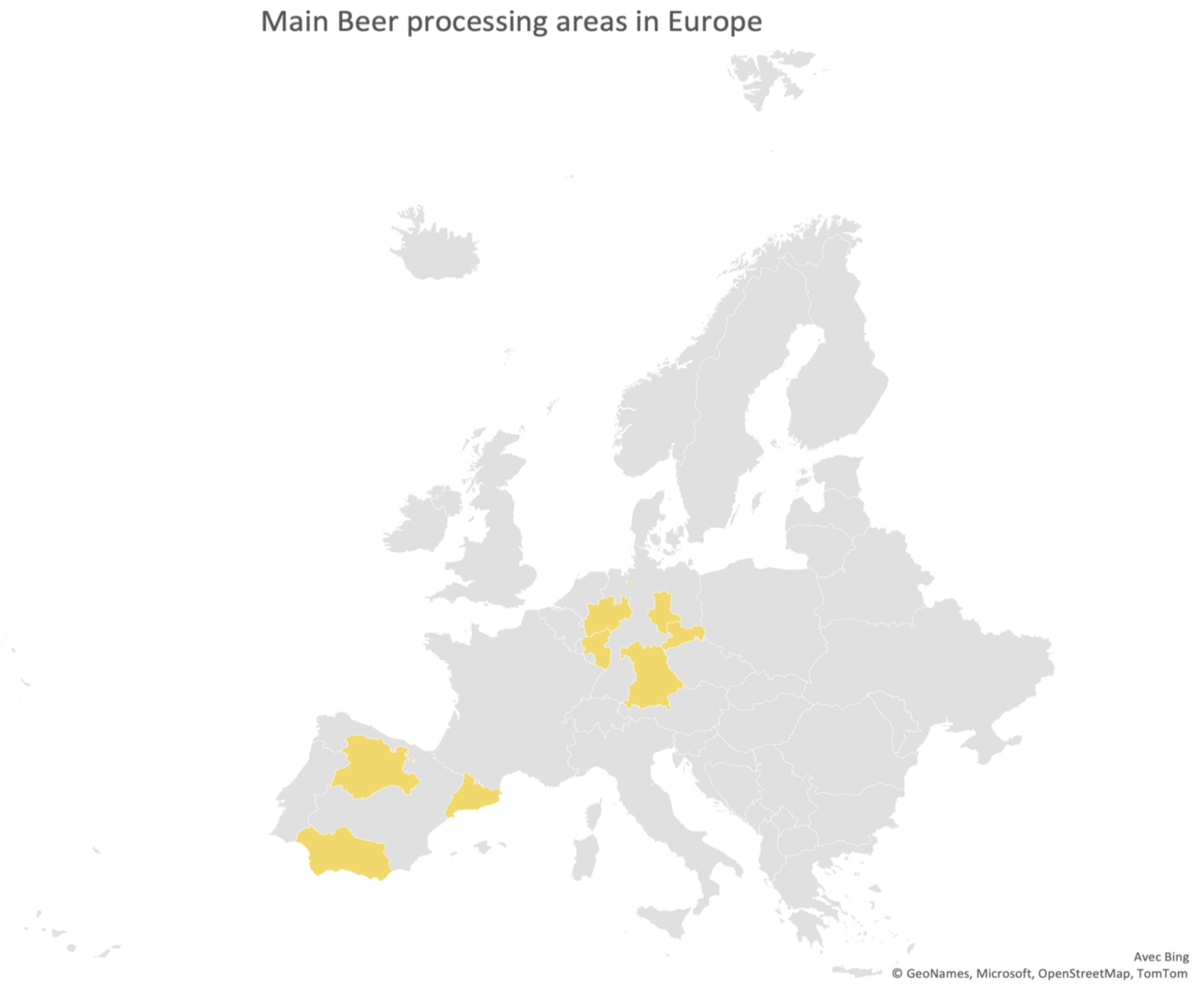

Figure 23: Estimation for the main beer producing regions within the top production countries (own compilation).

The Central-Eastern European Initiative BIOEAST supports transition to circular and sustainable bioeconomies comprising sustainable production and processing of residual biomass. BIOEAST member countries produce about 26% of the total EU27 beer production, meaning that BSG is an abundant resource to consider when creating a regional and national bioeconomical strategy. Among the BIOEAST countries, the largest potential for BSG processing to higher added-value bio-based products is in Poland with annual BSG production of 816 kt, followed by Czech Republic (403 kt) and Romania (359 kt). Other member countries are Hungary (120 kt), Bulgaria (96 kt), Croatia (65 kt), Lithuania (63 kt), Slovakia (34 kt), Estonia (28 kt), Slovenia (19 kt) and Latvia (15 kt) in 2019. According to 2021 data from European Beer Association, there are currently around 11,000 active breweries in the EU producing around 400 million hL of beer per year. Calculated based on market movements of the last 5-year period, in 2030 the EU will produce about 425 million hL of beer and 8.5 million tonnes of BSG per year, which makes BSG an interesting biomass resource for the future biorefineries (Zeko-Pivač et al., 2022).

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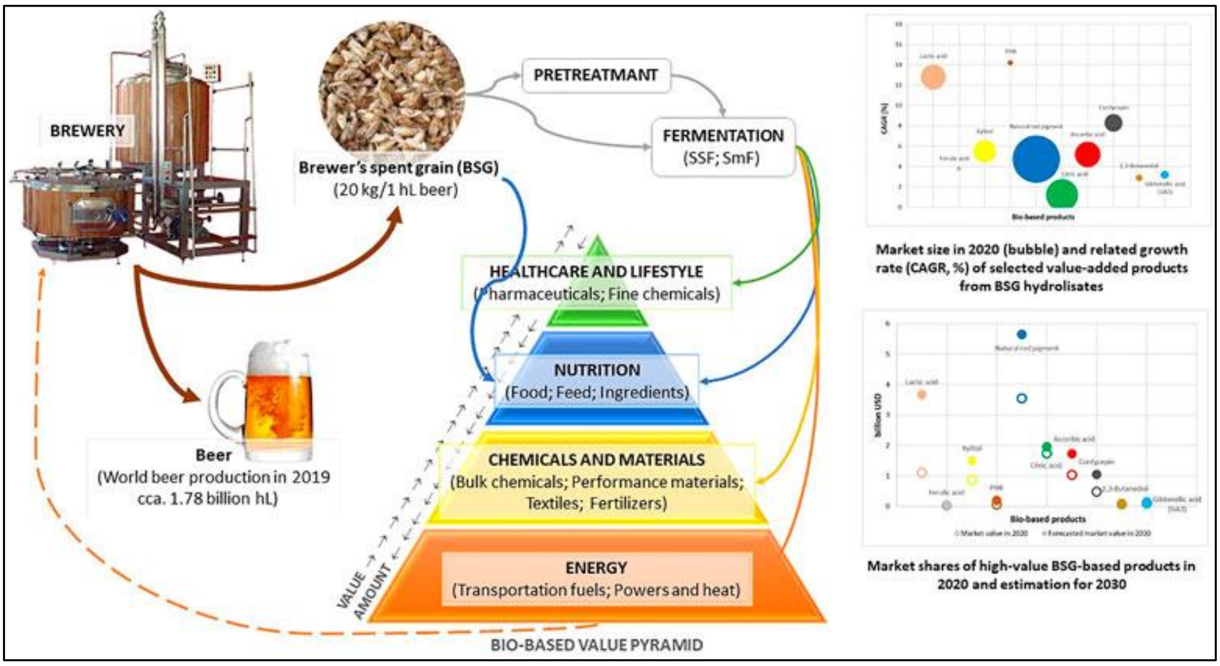

Figure 24 : The potential of brewers' grains in the circular bioeconomy (Zeko-Pivač et al., 2022).

At present, BSG is used for various purposes in wet form, directly after filtration, or in dried form after drying. Traditionally it is used in feed and food production. Its use in animal feed is related to its high fiber and protein content, with a market value of ~€35 per tonne. (Lynch et al., 2016).

In the food industry, BSG is used for the production of bread, cookies, muffins, pasta, cereal bars, chips and yogurt. The increased content of dietary fiber helps in the elimination of cholesterol and fats and improves the symptoms of ulcerative colitis. Moreover, the presence of phenolic compounds, which are considered as natural antioxidants, is associated with the prevention of chronic, cardiovascular, and neurogenerative diseases, certain cancers, and diabetes. Additionally, BSG is a suitable medium for the growth of various fungi, bacteria and other microorganisms due to its chemical composition, particle size, and water retention capacity (Zeko-Pivač et al., 2022).

Recently BSG also plays a role in bioenergy production and waste management. BSG could be used as a fermentation feedstock. Both cellulose and hemicellulose present in BSG have been successfully used for ethanol production. In an effort to reduce the production of synthetic materials and increase plastic recycling, BSG is a potential raw material for biofilm production. Biofilms used in food products and medicines must have thermal stability which has been successfully achieved with the arabinoxylan-rich fraction from BSG. Also, due to their rich protein profile, BSG have been used in the production of biofilms with potential application in active food packaging. Protein films showed balanced mechanical properties, water resistance and antioxidant capacity. The cost of transportation (especially of BSG in wet form), the cost of drying, and need for pretreatment process to reduce its recalcitrance, are some of the barriers to wider application.

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2.2.3 Examined end-products

Due to the aim to demonstrate the possibility to produce at integrated pilot scale, PHAs, plant extracted polyesters (cutin and suberin), proteins/peptides and polyphenols/carotenoids, as well as microbial proteins (MP) are examined in pilot plants.

The high-value agri-residue-based end-products resulting on the utilization of the feedstocks via biorefinery and extraction are:

- **Biopolyester PHA**
  - PHA-based materials
    - Blends, composites, multilayers
    - Flexible films and rigid materials
    - textile farming materials
- **Microbial proteins**
  - Microbial protein-based feed (or potentially food)
- **Plant polymers**
- **Plant biochemicals**
  - PPO, carotenoids and cutin

2.3 Research and surveys on expert level

2.3.1 General methodology: the Delphi method

After having conducted the desk research, experts of the EUG and the main targeted value-chains were interviewed by using qualitative research methods to investigate the market readiness of the innovations of AgriLoop for the B2B sector. In order to do so, we made use of the "Delphi" method. This approach is a systematic, multi-stage and iterative process of several "rounds" (or "waves") of interviews, mainly used to explore the "intuitive" (=non-documented, unwritten) expert knowledge namely in innovative and confidential domains which are to complex investigate (Haber & Schärli, 2021; Bui, Tsai, Tseng, & Ali, 2020; Conchin & Carey, 2018).

A first round of interviews ("Delphi I"), characterized by mainly open question and a semi-structured guideline explored the field of research. The results of this first round are expected to produce hypotheses for further refining and validation in the next round of expert interviewing.

The main principle of our Delphi-approach is a "2 steps forward, one step back movement", the interview (=data collection) rounds alternate with feedback to the experts on individual opinions, experiences, information and knowledge and assessing group judgements. The objectives of Delphi are, thus,

(1) to steer an indirect group communication process
(2) to enable each expert to understand his/her own position with regards to the group's opinion, and to revise or confirm his/her position in the next round of interviews
(3) to obtain, after a certain number of rounds, a reliable consensus of an expert group.

There is a double core benefit of the Delphi technique, it (1) verifies hypotheses and at the same time (2) opens new communication within the expert group (Padel & Midmore, 2005; Okoli & Pawlowski, 2004).

The Delphi approach that we applied for the expert research in AgriLoop consists of 2 rounds in total. This is shown in Table 7.

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Table 7: Overview of the framework for Delphi expert survey (own compilation).

Round	Time frame	Type of analysis	Objectives/content	Data collection method	Status
Delphi I	Jun-Aug 2023	Qualitative	Establishment of first insights about identification of market opportunities for the AgriLoop innovations	Phone interview	Data collection finished
Delphi II	Jun-Aug 2024	Qualitative	Validation, consolidation and supplementing of results	Phone interview	In planning

2.3.2 Set up of the product brief

As the first round of the Delphi method is aimed at identifying the market potential and readiness of agri-residue-based products, there is no specific product brief. The product brief will be developed and adapted during the course of the project.

2.3.3 Development of hypotheses

In order to develop the hypotheses for delphi, we have compiled research questions based on the desired results in the description of action. The research questions formulated are listed below:

RQ1. What are the general market opportunities for PHA, PHA-applications and extracted/microbial proteins?

RQ2. What are stakeholders' expectations regarding the valorisation/the function of PHA, PHA-applications and extracted/microbial proteins?

RQ3. What are the actual and potential limits/barriers for PHA, PHA-applications and extracted/microbial proteins?

Once we had identified the main research questions, we have formed hypotheses based on this. The hypotheses relate directly to the research questions and operationalize and concertize them. The research questions formulated are listed below:

RQ1

PHA

- (Due to their biodegradability and biocompatibility,) PHA applications are better suitable for agriculture than existing conventional products from petrochemicals.
- The production of PHA is a better valorisation of agricultural by-products than today's standard valorisation.
- Market potential of PHA from agricultural by-products is higher than for conventional agricultural applications from petrochemicals.
- The best applications of PHA in agriculture are mulch films.

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MP

- MP from agri-residues are an equivalent alternative to conventional products regarding its functionalities.
- It is more appropriate to use MP from agricultural by-products in non-feed applications than as feed products
- MP only have market potential for niche applications.

RQ2

PHA

- PHA for agricultural applications fulfils the same functions as conventional alternatives.
- PHA from agricultural residues must not be more expensive than conventional materials in order to be accepted on the market.

MP

- Extracted/ microbial protein must have the same properties when compared to conventional alternatives (for fish feed, e.g., soybeans or fishmeal).
- Extracted/ microbial protein from agricultural residues cannot be more expensive than conventional feedstuff.

RQ3

PHA

- Logistical challenges are the biggest barrier for market potential of PHA for agricultural applications.
- Missing scalability of PHA production is the biggest barrier for market potential of PHA.

MP

- Regional availability of feedstock in Europe is the biggest barrier for processing of extracted/microbial proteins.
- Extracted/microbial proteins make good economic sense compared to conventional proteins.
- Current legislation for the approval of extracted/microbial proteins as feed is the biggest barrier for their market potential.
- Missing scalability of MP is the biggest barrier for their market potential.

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2.3.4 Development of the questionnaires

Subsequently to the creation of the research questions and hypotheses, Ecozept drafted a questionnaire with respective topics for experts' assessment of the market potential of the innovations, and the Work Package leader WR adapted and approved the interview guideline. Those are the following ones:

Valorisation

currently valorise of agricultural by-products, strengths and advantages in the current valorisation, challenges regarding the valorisation, challenges, payment for current valorisation pathway, satisfaction with valorisation, alternative valorisation pathways, ideal solution for the valorisation, support for valorisation, expectations regarding the valorisation,

PHA

assessment of the market opportunities, determining factors of market potential, best applications, not suitable applications, comparison of bio-based and bio-degradable with petrochemical products. advantages of bio-based and bio-degradable PHA applications, disadvantages, other bio-based and bio-degradable applications, not suitable applications; expectations on function, quality, contamination, composite products, purity, price, willingness to pay; challenges regarding the application, solutions, scalability of PHA

Extracted/ microbial proteins

Comparison with conventional proteins regarding purpose and function, the best use, other applications, inappropriate applications, promising markets, market potential; expectations regarding quality, compared to conventional proteins, expectations regarding the qualities of agri-residues as feedstock for processing of microbial proteins, willingness to pay; influence of geographical distribution agricultural residues, logistical challenges, other factors limit the market potential, assessment the costs compared to conventional proteins, price, future development of prices, legislation regarding approval of microbial proteins as feed, scalability,

The final version of the questionnaire is attached in Annex 6.1 of this Deliverable Report.

2.3.5 Conduction, study sample and analysis of the expert interviews

The interviews in the first round of Delphi with an overall number of 17 experts were conducted from June until August 2022. First contact with the respective experts was established via phone. They were briefly informed about our aim and asked, whether they would agree to take part in an interview. If agreed, further information about the project was given by a short e-mail. Participants had to give their consent about participating in the interviews by filling out a blank form on a self-administrable online form. The interviews were conducted by phone/ Microsoft Teams and the interview language was English, French, German and Spanish. Interviewees' answers to our questions were directly transcribed in a Microsoft Word document and served as the base for our analysis. The survey sample comprised a large spectrum of different kinds of experts. The Table 7different characteristics of the participants are depicted in Table 8.

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Table 8: Study sample for Delphi I (own compilation).

Expertise	Number of interviews
Residual streams/ valorisation	9
Bio-engineering/ Biopolymers	2
PHA/PHB	4
Extracted/ microbial Protein	2
Country	
Germany	3
Spain	7
Belgium	1
France	3
Netherlands	1
Australia	1
Switzerland	1
Type of company	
suppliers of residual streams	9
traders, processors, converters of PHA	3
users of the PHA applications	3
feed traders and processors of extracted and microbial proteins	2
Position of the interviewee	
Management	7
CEO	2
Coordinator	1
Production manager/ director	2
R&D manager	4
Chief New Business Officer	1

The results of the qualitative interviews were analysed by Ecozept using MAXQDA software. The basis is a thematic qualitative text analysis to reduce the large amount of qualitative data. The analysis is based on a defined category system which structures the data by categories derived from existing literature (deductive categories) and categories directly derived from the interviews (inductive categories)..

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2.3.6 Outlook: Round 2 of expert interviews

The next step after having finished the interviews and analysis of Delphi I is to conduct another round of expert interviews. In this second phase, we will validate the hypotheses derived from Delphi I and supplement the results with further expert assessments. The aim is to confront interviewees in the second round of data collection with pre-formulated hypotheses forged in previous interview rounds or derived from literature to verify these results (Padel & Midmore, 2005; Okoli & Pawlowski, 2004; Frewer, et al., 2011). The questionnaire will, inter alia, also include those topics that did not reach consensus during the first round.

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3. Preliminary results

In the following chapters, we present the results of the first round of data collection. We present the results of the expert interviews conducted with four different expert groups and with a focus on different target products. After each paragraph, the most important findings are summarized in a few sentences. These summaries are highlighted in green.

3.1 Results of the qualitative expert interviews (Delphi I)

Since the interviews were divided into 4 groups and therefore different expert groups, we present the results divided into the 4 paragraphs: agri-residues, PHA, PHA-applications and extracted/microbial protein. Within the paragraphs, we elaborated the stakeholder's expectations, possible limitations or barriers as well as the market opportunities of the different products. All results reflect experts' opinions, and therefore do not claim to be a holistic consideration of the subject matter.

3.1.1 Valorisation of agricultural by-product

One of the objectives of WP1 is to look at the current valorisation, to analyse strengths and weaknesses and to capture stakeholders' expectations regarding the valorisation process. Therefore, the current structures, advantages, opportunities and expectations are presented below.

3.1.1.1 Current structure

Current valorisation process

With regard to the current valorisation process, the processes described vary according to the agricultural by-products. For nuts, the shells of almonds and hazelnuts are combined and sold as biomass or in the form of flour for various applications. The shells are pressed and collected, but there is no use for them yet. The shells are thrown on the field or fed to cattle. Sansa is taken to an extractor to get the rest of the oil out, or thrown on the field. Pomace and lees are compulsory. In the case of fruit, the current process is described as the transformation of the second category of fruit into concentrates for the production of juice. In the case of olives, pomace oil is extracted from the by-products. The common feature of all the processes described is that they add value to the final product. On the other hand, a few operators work with charitable organisations. One expert mentioned that all waste is fed into their own biogas plant.

Payment also varies between by-products. For nut by-products, one expert mentioned that shells are currently paid at 100 €/t and shell flour at 250-300 €/t. With regard to fruit, it was mentioned that the payment varied according to the species. The price range for apples and pears is described as 6-18 €/kg, while yellow peaches are paid around 18 €/kg. Finally, the prices paid for olive by-products were given. Pomace oil is paid at 2.10 euro/tonne, pinyol at 160 euro/tonne and dried pomace at 180 euro/tonne. Some experts mentioned that there are products for which they are not paid or for which the payment is practically zero.

When considering transport, the experts also mentioned different processes. Several experts described that the transport from the field to the processing area is paid by the cooperative, as well as the transport from the company to the buyer, which is paid by the buyer. One expert added that there is usually a compensation of the transport costs by the costs paid by the cooperative for the by-product. In contrast, other respondents stated that they pay for the collection, transport or disposal of by-products. However, one company receives subsidies for the collection of by-products.

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Current valorisation processes vary depending on the agricultural by-products. All processes aim to provide an end-product with a greater value. Transportation is either paid by cooperatives or paid by the company itself.

Main benefits

When considering the main benefits of current valorisation, the experts identified several benefits resulting from the current processes. According to the experts, two of the main benefits were positive environmental and economic effects.

Taking a closer look at the environmental effects, several experts stated that the current valorisation of by-products has a positive impact on the environment and is linked to several Sustainable Development Goals (SDGs). One voice mentioned that there are also benefits in terms of environmental management of co-products by associated companies and cooperatives. In summary, it was stated that a centralised collection of by-products at farm and cooperative level could lead to a reduction in CO2 emissions. In line with the previous arguments, one expert stated that another additional benefit was the production of renewable energy. It was explained that the by-products are fed directly into the biogas plant. This reduces the dependence on fossil fuels. Finally, the residues from the upgrading process can be used as fertiliser.

Just as often, the experts mentioned economic effects as an advantage of the current valorisation. One of the main benefits mentioned was the elimination of by-product management costs. In this respect, one voice confirmed the ease of outsourcing the management of by-products, which helps to avoid costs and logistics. The experts went on to explain that valorisation has general economic effects. On the one hand, the producers themselves benefit from the process, as it creates new business opportunities, and on the other hand, it can lead to the creation of companies that work with by-products, thus creating new jobs in a region. Finally, one expert mentioned that there is a possibility to get a return on the by-products.

Several experts also mentioned that adding value to by-products is a major advantage. Firstly, it is in line with a company's ambition to get the best value for its production. In addition, the increase in value was seen as beneficial for the final price paid to farmers. Finally, one voice stated that valorisation makes it possible to build loyalty to the producer, as it allows all of his production to be marketed.

Experts highlight key benefits of current valorisation processes, with positive environmental and economic effects at the forefront. The positive environmental impacts linked to SDGs were emphasized, noting that centralised collection of by-products could reduce CO2 emissions. From an economic perspective, experts point to cost savings associated from reduced by-product management, new business opportunities and added value for both companies and farmers, as well as increased producer loyalty through the ability to market the entire production.

Satisfaction with current valorisation and challenges

Satisfaction with current valorisation is discussed below. As there is a strong correlation between low satisfaction and the main obstacles to valorisation, the challenges are also addressed in this section. The topics are presented in descending order of the frequency with which they were mentioned by the different experts.

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As mentioned above, most of the experts described their satisfaction with the current valorisation as low. The most frequently mentioned reason for low satisfaction was profitability. It was stated that the current valorisation does not generate enough profit and that the profitability varies too much depending on the production. It was also said that, at the level of the producer, it does not cover the costs and, at the level of the cooperative, it is done in order not to have to pay the price of destruction. Another voice mentioned that this business model is currently difficult to make profitable, even though a company has diversified enormously in terms of products and markets. It is therefore necessary to constantly improve processes. Finally, two experts highlighted the situation of farmers. Due to the recent increase in costs, some farmers have decided not to pick small fruit, with the consequent loss of labour costs and phytosanitary applications. In summary, the current effort is not being compensated. This is necessary because of the positive social aspect of contributing to social welfare before non-marketable production is damaged.

The second most frequently mentioned issue was legislation. Several experts consider it necessary for legislation to facilitate new ways of working with by-products. The current legislation was described as too restrictive at regional level and still needs to be developed at national level. One voice suggested that it should be harmonised in order to work under the same conditions. On the other hand, one expert pointed out that existing subsidies allow access to by-products of wine-growing. This shows that favourable legislation could contribute to the valorisation of by-products.

Furthermore, several experts agreed that there are unequal campaigns. It was stated that, depending on the campaign, it is difficult to plan the collection of by-products, as producers do not have a forecast either, and therefore the storage period is extended, which increases the costs for the company. In addition, one expert described the campaigns as uneven in terms of quantity and quality of production.

Contrary to the statements analysed so far, few experts found the current valorisation process satisfactory. One voice described the process as elaborate but well-functioning. Specifically, priority is given to the rapid disposal of residues from food production, which are immediately fed into the company's own biogas plant. The continuous removal of processing waste is successful, as is the disposal of biogas plant residues with the help of a reliable logistics company. Storing the residues would be costly and raise hygiene issues, so smooth cooperation with the logistics company is described as crucial. Another voice stated that there is a high level of satisfaction with the current valorisation because of the convenience of using an external company in the area. In addition, the process addresses environmental issues, thus reducing the carbon footprint. Finally, the solution of legal issues was mentioned, as more and more regulations are needed for the recycling of waste and for the sustainability of the cooperative.

Experts express predominantly low satisfaction with current valorisation practices, with profitability being the most frequently cited concern. Profit margins are described as inconsistent and often fail to cover costs, making it difficult to make the business model profitable. Legislation is also identified as a key issue, with experts calling for more supportive and harmonised regional and national regulations to facilitate by-product utilisation. Further, challenges related to unequal campaigns quality are noted. While most experts express low satisfaction, a few find the current valorisation process satisfactory, highlighting effective waste management and environmental benefits, particularly in reducing carbon footprints and meeting regulatory requirements.

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3.1.1.2 stakeholders´ expectations

general expectations and Ideal solution for the valorisation of by-products

When it comes to their expectations, all stakeholders are united in the opinion that the valorisation should generate more profit while adding an increased economic value with new business lines. This will make it possible to obtain a return on the farmers' work and to increase the price of the monetary settlements paid to the farmers by the cooperative. This issue seems to be very important, as one expert described the farmers as poorly paid and the weakest part of the chain, who are not sufficiently compensated for their work and the products they produce, and for the financial risks they are exposed to in each agricultural campaign. Another voice underlined the importance of a good cost-benefit ratio, as a minimum effort and investment is expected for a maximum benefit. In addition, the expert noted that in the absence of a clear benefit, direct valorisation by the company could not be justified as it would entail logistical and management changes that could not be expected to deliver the desired benefits to the company. However, one expert noted that a financial and human effort will be required as there are many emerging technologies and solutions. In the short term, it is recommended to take advantage of tested options, while in the medium to long term, solutions will be found to adapt to market needs and make the sector more sustainable.

In order to better understand the expectations and wishes of stakeholders, they described their ideal conception of the valorisation process. Several experts agreed that the ideal valorisation process for organic waste should have a high added value. Several voices underlined the importance of added value for producers. From the perspective of farmers and processors, the ideal valorisation process for farmers is to find a profitable way to sell their products while ensuring a stable demand. This can be achieved by extracting high value compounds from by-products that are useful in the agri-food or other sectors. Therefore, the process should take advantage of the properties and compounds of the products for human and animal food. In addition, one expert stated that it should be simple enough to adapt to logistical cycles and use less energy and water. A critical voice, however, doubted that the ideal processes would all require investment, knowledge, time and logistics that are not always properly compensated. Finally, several experts described promising valorisation processes. One said that it would be interesting to be able to use the wastewater together with part of the sorghum as an organic fertiliser. Another company is considering using protein to create new products, but doubts that some by-products may not have enough protein. Other processes described as difficult to obtain included green hydrogen, compounds for the food industry and approved additives in animal feed. On the other hand, a single voice stated that the current solution was the best at the moment and that they were not aware of any other and better valorisation.

More profit is expected from the valorisation of by-products. The ideal valorisation process should provide high added value to make the process more profitable. In addition, the process must be simple enough to fit into logistical cycles. Potential valorisation pathways could include organic fertilisers, protein products, green hydrogen and animal feed additives.

Support structure

The factors that can have a supportive impact on valorisation are discussed below. The most frequently mentioned factor by the experts was financial support. One expert stated that **financial support** is needed to initially carry out small-scale studies which, if positive, can be scaled up to a pilot plant. Another expert considered that support would not be needed if the residues were collected free of charge or if the payment for the residues was fair. The experts also considered legislative support to be important. There was a consensus that a **supportive legislative framework** was needed to extend authorised additives, e.g. in animal nutrition. In addition, the experts wished for a regulatory framework that did not hinder the commercialisation of the compounds obtained and that was adapted to the reality of the production processes. Finally, several experts mentioned a **functioning network** and **helpful organisational structures** as important supporting factors. The networks could create synergies with other companies in the area or possible suppliers/customers of by-products and products. In addition, joint efforts with cooperatives in the sector could make it possible to find the best alternatives and reduce costs such as transport. Several voices mentioned that they were looking for a partner for logistics and residue management. Finally, cooperation between technology centres and applied research at industrial level was identified as supportive. In terms of organisational support, one expert wished for support from the administration and other bodies such as the FCAC and research and technology centres.

The main supportive factors with an impact on valorisation identified by the experts were financial support, a favourable legal framework and a functioning network and helpful organisation. Payment should be fair, the legal framework should be adapted to the reality of production and networks should create synergies with other enterprises.

3.1.1.3 Main issues and challenges

In the following, the topics that are seen as the biggest obstacles for the market potential of the current valorisation are discussed. The topics are addressed in decreasing order according to the frequency they were mentioned by the different experts.

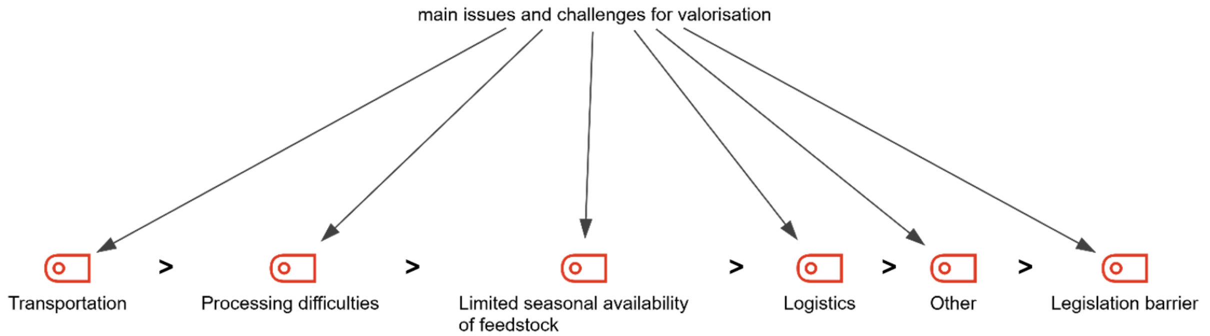

Figure 25: The most frequently cited limitations or challenges to the current valorisation process by experts (own compilation).

Transportation and logistics

Transport and legislation were the most frequently mentioned challenges. Regarding transport, there are certain limitations that make transport costly. In particular, the high water content of digestate makes transport costly. Drying the residues is not feasible due to the high energy and cost requirements. In addition, long transport routes are not feasible with the current water content. Furthermore, one voice expressed the need for sufficient space for collection.

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In terms of logistics, all experts agreed that there is currently a problem with the volumes needed to be profitable. One voice stated that large volumes need to be generated in a short time. However, the transformers are sometimes unable to absorb them, resulting in a lower added value to the product. In addition, another expert doubted that the current problems could be caused by environmental conditions (rain and humidity). The second major problem mentioned by several experts is the storage of by-products. One expert pointed out that by-products cannot be stored on central logistics platforms for optimisation purposes, as the raw materials need to be collected and processed quickly. He added that central platforms for concentrating raw materials would require large facilities that meet food standards. Another voice noted the challenge of storing waste during the winter months when farmers cannot fertilise their fields. It was felt that the solution could be to work with an external logistics company. Finally, several experts assessed that hygiene was a major issue in storing the waste, while oxidation and chemical degradation were not a concern.

High-water content in fermentation residues makes transport costly. Further, a logistical challenge lies in the volume management as large volumes are needed in order to be profitable. Experts doubted the feasibility of central logistics platforms.

Processing difficulties

The second most frequently mentioned issue was processing difficulties. The experts gave different reasons for the difficulties. Several experts stated that there could be difficulties due to the chemical composition, e.g. high lignin content of grape stalks. In addition, one expert stated that products with a high water concentration make it difficult to compost the whole fraction. Another voice raised the specific case of almond shells, where the need for prior drying makes the cost of treatment high. Finally, one expert mentioned the changing quality of by-products as a result of climate change. As a result, the compounds extracted from the raw materials can vary.

Experts identified processing difficulties due to chemical composition of the co-product as well as changing quality of the co-products as a consequence of climate change.

Limited seasonal availability of feedstock

The limited seasonal availability of raw materials is a major challenge. Due to the seasonality of production, the work is highly seasonal, which is currently exacerbated by the need to work quickly to avoid decomposition in the open air. Depending on the type of raw material, the by-products must be processed within a few months. Another expert identified another challenge in predicting the volume of feedstock. Accurate forecasting of volume is necessary because a constant volume is required to make a very accurate forecast of product availability. Finally, another voice noted that there is a strong correlation between transport and limited seasonal availability.

Limited seasonal availability of feedstock is a huge challenge as processing needs to be quick in order to avoid decomposition. Further, precise prediction of the volume is difficult.

Legislation

As mentioned above, the experts considered legislation to be a constraint. It was noted that regional legislation can differ from national legislation. One voice stated that there is a problem to reuse water from olive oil production in agriculture due to the restrictive legislation in Catalonia compared to Spanish legislation. Another expert pointed out that legislation in the field of animal nutrition is highly regulated. Therefore, only one additive is allowed for grapes. Finally, the experts wished for a legal framework that would not hinder the marketing of the compounds obtained and that would be adapted to the reality of the production processes, including the reuse of by-products.

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Legislation is described as restrictive and diverse. The regulatory framework should not hinder the commercialisation of the compounds obtained and should be adapted to the reality of the production processes.

Solutions

Several experts shared their solutions to the existing challenges. One solution, mentioned by several voices, is the collaboration of technological centres, research and universities with the productive sector in order to deliver and adapt the results to the real needs of the companies. At the same time, it could be useful to pool efforts between companies in the sector in order to reduce costs, for example in transport.

In terms of processes, there is a consensus among the experts that optimising industrial use and transformation would help to reduce the problems of possible odours, seasonality and logistics. One voice further stated that another solution would be to find non-commercial fruit processing products with added value whose transformation could be profitable. Finally, one expert noted the need for new extraction, cleaning, separation, transfer, assembly and concentration processes that consume less water and energy.

The collaboration of technological centres, research and universities with the productive sector to deliver, as well as the unification of efforts between companies, is identified as crucial to overcome the challenges. In terms of processes, optimising industrial use and transformation could be a solution to several challenges.

3.1.1.4 Outlook and perspectives

When asked about the outlook for the development of the valorisation process, the experts considered that the economic and market situation of production is not fully taken into account in the scenarios for more profitable valorisation. The experts also identified farmers as key actors in making these scenarios a reality, but a lack of funding and cooperation is hampering progress. However, the valorisation of by-products can add value to the price the farmer receives for his production.

In addition, experts are looking for new solutions to make use of by-products. Possible new applications include food for insects, transformations with microorganisms to obtain compounds of interest such as polymers for the production of plastics, and fermentation to obtain energy and/or green hydrogen. However, when considering biorefineries, the expert noted that trying to exploit everything that can be extracted from a by-product is theoretically simple, but more complicated in practice due to logistical and transport issues, the temporary seasonality of cultivation, and the difficulty of agreeing with cooperatives and companies to resolve the issue of minimum quantities. Finally, one voice stated that they were looking for new solutions for the ornamental plant sector, particularly in terms of reducing peat in substrates and plastic in packaging. They are therefore participating in the SACS project to produce biodegradable bags for horticulture from maize by-products. Development in this sector is focused on research into suitable raw materials and by-products for bioplastics and alternatives to peat.

The economic and market situation of production is not fully taken into account in scenarios for more profitable valorisation. Farmers play a crucial role in making these scenarios a reality. The industry is looking for new solutions such as food for insects, transformations with micro-organisms to obtain interesting compounds and ornamental plants.

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3.1.2 PHA

In the following, the stakeholders' expectations as well as possible limitations and challenges with regard to PHA its end-products are illustrated based on the assessments of experts from traders, processors and converters of the end-product PHA. A deliberate distinction was made between experts from traders, processors and converters of the end-product PHA and users of the end-product PHA applications such as arable farming or horticulture businesses, as this allows the different requirements and desires of the groups to be identified.

3.1.2.1 stakeholders´ expectations

When it comes to stakeholders' expectations, the experts were asked to assess PHA with regard to their expectations and desires in terms of the quality of PHA-products, function of PHA-products and Price development of PHA applications in agriculture.

<u>Quality of PHA-products</u>

Regarding the quality of the PHA product, several experts described that applications for food packaging would require extensive testing for food contact safety, which could be a major challenge. In addition, the experts agreed that GMO-free products are mandatory. In Europe, the cultivation of GMOs is prohibited, so it is necessary to ensure that biodegradable products are GMO-free. Care must therefore be taken to ensure that the bacteria are not genetically modified organisms, as are the raw materials, e.g., transgenic crops. In terms of biodegradability and composability, experts stated that 100% PHA would be the best choice to create a product that is fully biodegradable and bio-sourced. A blend of PHA and starch was also considered viable. The expert went on to describe that the addition of PLA would change the end-of-life cycle, even if PLA is bio-sourced, due to its difficulty in biodegradation. Finally, the voice mentioned that the composition of PHA material should not be an issue as it is possible to change the basic properties of PHA, in particular its biodegradability. Finally, one expert stated that PHB products need additives to be a plastic. Therefore, they are not compostable as components such as cellulose are not. Finally, one expert stated that the use of lignin in biopolymer films is limited due to its low molecular weight and lack of mechanical properties. In addition, lignin films are not suitable for food contact. Another expert stated that the blending of materials in terms of texture is perfectly feasible, e.g., PHA + cellulose.

Experts expect PHA-products to be GMO-free and consider food contact safety to be difficult. 100 % PHA is expected to be the best choice in terms of biodegradability. However, mixtures could be practical to. In practice, PHB-products are not compostable in practice.

<u>Functionality of PHA-products</u>

With regard to the functionality of PHA products, the experts described their expectations in terms of durability, purity, contamination, compostability, flexibility and in contrast to conventional products. In terms of **service life**, one expert expects the product to be used during the growing season, particularly in the first few months when use is at its peak. The more the plant grows, the less the clip or other production aids will be used. Other experts agreed that the life of a film depends on the type of crop. They added that thin films should be used for crops such as lettuce, while thick films are needed for crops such as peppers. The film should also disintegrate more quickly in crops with less shade.

When it comes to **contamination** and **purity**, there is a strong link between the two. However, expert opinions differ. One expert highlighted the importance of purity in downstream processing, as impurities can lead to brittle and weak material. It was also noted that optical purity also affects material properties, as even tiny bits of cell debris can degrade material quality. In line with this, another expert stated that

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the raw material must be very pure and uniform in terms of properties, and even more so the raw PHA. If the raw PHA is not pure, it cannot be processed into plastic. Therefore, it cannot be processed with residues from food processing as this could accelerate the degradation rate by a factor of 10 or even 100. On the other hand, one voice argued that there are no additives that would cause a contamination problem. Concerning PHA **composites**, one expert stated that composites with a broad spectrum of nutrients, including nitrogen and phosphate, are described as beneficial for biodegradation as they provide a wider range of nutrients for decomposing organisms. In addition, another expert mentioned that PHA composites lose their flexible properties when straw or lignin is added. Finally, another voice pointed out that there is no use for pure PHA for long term applications (10-15 years life) as there will always be an Esther bond in the mix which can be hydrolysed with water. In conclusion, this voice expects that long term applications with pure PHAs will not work.

Finally, the experts compared PHA products with conventional products. One expert suggested that PHA could be a viable alternative for cheap products such as plastic clips and twine, where it is not feasible to invest time and money in recovery. However, the expert expected that biodegradable mulch film would be the easiest and best application for PHAs at the moment, replacing conventional mulch film, as it could save time and money.

Experts expect that the service life should correspond to the type of crop and its growth period. Concerning contamination, purity is very important for material properties as impurities can lead to brittle and weak material. Compostability is expected to be better with composite materials consisting of more than just of PHA. Biodegradable mulch film is expected to be the best application for replacing conventional products.

Price development of PHA applications for agriculture

According to the experts, the cost of PHA has fallen from 5 €/kg to 2.5 €/kg. The experts believe that a number of factors can influence the price development. Copolymers and economies of scale, where larger plant sizes reduce the price, have been identified as influential factors. Research is also being carried out to reduce the cost of working with the bacterial stream and the use of waste streams. Finally, the purification process was identified as a major cost driver in current production and is expected to be reduced.

However, the experts agreed that customers will not accept any price. It is expected that end users and processors will not be willing to pay a significantly higher price compared to conventional products. One voice further estimated that farmers will not pay more than 3-5% more for PHB-based products. In addition, the expert expects that due to the production process, a price less than 3-5% higher than for PHB-based products is not feasible, unless there are large scale fermentation plants, e.g. >100,000 tons/year.

Experts estimate that the cost of PHA has fallen from €/kg to 2.5 €/kg. However, it is expected that the end consumer will not be willing to pay a price that is significantly higher than the price of conventional products. Farmers will pay no more than 3-5% more than for PHB-based products. Large scale fermentation plants are needed to achieve lower prices.

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3.1.2.2 Main issues and challenges

In the following, the topics that are seen as the biggest obstacles for the market potential of PHA and PHA-end products are discussed. The topics are addressed in decreasing order according to the frequency they were mentioned by the different experts.

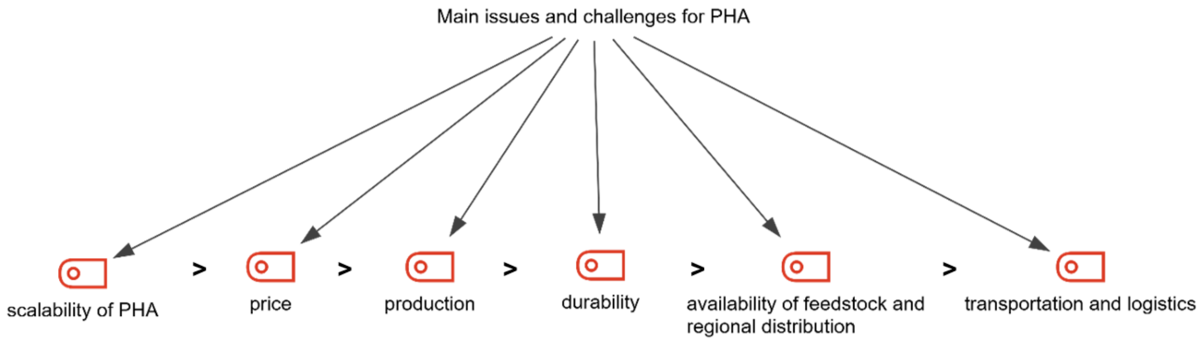

Figure 26: The most frequently cited limitations or challenges for the market potential of PHA by experts (own compilation).

Scalability

Scalability is the most frequently mentioned issue. However, expert opinion is divided. The majority of experts believe that the scalability of PHA production is limited by physics and that it will take at least five to seven years to reach commercial scale production. During the pilot phase, it is expected that companies will have to invest money without seeing revenues in order to achieve economies of scale. In addition, economy of scale is limited by the size of the fermenter. In addition, one voice mentioned that there is only one 50,000 ton production plant, which required a development phase of 40 years. In contrast, another voice believes that the issue of scalability in PHA production can be overcome by increasing the number of bioreactors, as seen in China. The expert further explained that there are technical limitations on the size of bioreactors, but is convinced that these problems can be overcome by increasing the number of bioreactors. Finally, he believes that with sufficient funding, large-scale PHA production could be achieved within 5 to 10 years.

Most experts believe that the scalability of PHA production is limited by physics, although one expert estimates that increasing the number of bioreactors could solve the scalability problem within 5 to 10 years.

Price

As described in 3.1.2.1, price could be a major limitation to the market potential of PHA, as end-users and converters are not willing to pay a significantly higher price compared to conventional products. One expert stated that current processes are still too expensive. It was also mentioned that the raw materials only account for about 50% of the total cost. In addition, PHAs were described as by far the most expensive biopolymer on the market. One voice estimated that they cost €5 or more and therefore simply cannot compete with conventional polymers or other biopolymers. Another voice doubted that the cost of PHAs above €5/kg would change in the near future. In addition, it was mentioned that up-scaling requires a significant investment of a few 100 million € as large scale fermentation facilities are needed.

Experts have identified price as a key barrier to PHA's market potential. Current prices are too high to compete with conventional polymers or other biopolymers. Upscaling is needed to achieve lower prices, but requires significant investment..

Production

The production of PHAs is also a major challenge. It is described as a difficult and complex process that requires uniform raw materials with predefined properties. Typically, sugar or vegetable oils are used as raw materials, but residues cannot be used without processing. The residue must be concentrated to around 60% sugar to be suitable for fermentation. However, the fermentation process is not environmentally friendly and requires a lot of energy. The polymer becomes trapped in the bacteria during fermentation and must be extracted by removing the bacteria biomass.

The production of PHAs presents significant challenges due to its complex and resource-intensive nature. Raw materials like sugar or vegetable oils are typically used but require specific properties, and residues must undergo processing to reach a suitable sugar concentration for fermentation. However, the fermentation process is environmentally unfriendly and energy-intensive.

Durability

With regard to durability, experts stated that any outdoor application that needs to be durable is not a viable option for PHAs as they degrade very quickly. In this regard, one voice further explained that PHAs hydrolyse when in contact with soil or water and are easily degraded by bacteria and fungi. In addition, organisms can degrade PHAs within days or weeks because PHAs have been around for billions of years and are known to every organism, making them susceptible to degradation. Finally, the use of PHAs in agricultural or horticultural applications was questioned. Specifically, the use of biopolymers for silage is not possible because bacteria would eat the film and the silage film should not be fed to cattle.

PHAs degrade really quick They hydrolyse when in contact with soil or water and are easily broken down by bacteria and fungi. Usage of PHAs in agricultural or horticultural applications is assessed to be difficult. E.g., usage of biopolymers for silage as bacteria would munch away on the foil.

seasonal availability of feedstock and regional distribution

The availability and transportability of raw materials is seen as a limiting factor. However, there are examples of industries that have found a solution, e.g. the sugar industry has solved the storage problem by producing in campaigns. Also in Greece, different varieties of oranges allow continuous harvesting throughout the year, ensuring a steady supply of orange peel.

Availability and transportability of feedstock is considered as a limiting factor.

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3.1.3 PHA-Applications

In contrast to 3.1.2, the stakeholders' expectations as well as possible limitations and challenges with regard to PHA applications are mapped in the following based on the assessments of experts who are potential users of the end-product PHA applications from the arable farming or horticulture businesses. The expectations of stakeholders with regard to protein function and quality as well as potential challenges are discussed in more detail.

3.1.3.1 stakeholders´ expectations

Functionality of bio-based and bio-degradable PHA-applications

Regarding the general functionality of bio-based and biodegradable PHA applications, the experts expected them to be resistant to weight and climatic conditions, especially humidity. Two voices also mentioned that applications should be cheaper than products, including recycling costs. In addition, the ideal application should have the same lifetime, meet agronomic needs and save time. Finally, one expert mentioned that applications in bio-packaging need to be transparent as they need to be shown to customers. However, attempts to use "bio" plastics have resulted in higher prices and consumer perception of plastic.

When looking at PHA applications in detail, experts had specific expectations for each application. One expert stated that **greenhouse materials** should be durable in multiple campaigns to save installation time and money. Greenhouse film is expected to last 7-8 years and needs to be transparent and UV resistant. Another expert expected **pots** to degrade quickly and did not consider them suitable for long-term use. In contrast, transport pots or trays are expected to have a life expectancy of 6 months to 5 years. The material should be weatherproof and rigid, with no light penetration. It must also be able to withstand production, logistics and home storage. In terms of appearance, it must not be transparent and must be able to be dyed. In terms of **twine**, it was noted that garden twine would be needed for our tomatoes, cucumbers and beans. It was mentioned that they need to be physically stable for 6 months, UV resistant and degrade within 2 to 4 months when thrown on compost. Reusable twine would save time, but would be more expensive than conventional products. The function of **strapping and oil bottles** must meet certain standards, including correct elasticity, thickness, compatibility with equipment and good resistance to protect the load and prevent oil migration and light damage. Finally, two experts expected the **mulching film** to retain its properties for a certain period of time and have a service life of at least 6 months. After that, the mulch film should degrade sufficiently quickly. It was also stated that it should have the same life expectancy as fossil-based film or be much cheaper, both in terms of purchase price compared to the conventional product, including recycling costs.

Experts expect bio-based and biodegradable PHA-applications to be cheaper than conventional products, have the same life span, meet agronomic needs and save time. However, current attempts to use "bio" plastic have resulted in higher prices and consumer perception as plastic.

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Quality of PHA-applications

With regard to the quality of PHA applications, the experts were asked specifically about **contamination** and **purity**.

With regard to **contamination**, the experts judged that there should be no dangerous contaminants, either for human health or for the environment. For agri-food applications, materials should not contribute toxic substances to food, water or soil. It was also stated that packaging materials in contact with the product must be absolutely free of any product harmful to food or the environment. A more critical voice stated that contamination should not be a problem during re-use when disinfected, as it is with conventional products. With regard to **purity**, the experts were unanimous in their opinion that purity is not the decisive factor. One voice stated that purity is not important as long as the functionality is there and the price is right. In line with this, another voice mentioned that a specific purity is not necessary as there is a possibility to adapt to any origin as long as it is safe, sustainable, truly renewable, biodegradable and does not involve an excessive increase in production costs. Finally, in the case of fruit, 100% PHA purity is not necessary, as assessed by an expert. It is possible to combine it with a certain amount of other materials, but especially with cellulose, the issue of moisture has to be taken into account.

In terms of the quality of PHA applications, experts expect materials to be free of any contamination that is harmful to food or the environment. In terms of purity, the experts agreed that purity is not the critical factor.

Customers' willingness to pay

According to one expert, there is an awareness that organic plastics can be more expensive. She considered that it is possible to pay a little more for a new product as long as it meets the necessary requirements. In line with this, one expert stated that there would be a willingness to pay 10% to a maximum of 20% more than for the conventional product if the biodegradability works as well as advertised and expected. In addition, one expert suggested exploring new materials and scenarios that are cost effective, environmentally sustainable and accepted by consumers. The focus should be on finding formulations that give an "eco" feel and have a positive impact on the environment.

Other experts were more sceptical about the acceptance of higher prices. One expert stated that there is no willingness to pay a higher price for these types of materials as customers do not value them and therefore do not want to increase the price of the product. In addition, he assessed that companies in this sector operate on very tight margins and are therefore unlikely to absorb this increase in costs. However, one voice mentioned that a slight increase in costs for the use of biomaterials could only be considered if the resulting new business plan included the development of new market niches with more guaranteed profits.

Experts believe that customers may be willing to pay higher prices for bio-based and biodegradable PHA applications. However, companies in the sector operate on very tight margins and therefore need new business plans that include the development of new market niches where higher profits can be expected.

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3.1.3.2 Main issues and challenges

In the following, the topics that are seen as the biggest obstacles for the market potential of PHA-applications are discussed. The topics are addressed in decreasing order according to the frequency they were mentioned by the different experts.

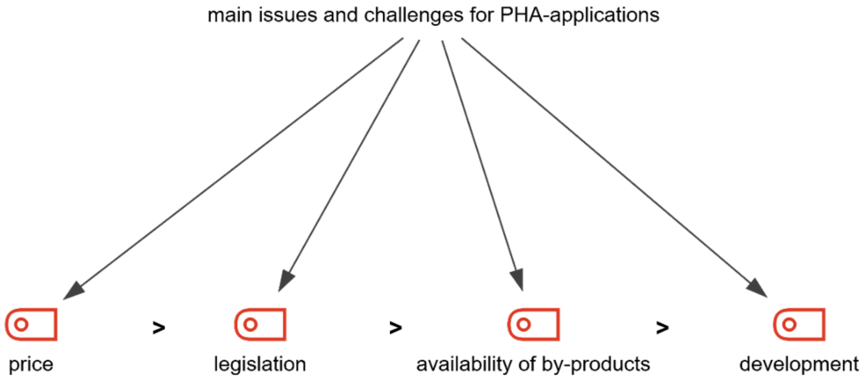

Figure 27: The most frequently cited limitations or challenges for the market potential of PHA-applications by experts (own compilation).

Main challenges

With regard to possible challenges or limitations to the market potential of bio-based and biodegradable PHA applications, experts mentioned several factors. The most frequently mentioned and therefore the most important factor was **price**. It was mentioned that the price of the end product is important, as customers and end users do not want to pay more for certain products. In addition, one voice stated that there will be additional costs as machinery will need to be adapted to new packaging and different crops.

The second most frequently mentioned factor was **legislation**. One expert explained that it is possible to find good solutions because of scientific progress. However, the administration (government) and its legislation change so quickly that the problem encountered is the legislative framework. In line with this, another voice stated that there was a need to facilitate the testing and purchase of new solutions, both for agricultural use and for packaging for final consumption. This would require solid networks of cooperation between companies, technology centers and administrations, as well as the creation of facilities and the removal of barriers.

One expert also identified the pace of **development** as a challenge. He stated that the challenges of generating new solutions from by-products in collaboration with research or technology centers include difficulties in finding funding for trials with new materials and the need for investment to produce or manufacture these materials locally. In addition, the slow pace of technological and knowledge development was mentioned as a practical challenge. Finally, one expert identified the **availability of by-products** as a limiting factor. He further assessed that ensuring a stable supply of co-products without stock-outs and having bioproducts available that meet the specific needs of the industry could be problematic.

The main concern was the price of end products, with customers reluctant to pay more and the additional cost of adapting machinery. Legislation was the second most frequently cited factor, with the need for a more favourable regulatory framework to facilitate the testing and adoption of new solutions. The pace of development, including securing funding for trials and local production, and slow technological progress were identified as challenges. In addition, ensuring a stable supply of by-products that meet industry needs was recognised as a potential limiting factor.

Solutions

When asked about possible solutions to the existing problems, all experts stated that **favourable legislation and policies** could help. One expert explained that there is a need for innovation support policies that enable collaboration between companies, manufacturing partners, other material companies and innovation centres such as universities. In line with this, another expert stated that the need for solutions to replace plastics of petrochemical origin requires supportive legislation.

In addition, two experts mentioned that the challenges of finding bio-based alternatives that are price-competitive and meet technical specifications require **further research**. In addition, one voice mentioned that a lot of research is still needed, applied to the working conditions of the industry, to be able to respond to all the challenges of using by-products in the production of new packaging.

The experts agree that supportive legislation and policies are essential to address current challenges. They emphasise the need for innovation support policies that encourage collaboration between different stakeholders. They also highlight the importance of additional research to overcome the challenges of finding bio-based alternatives that are cost-competitive and meet specific technical requirements.

Outlook

Regarding the prospects for biodegradable products in agriculture, including mulch films, tree growth protectors and plant pots, all experts expressed a general interest in finding a solution for the use of biodegradable plastics. Two experts emphasised that for new products to be accepted on the market, the barrier for consumers must be low. If the price or the workload associated with the new product is high, it will not be feasible. He also noted that no one will invest time and money for ethical reasons alone. The expert also suggested that the best suppliers of agricultural residues are industries such as apple juice and wine processors. He sees a big opportunity for biodegradable products in crops with a fast turnaround time.

One expert shared his views on specific applications. For plant pots and especially for machine planting, such as automated planting similar to lettuce seed bands (young plants, not seeds), he saw a big opportunity for the automated planting sector in general. He also saw a big opportunity for mulch films for normal growers, e.g. lettuce growers who use a new mulch film every 8 weeks. The expert went on to say that durability and functionality over 3 years would make them perfect for protecting tree growth. But they would have to be able to break down on topsoil without being ploughed or mulched, and they would have to protect against rabbits for 3 years and perform really well over those 3 years. Finally, biodegradable products were judged to be perfect for all crops with a quick turnaround time, as there is no controversial need for relatively long performance coupled with the need for a high degradation rate.

Critics argue that the agribusiness industry faces unfair business risks and low returns for farmers. In addition, bureaucracy has increased, further reducing profits. It is hoped that solutions will benefit farmers through consumer demand, but burdening them with higher costs or difficult materials would not be viable. The voice added that the industry was already at its economic limit. Another voice said that the problem of homogeneity in their characteristics needed to be solved.

Experts are generally interested in the use of biodegradable plastics in agriculture. Specific applications, such as plant pots for automated processes and mulch film for regular growers, are seen as promising. However, concerns are raised about unfair business risks and low profits for farmers, increased bureaucracy and economic constraints on the industry.

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3.1.4 Extracted and microbial Proteins

3.1.4.1 stakeholders´ expectations

Protein quality

According to the experts, the quality of protein is very important and should be ensured through strict hygiene and quality control protocols to minimise microbial risks as well as contamination risks, including those from heavy metals and pesticides. It was also mentioned that proteins should meet specific nutritional requirements, including essential amino acids, vitamins and minerals, for different animals.

Looking more closely at potential factors affecting quality, microbial risks, contamination, toxicity and anti-nutritional factors were mentioned. In terms of factors, the experts distinguished between extracted protein and microbial protein. One expert considered that extracted proteins generally do not pose problems in terms of microbial risks. In contrast, microbial proteins could pose problems in terms of nucleic acid sensitivity, especially in fish feed. Contamination was also considered to be an issue, particularly in food applications, but also in feed. However, all experts stated that the problem of contamination could be overcome with strict control protocols. With regard to anti-nutritional factors, the experts noted that extracted proteins could vary depending on the type of protein extracted, but these should be easier to overcome. On the other hand, microbial protein applications could cause problems in fish, as some species are more sensitive to nucleic acids. However, the industry is aware of this and by adding minimum amounts of certain ingredients to the mix with microbial proteins this challenge could be overcome. Toxicity is not expected to be a problem for either extracted or microbial proteins.

Most experts expect protein quality to be unproblematic for extracted protein, but uric acid may be problematic for microbial protein. Microbial risks, contamination, toxicity and antinutritional factors were identified as factors affecting quality.

Comparability with conventional protein

Regarding the nutritional aspects, microbial proteins were assessed to be practically the same as conventional proteins. However, However, there were also some restrictions on the comparability. Microbial proteins are more difficult to ferment. But as they will never be the sole feed source, the protein can replace part of the feed mix, with the remaining diet balanced around it. In this way, they can replace part of the fish fed. Doubts were expressed by all expert regarding costs and the lack of texture.

In addition, one expert assessed microbial protein as an alternative for conventional fish fed more detailed. He stated that the increase in manure from fish fed with microbial protein can lead to more added costs after the feeding process. Other aspects, such as floating characteristics in fish feed, are also important. In conclusion he pointed out that fish feed is the most sensitive application for protein feed.

Experts generally consider microbial proteins to be nutritionally comparable to conventional proteins, but express concerns about their fermentability and texture. They suggest that microbial proteins may not be the sole feed source, but could replace part of the feed mix in applications such as fish feed. However, doubts remain about the costs involved and texture issues.

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Qualities of agri-residues as feedstock

According to the experts, the quality of agri-residues as coproducts is constantly changing, making it difficult to maintain a stable product. Therefore, preparation for processing into microbial proteins is required. While extracted proteins for feedstuff are not affected, food applications require constant quality characteristics. Another expert stated that there has to be a distinction between waste and by-products. This is due to the fact that anything produced from waste cannot be introduced into the human food chain. In summary, the experts assessed the residues/by-products chosen for AgriLoop as generally relevant and suitable.

Experts considered the residues/by-products selected for AgriLoop to be generally relevant and suitable. The constantly changing quality of agricultural residues makes it difficult to maintain a stable end product.

3.1.4.2 Main issues and challenges

In the following, the topics that are seen as the biggest obstacles for the market potential of MP are discussed. The topics are addressed in decreasing order according to the frequency they were mentioned by the different experts.

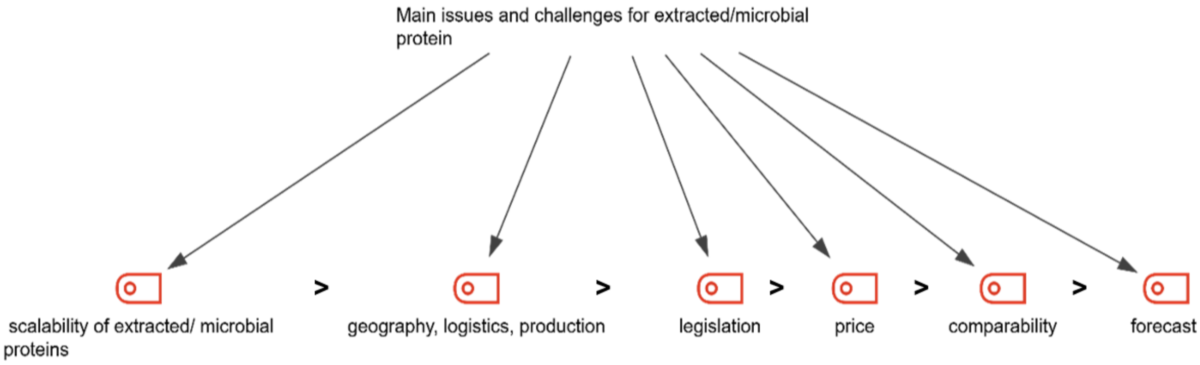

Figure 28: The most frequently cited limitations or challenges to the market potential of extracted / microbial protein by experts (own compilation).

Price and production cost

The Price was assessed to be one of the main factors limiting the potential of extracted/ microbial proteins. Factors that can be considered influencing the price range and the development of new proteins from coproducts are the price of the coproducts, the costs of processing, e.g. purification, the price of microbial broth and the production volume.

With regard to production costs, all experts were united in the opinion that the costs are still too high, therefore more progress in development is needed. Moreover, a large amount of feedstock is needed in order to be profitable. In contrast, one expert assessed the range of costs for conventional pant-based proteins and for extracted protein as roughly the same, as the spread can be huge and can range from 4 € /kg to 30 € /kg. When considering microbial proteins, it needs to compete with the price fish meal is described as the highest priced protein.

All experts consider price to be one of the main limiting factors. The price of co-products, the cost of processing, the price of the microbial broth and the volume of production all play a significant role in the price range.

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Legislation

Legislation is one of the issues most frequently mentioned. It was stated that legislation plays a crucial role in the development of new food and feed products, especially in terms of safety and compliance with regulations. The process is assessed to be challenging and time-consuming, requiring thorough checks of every aspect of production and original resources on order to ensure that all aspects comply with the requirements of food and feed safety.

In terms of food safety, there is a predefined process according to the EU NovelFood regulation. It is determined that the protein needs approval in order to be used in human food. One expert assesed that the process costs 1-1.4 million euros as several laboratory tests and trials are required. The process was described as complicated but necessary process. Also, feed safety was described to have high requirements, e.g., the requirement to have low heavy metal levels. All in all, developing stable, food-secure processes is assessed to be the key challenge, particularly when dealing with coproducts with varying properties and characteristics.

However, it was stated that once a company has established itself and its products on the market, subsequent products could enter more easily. One expert even mentioned that legislation should not be considered as the biggest problem as it could change. Besides one expert named China as market, as food legislation is more relaxed.

Legislation is often cited as a major challenge in the development of new food and feed products because of its critical role in ensuring safety and compliance. The process is described as complicated and time-consuming, requiring meticulous checks to ensure compliance with food and feed safety requirements. Developing stable and safe processes, especially for co-products with variable properties, is identified as a key challenge. However, experts are optimistic that legislation can be changed.

Geography & Logistics

All the experts are unanimous in their assessment of the logistical problems: There is a consensus that logistics is very important because profitability depends on it. The high moisture content of by-products makes it difficult to transport them over long distances without spoilage or high costs. Therefore, one expert recommended that processing should take place in the area of origin, preferably close to the production site or even directly at the production site. This ensures quality as the final product can potentially be shipped further, but from a sustainability perspective it should be sold as close to the production area as possible.

In terms of potential geographical challenges, one expert noted that the industry is becoming more interested in the use of co-products, such as the conversion of proteins from brewing to feed. It is mentioned that there has been a change in attitude towards co-products, which could increase competition and limit their geographical availability.

Most experts identified logistics as a key challenge to profitability. Production should take place in the region of origin. Regional availability may be limited due to increased competition for by-products.

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Scalability

Scalability is assessed to be very good with regard to coproducts as there are high amounts of coproducts on the market. In detail it depends on the business case, e.g., on the paybacks of each product, the required energy input, the downstream processes. The expert assed that if the business case is right the product will skyrocket based on market looking for and demanding more sustainable proteins. In contrast, one expert an expert assessed that the scalability needs to be further developed. It was mentioned that AgriLoop trials are still on a very low scale. In order to meet industry demands, 5-10 tons per day of final product or 100 tons per day of raw material would be required. The minimum requirement for scalability would be 1 ton per day of final product.

With regard to limitations several experts named the technology capacity be important for meeting the demand. Another limiting factor mentioned was contamination. The system needs to be clean from contamination from other bacteria or other sources. In this regard there are certain limitations in size to be able to clean the fermented and keep it hygienic. From a practical point of view, the experts have described AgriLoop as helpful in order to overcome the challenges of developing from lab scale to full scale. It is mentioned that trials on a lab-scale are usually financed, whereas developing a product at sufficient scale for the market is a financial challenge. Especially for smaller companies' investment costs a described as a limitational factor.

Scalability is considered to be very good, depending on the specific business case and factors such as energy input and downstream processes, with potential for significant growth in response to market demand for sustainable proteins. However, it was suggested that further development of scalability is needed, as AgriLoop trials are currently at a small scale and industry demand requires larger production capacities. Technological capacity and contamination control are identified as key limiting factors. Further, the transition from lab-scale development to full-scale production can be financially challenging, particularly for smaller companies with significant investment costs.

Consumer acceptance and comparability

Costumer acceptance is also assessed to be a limitational factor. It was stated that depending on the application and especially if it is intended for food applications, there could be customer resilience. For example, insects are a perfect alternative protein source, but consumer acceptance is really low in European countries. However, the experts do not consider acceptance to be a problem in animal nutrition.

In Addition, it described that there could be a comparison between MP and conventional proteins. Here, conventional proteins are very cheap and well known. They are very practical and can be used for everything. They have no limitations like MP, e.g., high uric acid content, which can accumulate in humans and cause gout. Therefore, the advantages of extracted/microbial proteins should be well communicated.

Consumer acceptance is seen as a potential limitation, particularly in food applications where there may be consumer resistance. In animal nutrition, however, acceptance is not seen as a problem. When compared, conventional proteins are favoured because of their low cost, versatility and widespread familiarity, while MP have limitations, such as high uric acid content. Effective communication of the benefits of MP is highlighted as important.

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Outlook and perspectives

It was assessed that the price of protein will probably increase 20-25% over the next 15 years. The price of the production of bacterial protein is predicted to be lowered simultaneously and resulting in the same price level as that of conventional protein.

On the costumer side, experts named that there could be a very small group who buy organically grown sustainable foods due to ideological reasons. This group is willing to accept higher prices but is assessed to not to be focused due to their height. In commercial volume one expert estimate that 5 -10 % price increase would be accepted and therefore could be targeted for mass production.

From the production perspective, experts assessed a decrease of the cost-price in the future, even though they depend on a lot of different factors. Further, the admission of GMOs by the European union could make a huge difference, as more efficient microbes could be produced.

Experts predict a 20-25% increase in protein prices over the next 15 years, but the cost of producing bacterial protein is expected to fall and eventually converge with conventional protein prices. It's recognised that there is a niche group of consumers who are willing to pay higher prices for organically grown, sustainable food, but this is seen as a limited market. Experts estimate that a price increase of 5-10% could be accepted in commercial quantities.

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3.2 Exploration of the market potential

In the following paragraph, we will give an assessment of the market potential for agri-residue based products on the information from the expert interviews. The market potential will be evaluated and we will give an overview about the general market potential, determining factors for a high market potential and the best fitting applications.

3.2.1 Estimates of market potential of PHA

The market potential of PHA or PHA end-products is mapped based on the assessments of experts from the traders, processors, converters of the end-product PHA. Further, the market potential of the end-products, factors influencing the market potential and possible applications are discussed in more detail.

3.2.1.1 Market potential of PHA-end products (mulch films, horticultural pots, twines, growth protectors, greenhouses, nets, grow/seedling bags)

Regarding the market potential for PHA end-products, all experts agreed that the potential was very high. One expert described the global starting point for PHA in more detail. It was described that global production of bioplastics will increase from 2.2 million tons in 2022 to 6.3 million tons in 2027, with biodegradable plastics accounting for over 51% of production capacity. In addition, packaging is expected to remain the largest market segment for bioplastics, but other segments such as automotive and construction are expected to grow. Finally, the potential for PHA production in Europe is described as huge, as there are no major local producers. Several experts identified agriculture as the leading sector for the use of bioplastics. One reason for the high agricultural potential is that there is a real interest in having solutions for agriculture that are ideally biodegradable in the soil, at least compostable at home or industrially. The potential was also underlined by the fact that the number of clips for one hectare of crops is estimated to be between 800,000 and 1 million. One voice highlighted the importance of PHA as the majority of agricultural materials are made from fossil fuels or contain some PLA. Therefore, these materials will not be certified as biodegradable in soil, but may still be compostable at home or in industry. Finally, Asia is described as the current major production centre for bioplastics, with PHA mulch film already being used in China. However, Europe's share is predicted to decline.

The experts also identified several potential markets for PHA end-products. Firstly, bioplastics are used in various markets such as packaging, catering, electronics, automotive, agriculture, toys, textiles and more. Agriculture is expected to be the leading sector for bioplastics. Asia is currently the main production centre for bioplastics, accounting for over 41% of production, and is expected to increase to almost 63% by 2027. The agricultural and horticultural markets are considered suitable for the use of biodegradable materials.

Experts unanimously assessed that there is significant market potential for PHA end-products, particularly in the global bioplastics industry. Forecasts indicate a significant increase in bioplastics production, with biodegradable plastics taking a dominant share. The agricultural sector will be a primary area for bioplastics, given the desire for biodegradable or compostable solutions. Agricultural and horticultural markets are recognised as promising segments for biodegradable materials.

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3.2.1.2 Determining factors for market potential

In the following, the determining factors for the market potential of PHA and PHA end products are elaborated. The factors biodegradability, logistics, price and legislation are discussed in detail.

Biodegradability

Experts were united in their opinion that the market potential is determined by the biodegradability potential. Ideally, agricultural materials should be non-fossil but soil biodegradable, at least home compostable or industrially compostable. The main advantage over PLA is that even 100% bio-based PLA is slowly biodegradable. Therefore, PHA-based components must be 100% biodegradable and free of persistent micro- and macro-plastics to maintain market acceptance. In addition, it was described that large pieces of PLA left in the soil could damage agricultural machinery. Finally, one voice mentioned that PHA and PHB have been observed to degrade faster than expected and therefore the right conditions need to be researched. This voice also mentioned climate change as the main challenge for degradation, as climatic conditions vary greatly across Europe and even more so globally.

Ideally, agricultural materials should be soil biodegradable, at least home compostable or industrially compostable. In addition, materials should be 100% biodegradable and free of persistent micro- and macro-plastics. Finally, climatic conditions should be considered in relation to degradation.

Price

Market opportunities also depend on price. The agricultural industry is price-driven and is only willing to accept a small additional cost for biodegradable PHA-based products. One expert estimated that an increase of 0.1 to 0.2 €/kg would be accepted. However, a significant price difference will not be accepted unless there is a significant time saving. The current price of PHA is around 2.5 € /kg, which is twice the price of PE, PP and PLA and makes it too expensive for the agricultural industry, despite high consumer interest in environmentally friendly products.

However, several experts considered PHA to have "great" pricing potential. It was stated that there is a great opportunity because the price of fossil-based plastics (PE, PET, PP) is quite volatile due to oil prices. Therefore, the price of recycled plastics and ultimately bioplastics could become more attractive. Furthermore, the potential is even greater if all costs are included in the total price. If the cost of production is added to the cost of collection, disposal, recycling and logistics, the 100% biodegradable product is more attractive because it costs the same or less overall. Finally, one expert questioned whether the price advantage of converting in China might be negative for converters in other parts of the world.

The agricultural industry is only willing to accept a small additional cost for biodegradable PHA-based products. Currently the price of PHA is twice that of PE, PP and PLA. An increase of 0.1 €/kg to 0.2 €/kg could be accepted. However, due to the volatile price of fossil-based plastics and the total cost of conventional products, there are large price opportunities.

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Logistics and Legislation

Regarding logistics, one expert noted that transporting highly concentrated waste streams is more efficient and cost-effective than transporting waste with a high water content. Furthermore, processing waste at source can also reduce transport problems. The use of waste from apple processing, tomato pulp, orange peel and spent brewing grains is considered common.

Legislation and policy were also identified as key to market potential. One expert estimated that there could be a large market for PHA and PHB if the use of petrochemical products was no longer allowed. Another voice noted the need for subsidies, financial incentives or stricter legislation, e.g. obligation to declare the amount of PP per hectare.

In terms of logistics, the transport of highly concentrated waste streams or the processing of waste at source were recommended. Favourable legislation with subsidies or financial incentives was also considered important.

3.2.1.3 Applications

Best applications

The experts were divided on the most appropriate applications. In general, all experts agreed that the best applications for PHA are for products that need to be biodegradable in soil. It was also noted that there are three bottlenecks when considering the most suitable applications: material properties, availability and price. It was also judged that in agricultural and horticultural applications, functionality and price are more important than aesthetics.

When looking at specific applications, the experts' opinions differed. The applications mentioned by the experts were agricultural mulching films, vine clips, grow bags, blends and twines. One expert recommended the production of PHA **clips** that are biodegradable in soil, as they would be superior to those made from PLA due to their biodegradability. It was also mentioned that PHA products are well established in the extrusion industry, but not in the injection industry for products such as clips. It is not currently possible to produce a clip that is strong, flexible and durable enough for cultivation. Another expert suggested that there could be market potential in special applications for **blends**. The expert went on to say that there could be an application in cold regions where biopolymers do not degrade quickly enough. In this case, PHA could be added to a blend to speed up degradation. Several experts identified the use of PHA for **grow bags or seedling bags** as a potential application. However, PHA degrades rapidly in soil. This is not necessarily a limitation, but can add value to the application. Another voice suggested the use of twines that retain their properties for a year. Furthermore, **twines** would be beneficial in greenhouse horticulture, as most of these elements are currently made of polypropylene, which leads to problems with plastic particles in the compost. On the other hand, one critic questioned the suitability of PHA for flexible applications due to its lack of flexibility, high crystallinity and brittleness.

Finally, three experts assessed **mulch film** as a suitable application. One stated that PE mulch film is contaminated by up to 80% (humus, organic matter, water, sand, etc.) when removed from the field. This means that soil fertility is exported with the film waste. Therefore, biodegradable film solutions are described as very interesting because they leave the organic matter in the soil. One expert considered that biopolymers mulch films would be purchased despite their higher price compared to conventional films if they had advantages such as biodegradability. Another expert suggested that mulch film might be more suitable for large-scale agriculture, where handling large quantities of mulch film becomes a logistical challenge. Here it might be much easier to simply mulch and plough the film into the soil at the end of the season. One critical voice questioned the suitability of PHA mulch film as it may be limited by farmers' cost sensitivity and the fact that it is often reused for several years, making it less suitable for

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crops such as asparagus, potatoes and strawberries. Another critic went further, stating that PHAs are not suitable for outdoor or agricultural applications because they degrade too quickly.

Other possible target applications mentioned by experts were all kinds of different blends, e.g. coffee capsules, which are a typical application well suited for biopolymers. In addition, one expert identified tree protection products such as tree guards, shelters and tubes as suitable for PHA. Finally, one expert considered that traditional party cups, fishing nets and plastic bags could be replaced by PHA products. With regard to PHB, it could be used to replace plastics on harvesting machines that can break and get lost. PHB would be able to replace these parts and, if broken, would not be harmful.

The experts had different views on the most suitable applications for PHA, with the emphasis on the need for soil biodegradability. Agricultural mulch film, clips, grow bags, blends, twine and tree protection products were the most commonly cited applications. The use of PHA in mulch films was considered interesting due to its potential to leave organic matter in the soil and reduce the export of soil fertility. Despite its higher cost, it could be preferred by large-scale agriculture. However, critics were concerned about the rapid degradation of PHA mulch films, particularly for multi-year crops. While one expert recommended PHA clips for their superiority over PLA, others pointed out the limitations in achieving flexibility and durability in products such as clips. Other potential applications included coffee capsules, tree protection products, traditional party cups, fishing nets and plastic bags, with PHB as a replacement for fragile parts in harvesting machinery.

Not suitable applications

The experts also identified several applications that are not suitable for PHA. In contrast to the previous mentioned opinions, one expert stated that PHA material lacks flexibility and is characterised by high crystallinity and brittleness, making it unsuitable for **flexible applications** such as twines. She added that although copolymers can improve flexibility, no products have yet been made with this material property. It was also explained that the **injection** process for PHA is already known, but the injection process has yet to be found. Another voice suggested that PHA is not viable for **plant pots** because the raw material cost is too high and the price is not competitive with fossil-based materials. Therefore, PHA is not recommended for horticultural pots. In addition, one expert mentioned that PHAs have significant disadvantages compared to fossil-based plastics. Processing in conventional extruders is not a problem for biopolymers. However, PHAs degrade at 140°C and degradation accelerates as the temperature rises. In the case of PHB, two experts considered that PHB is not suitable for all applications due to its brittleness. Specifically, mulch films are not possible with PHB.

The experts highlighted several applications that were considered unsuitable for PHA. Flexible applications such as twine were seen as problematic, even with the potential improvement of copolymers. PHA was considered unfavourable for plant pots due to high raw material costs and price competitiveness issues. PHB was considered unsuitable for certain applications due to its brittleness, with mulch films mentioned as a non-viable option. In addition, some experts pointed out the disadvantages of processing PHAs at higher temperatures, resulting in degradation.

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3.2.2 Estimates of market potential of PHA-applications

In the following, the market potential of PHA applications is mapped on the basis of the assessments of experts who are potential users of the end-product PHA applications from the arable farming or horticulture businesses. Here, the market potential of the end-products, factors influencing the market potential and possible applications are discussed in more detail.

3.2.2.1 Market potential of bio-based and bio-degradable PHA-applications compared to products from petrochemicals

Comparison

When comparing bio-based and biodegradable PHA applications with petrochemical products, experts mentioned several potential applications. In general, one expert considered that there is currently no alternative to petrochemical products in use. The main reason for not switching to this other type of product is that it is not sufficiently valued in the niche market and neither customers nor consumers want to bear the increased cost of the product. Concerning specific products, one expert stated that in the cultivation of plants for public landscaping, it would be very necessary to find solutions for biodegradable bags and pots that would eliminate the work of managing them after the death or planting of the annual plant. In addition, one expert stated that mulching film and covers for seasonal plants would be a viable option, as they don't need to be removed and put in the bin, thus reducing labour. However, he added that the reality of the current market is that biodegradable products that could be buried are not a good option in terms of price or commercial conditions, e.g. they force you to buy quantities that you may not use and that deteriorate in storage from one year to the next. Finally, one voice considered that bio-based and biodegradable PHA applications may be suitable for materials such as ribbons and staples. However, the expert went on to say that the use of bioplastics in greenhouses could be challenging because of competition from conventional plastics and because it is unclear whether they would work as well.

Currently, no alternatives to petrochemicals are widely adopted, mainly due to insufficient appreciation in the niche market. For specific applications like plant cultivation in public landscaping, experts suggested a need for biodegradable bags and pots. Mulching film and coverings for seasonal crops were considered viable, but challenges include market realities like higher prices, forced bulk purchases, and product deterioration.

Advantages

According to the experts, one of the main benefits of bio-based and biodegradable PHA applications replacing currently used plastic materials is the environmental sustainability and carbon footprint impact. One expert considered that this could be a differentiating aspect compared to other competitors in the market. She also mentioned that it would be more sustainable and would allow companies to work together to obtain a value-added product from their by-products, thus closing the loop (circular economy). Finally, three experts stated that another important benefit could be the reduction of waste management and costs related to the management of plastic packaging. In addition, it can reduce the workload with applications as mulching film, tree protection and garden twine, as it can be buried or composted, thus contributing organic matter to the soil.

The main benefits of bio-based and biodegradable PHA applications are environmental sustainability, carbon footprint impact, circular economy, waste management reduction, labour reduction and contribution of organic matter to soil.

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Possible barriers or disadvantages

The experts also assessed the main barriers to bio-based and biodegradable PHA applications with high market potential. All experts agreed that **higher prices** are the biggest market barrier for bio-based and biodegradable PHA applications. One expert estimated that PHA products will not be profitable if they are more expensive than those of conventional plastics. In addition, another expert commented that the higher costs associated with alternatives cannot be passed on to customers. In terms of cost, one expert considered that machinery would need to be updated, as the same type of **machinery** could not be used for those of petrochemical origin as for those of biodegradable and biological origin. It was also mentioned that **commercial conditions** may require the purchase of large quantities which may deteriorate during storage. It is therefore important to have a stable and sufficient supply to buy only the quantity needed. There is also the question of whether bioplastics can achieve the same **properties and resistance** as conventional plastics. One expert noted that experience with bioplastics to date has been patchy, as they are not sufficiently resistant to moisture and other environmental conditions, which means that their durability is not adequate. Finally, in terms of general limitations, one voice noted that the **recycling process and infrastructure** could be complicated as the composting facility needs to be close by. In addition to the production side, the consumer side was also highlighted by experts. One expert considered that if bioplastics are too similar to conventional plastic, it could have the opposite effect as customers may still consider it as plastic and not buy the product. It was also noted that the vast majority of customers do not value sustainable packaging alternatives and are not willing to pay more for them.

When considering specific applications, one expert specifically mentioned **mulching film**. He discussed that mulching film has been tried but has been found to have several disadvantages. The film has to be completely covered by soil and left in the ground for a few weeks or months for it to decompose completely. He added that it did not look good to customers as it looked like plastic was being thrown on the fields, with pieces of film flying around and sticking out of the ground. There were also a lot of complaints because the film is light and difficult to cover completely with soil. The expert also raised the issue of degradation. He stated that the mulch film started to degrade at the end of the season. This is a real problem because it has to be stable until the end of the season and then it degrades very quickly. In addition, one voice felt that there was also a limitation with the specific use of the **pots**. The pots are used for 5-10 years. Therefore, biodegradability would result in a long life cycle, which would be incredibly expensive. It was explained that it is simply not viable to buy new pots every year as the old ones degrade. Finally, one expert explained that in the case of ribbon, there are not many suppliers and therefore expensive products. In addition, there is a reluctance to ensure that all spools behave in the same way, as the technology is too new for the product supplied to be homogeneous.

The main disadvantages of bio-based and biodegradable PHA applications are higher prices, need for updated machinery, need for stable and sufficient supply, lack of properties and resistance, and recycling process and infrastructure. When considering specific applications, mulching film was judged to have problems with appearance, lightness and degradation. Pots used in long life cycles are not viable as a biodegradable application. For ribbon, issues of product homogeneity need to be addressed.

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3.2.2.2 Bio-based and bio-degradable PHA-applications and suitability in agriculture

Assessment on suitability

Regarding the most suitable applications, experts' opinions diverge. One expert generally stated that bio-based and bio-degradable PHA-applications are very important since there is a huge need to replace plastic that comes from oil and the consumption of plastic will not decrease too much in the coming years. Another expert assessed that bio-based and bio-degradable mulch films, horticultural pots, twines, growth protectors, greenhouses, nets, grow/seedling bags are well suited applications from agri-residues in agriculture. Two experts highlighted mulch foil and assessed that they could be a viable option if they perform well and meet the necessary requirements. Another voice mentioned that it is advantageous to use agricultural waste or agricultural by-products in the agricultural sector. He added that it is important to give priority to being used first in the food chain itself (human and animal food), and after that, think about other valorisations in new materials. Finally, one expert stated that priority should be to work to obtain containers of biodegradable materials that meet the requirements of durability and resistance at prices that can compete in the market.

In contrast, one critical voice stated that currently fossil-based materials are preferred due to their low cost and high performance. He further assessed that it is important to not leaving any residues in the field, as customers are sensitive to any visible plastic that could be associated with environmental pollution, even if it's biodegradable plastic. Another critical voice mentioned that, depending on the specific applications and materials, it would still be a long way to go before products of acceptable quality can be used by the industry.

Experts considered mulch film, horticultural pots, twine, growth protectors, greenhouses, nets, grow/seed bags as generally suitable applications. One expert stated that priority should be given to work on biodegradable containers. Critical voices, however, questioned the suitability on cost and performance grounds and noted that there is still a long way to go to achieve high quality products suitable for industrial use.

Other attractive Applications

In terms of other attractive applications, the experts identified several promising alternatives. One expert considered that the use of biodegradable pots for seedlings could save time. However, they may not meet the high demands of certain plants. In addition, the expert explained that biodegradable pots could also work well for courgettes, cucumbers and tomatoes. Other alternatives mentioned were boxes for product transport, agro-film (greenhouses), rigid plastic crates from bulk distribution and bioplastic pallets, as well as mesh bags, rigid bioplastic crates from bulk distribution and bioplastic sticks. Finally, one expert stated that weed cloth could be a promising option. However, the product would have to perform really well and meet our requirements.

Other suitable applications identified by the experts included biodegradable pots, weed wrap, transport boxes, agricultural film (greenhouses), large distribution rigid plastic boxes and bioplastic pallets, as well as mesh bags, large distribution rigid bioplastic boxes and bioplastic sticks.

Unattractive applications

Finally, experts assessed which agricultural applications of agricultural residues are not suitable for bio-based and biodegradable PHA. One expert stated that they are not suitable for the production of bio-packaging because the resulting packaging is not sufficiently resistant to moisture and other environmental conditions, which means that its durability is not adequate. Another expert considered that thermoformed containers would not be suitable because multi-layer plastics that protect against light and oxygen barriers would generate large amounts of agricultural waste. Furthermore, bio-based and biodegradable PHAs are not suitable for use in greenhouses as current applications require the least amount of time and investment to install. Finally, PHA applications were not considered suitable for pots in very intensive production cycles. If the roots are hindered in their development by the biodegradable pot, this will be the case with PHA pots, as the seedlings have to start growing from the moment, they touch the soil.

Bio-packaging, thermoformed containers, greenhouse applications and pots in intensive production cycles were considered by the experts to be unsuitable for bio-based and biodegradable PHA.

Table 9: Summary of applications assessment (own compilation).

Application	Advantages	Disadvantages	Requirements	Open questions/
Mulch films	- Degradability delivers a workload reduction - Reduction of logistical costs - Increased soil fertility - Decreased Contamination - Added value - Reduction of carbon footprint	- Difficulties with Degradability: - Unsightly view on field - Impossible with PHB - Price	- Correct biodegradability (Keeping properties long enough then degrading fast enough) - Service life: 6months Competitive price	- Combining Durability with Degradation - Service life - price
Horticultural pots	- Fast degradation - Reduction of carbon footprint	- Not viable for long-term use - Obstruction of develop of rootstock - Price	- Correct biodegradability - Service life: few days Competitive price	- Biodegradable pots with advanced properties for added value in soil
Twines	- Degradability, as it delivers a workload reduction - Reduction of carbon footprint	- Real price would go up - Lacks flexibility - Price	- Physically stability - UV resistance - Service life: 6 months Competitive price	- advanced properties like flexibility - Combining Durability with Degradation
Blends	- Degradability - Cold regions: Accelerate the degradation	- Price	- Competitive price	- /

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Agro films/ greenhouse films	- Reduction of carbon footprint - Reduced work and waste management	- Lack of Resistance to atmospheric phenomena - Lack of stability - Price	- Transparent and UV resistant - Same service life expectancy as fossil-based foil - Service life: 5-7 years Competitive price	- Sufficient Resistance and Stability
Growth protectors	- Degradability, as it delivers a workload reduction - Reduction of carbon footprint	- Durability and functionality - Price	- Durability and functionality for 3 years - Competitive price	- Viable durability and functionality
Grow/seedling bags	- Degradability - added value through Dissolution in the soil - Reduction of carbon footprint	- Durability and functionality - Price	- Durability and functionality competitive price	- Viable durability and functionality
Clips	- Cold regions: could be added to a blend to accelerate the degradation - Reduction of carbon footprint	- Yet, impossible to produce strong and flexible clips - macro and micro plastic load in compost	- Strength and flexibility - competitive price	- Viable injection methods
Bio-packaging	- Reduction of carbon footprint - Reduction of managing cost	- Durability - Low resistance to humidity and other environmental conditions - Potential migration	- Avoiding cross-contamination - Durability	- Coss-contamination

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3.2.3 Estimates of market potential of MP

3.2.3.1 General market potential and markets

The experts rated the market potential of MP in general as very high, especially for animal feed. The main factor influencing the market potential as assessed by the experts was price. It was noted that the main question is whether it is worthwhile, in terms of price, to replace, for example, conventional animal feed with alternative protein sources. The experts also mentioned that the market is not yet developed. The proteins currently used, such as soya, are very cheap and produced in industrial quantities. There are also a few solutions that provide protein, such as sunflower oil residues. When looking at microbial proteins, experts have pointed out that they have very high costs combined with a lack of texture to make them acceptable for human consumption. Extra effort is therefore needed to create texture. In terms of potential markets, experts identified animal feed and plant fertiliser as suitable. One expert even suggested that there is no limit to the applications as there is a demand for all types of protein.

The market potential for MP is generally considered to be very high, especially for animal feed. The experts also identified animal feed and plant fertilisers as suitable markets for extracted/microbial protein.

3.2.3.2 Comparability with conventional protein in terms of functionality

In terms of functionality, the experts judged that MP can generally perform the same functions as conventional proteins. This is due to the almost identical amino acid profile in arthropods and animals. The experts also distinguished between animal and human nutrition.

With regard to animals, one voice emphasised that nutritional value is the main concern and that proteins can easily be replaced by extracted and microbial proteins. If the focus is on nutritional value, it is easy to substitute one protein for another and amino acid for amino acid. Furthermore, animal feed is a composition of many different ingredients and protein is only a small part of the animal's diet (between 10% and 20%). Therefore, experts have estimated that 100% of conventional protein in animal feed can be replaced by extracted and microbial protein.

In terms of humane nutrition, food must also have functional properties. Therefore, experts considered that microproteins from fungi have a high potential as they are well suited to produce a structure with bite that can replace meat. Another voice pointed out that arthropods have the same amino acid profile as animals and can be used for human food without causing gout. In contrast, microbial proteins have a high uric acid content and cannot be used directly for human food because of the gout problem.

Finally, the experts looked at areas where proteins might be less effective. Here it is difficult to replace eggs with alternative proteins because of their binding and gelling properties. As mentioned above, microbial proteins can cause gout due to their high uric acid content.

Experts have found that MPs can perform similarly to conventional proteins, especially in animal nutrition, where they can be 100% replacements. In human nutrition, microproteins from fungi are considered to have high potential. Arthropods are also considered suitable for human nutrition. On the other hand, microbial proteins are not perfectly suited for human consumption.

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3.2.3.3 Applications

In terms of the most suitable applications, all experts agreed that animal feed was the most promising use. One expert described feeding fish as a replacement for fishmeal as the holy grail because carnivorous fish species need this type of feed. To feed carnivorous fish, you have to kill other fish first. This is, of course, a very resource-intensive way of feeding. Being able to replace fishmeal would therefore be the best application for alternative protein feed. However, it requires a good amino acid profile, high digestibility and certain unsaturated oils. To this end, microbial proteins have been evaluated as having a better chance of replacing fishmeal than extracted proteins. Algae or yeast could also be considered.

As for other attractive applications of extracted/microbial proteins, many different options were mentioned. One voice mentioned potato protein and extracted protein from brewer's grain as proteins suitable for applications in the food industry. Extracted protein from potato by-products was described as usually highly functional and having very good properties. In addition, extracted protein from brewer's grain is considered to be more of a nutritional protein that could replace soya concentrate, but would not be as functional as potato protein. Finally, microbial proteins were judged to be not a good substitute for functional properties in protein production, but valuable for nutritional properties. Other applications worth mentioning are microbial broth derivatives for plant fertilisers, larval fat as animal antibiotics and pet food.

Finally, when it comes to challenging factors for applications of extracted/microbial proteins, experts identified several challenges. One expert indicated that there is no general limitation in terms of applications. The only challenges he mentioned were functionality and price. In addition, the expert stated that proteins need to be extracted at high concentrations in order to be used in food applications. Use in food applications is recommended because the price paid for food is estimated to be 5 times higher than the price paid for feed. On the other hand, another expert pointed out that the fermentation process requires a lot of energy. Furthermore, there will always be losses during the process as the efficiency is not very high. At the same time, it was mentioned that it could offer the potential to use carbohydrates instead of animal proteins.

Experts agreed that the most promising application for MP is in animal feed, particularly for carnivorous fish as a replacement for resource-intensive fishmeal. To fulfil this role effectively, these alternative proteins must have a good amino acid profile, high digestibility and certain unsaturated oils. Microbial proteins, algae or yeast have been identified as potential sources. In addition, several other applications were considered attractive, such as the use of extracted proteins from potato by-products and brewer's grains in the food industry. Extracted protein from potato by-products is valued for its functionality and properties, while protein from brewer's grain could replace soya concentrate in animal feed. Microbial proteins were valued for their nutritional properties, but not as functional replacements.

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4. Summary and Conclusion

By the first round of expert interviews, we got valuable insights. The implementation of the methods was successful and the intermediate results confirm the research strategy.

The general feedback of the experts can be summarized in three points:

- PHA, PHA-applications and MP were assessed to be promising targeted end products
- The market potential of these products is generally seen as very high
- Challenges in technology novelty, set up and upscaling were mentioned
- There are several limitations and potential barriers to be considered with valorisation and end-products.

This feedback shows that the challenges/barriers we are tackling on in this project are well known and that the interest in finding solutions in the industry is high. In the following, the most important results of Delphi 1 are divided into 4 sections as done before.

Valorisation

The current valorisation processes for agricultural by-products aim to enhance their value, with benefits including environmental and economic gains. Satisfaction is often low due to profitability, legislation, and unequal campaigns, but it improves when environmental concerns or profit strategies are prioritized. Experts expect increased profits through ideal valorisation processes focusing on high added value and simplicity in logistics. Potential pathways include organic fertilizer, protein products, green hydrogen, and animal nutrition additives. Supportive factors include financial aid, favorable legislation, and effective networks. Challenges include transportation costs, volume management, processing difficulties, climate change impacts, and restrictive legislation. Collaboration between research institutions, universities, and companies is crucial, and innovative solutions like insect-based food and microorganism transformations are explored. The economic and market situation of production, along with farmer involvement, is vital for successful valorisation scenarios. The industry explores innovative solutions like insect-based food and microorganism transformations for added value.

PHA

Experts expect PHA products to be GMO-free, prioritize 100% PHA for optimal biodegradability, and foresee a decrease in PHA cost to €2.5/kg within the next 5 years. Market potential is high in agriculture and horticulture, with soil or compostable properties desired. Limitations include high production costs, scalability challenges, ecological concerns, quick degradation in soil or water, and limited feedstock availability. The agricultural industry is open to a small added cost for biodegradable PHA, presenting opportunities with favourable legislation and subsidies. Suitable applications include mulching films, vine clips, grow bags, blends, and twines, while some applications like flexible twine, injection products, plant pots, and PHB mulch films are deemed unsuitable.

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PHA-Applications

Experts anticipate that bio-based and bio-degradable PHA applications should be cost-effective, durable, and meet agronomic needs while saving time. However, current attempts with "bio" plastics have led to increased prices and consumer perceptions. Regarding PHA application quality, experts emphasize the importance of materials being free from harmful contamination, with purity considered less decisive. While customers may be willing to pay more for bio-based and biodegradable PHA applications, tight profit margins in the industry necessitate new business plans for guaranteed profits. Limitations include the decisive factor of pricing, the need for favourable legislation, and concerns about by-product availability. Supportive legislation, further research, and interest in biodegradable plastics in agriculture are seen as potential solutions, with specific applications like biodegradable bags and pots for plant cultivation suggested. Despite environmental benefits, challenges include higher prices, machinery requirements, stable supply needs, and issues with recycling processes. Experts find certain applications, such as mulch films, horticultural pots, twines, and more, generally suitable, but scepticism arises due to cost and performance concerns. Additionally, suggestions for biodegradable pots, weed fabrics, and other applications are noted, while certain applications like bio-packaging and pots in intensive production cycles are deemed unsuitable.

MP

Experts anticipate unproblematic protein quality in extracted proteins but recognize potential uric acid issues in microbial proteins. Quality-inhibiting factors for microbial proteins include microbial risks, contamination, toxicity, and anti-nutritional factors. Despite concerns about fermentation, texture, and practical conditions, experts view microbial proteins as practically similar to conventional proteins. While AgriLoop's chosen residues/by-products are deemed generally relevant and suitable, the changing quality of agricultural residues poses challenges. Major limitations include pricing factors, legislative constraints, challenging processes, and logistical difficulties, with experts expressing optimism about potential legislative changes. Scalability is considered good in terms of coproduct availability, but technological capacity, contamination, and investment costs may limit scalability. Experts doubt customer acceptance in food applications due to the well-known nature of conventional proteins, and price convergence between microbial and conventional proteins is expected, with a 5-10% price increase accepted in commercial volumes and potential future cost decreases. The market potential for MP is considered very high, especially in animal feed, plant fertilizers, and human nutrition, with MP seen as 100% replacements for conventional proteins in animal nutrition. While arthropods are deemed usable for human food, microbial proteins are viewed as less suitable. Animal feed is unanimously seen as the most suitable application, with potential in the food industry, plant fertilizers, and pet food, while challenges include energy costs, functionality, and pricing.

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6. Annex

6.1 Interview guideline for expert interviews

Overview of the AgriLoop stakeholder interviews (for intern overview for DSS+/Ecozept only)

Research questions:

1. What are the general market opportunities for xyz?
2. What are stakeholders' expectations regarding the valorization/the function of xyz?
3. What are the actual and potential limits/barriers for xyz?

Table 10: Examined feedstock (in line with examined residue streams of DSS+):

Apple
Tomato
Grape
Potatoes
Brewer's grains

Table 11: Examined end-products

Raw material	Sub-category
PHA	mulch films
	horticultural pots
	twines
	growth protectors
	greenhouses
	nets
	grow/seedling bags
Microbial proteins (for animal feed)	
Extracted proteins (for animal feed)	

Table 12: List of stakeholder groups

Stakeholder category	Sub-group	Feedstock/end-product
Suppliers of residual streams	Arable farmers, horticulture businesses and plant production as far as they produce or re-use by-products themselves	All feedstock (Table 10)
	Food processors	All feedstock (Table 1)
	Traders by-products	All feedstock (Table 1)
Converters, traders and processors of PHA	Converters and users of bioplastics	PHA applications (Table 11
Feed traders and processors of microbial and extracted proteins	Feed traders	Microbial and/ or extracted proteins
	Feed processors	Microbial and/ or extracted proteins
Potential users of microbial and extracted proteins	Livestock farmers	Microbial and/ or extracted proteins

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Potential users of PHA applications	Arable farmers/ horticulture businesses; applied practical research (national research centers, e.g. Landesanstalten in Germany)	PHA applications (Table 2)

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First page for all the following interview guidelines

AgriLoop stakeholder survey – Delphi round 1: Market opportunities, stakeholders' expectations, potential limits and barriers of PHA, microbial and extracted proteins

Last updated 17/07/2023

AF: Important hints
The interviewees will have to sign the consent form if they agree to participate in the study. Please make sure that he or she has received the lime survey link and agreed to the terms before the interview. If it is not the case, remind the expert to open the e-mail and click on the link to fill in their personal information and agree to the displayed terms.
In case the interviewee cannot respond to the question asked, you should first ask him or her if another person within her or his company could answer this question and who it would be. If no one can answer the question, just document it in the records that they do not know the answer.

Name:	Organisation:	Job:
Date:	Country:	Residue-stream/ application:
Website of company Interviewer: *Only for interview administration. Results will be treated anonymously.*		

Formatting guide
Green: adaptions for the individual expert

Introductory words (can be adapted freely according to stakeholder groups)
The AgriLoop project aims at eco-efficiently upgrading underexploited residues into a portfolio of high added-value bio-products. We will develop processes to convert a range of agri-residues (e.g. tomato, potato, livestock sectors) into extracted and microbial proteins, bio-based and bio-degradable material to be used for feed and materials applications, especially by the farming sector without competing with food supply. We are now identifying market opportunities including limitations and try to identify expectations of stakeholders within the value chain.

We thank you very much that you are taking time for this interview. It is important for us to get insights from professionals of the sector. You can obtain a free copy of the resume of this study.

I will document this interview in written form by typing your answers directly into a document and your answers will of course be treated confidentially.

In the AgriLoop project, Ecozept/DSS+ is responsible for the market studies. If you have in-depth questions about the technologies, we are happy to clarify these in consultation with the project partners after the interview.
Is the procedure clear to you? Do you have any questions? Then I will directly start with the first question.

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I. Questionnaire 1 for arable farmers/ horticulture businesses/ plant production / food processors (= suppliers of residual streams)

Block "Introduction and ice breaker":

1. To begin with, please briefly describe your company and your position within the company.
2. Which type of residue stream (apple, tomato, grape, potatoes, or brewer's grains) do you deal with in your company?

Block "strengths and challenges"

3. How do you currently valorize your agricultural by-products of apple-/tomato-/grape-/potato processing/brewer's grains (see Table 1)? (Q6) (additional question)
4. Which are the strengths and advantages in the current valorisation of by-products of apple-/tomato-/grape-/potato processing/brewer's grains ? (Q7)
5. Please describe your challenges regarding the valorisation of your agricultural by-products from apple-/tomato-/grape-/potato processing /brewer's grains (Q34) as of today, e.g.:
   - Transportation
   - Logistics of the required volumes (e.g. storage, regional distribution)
   - Oxidation/ chemical deterioration
   - Smells
   - Limitation for use as fertilizer / as compost component
   - Processing difficulties due to chemical composition (e.g. high lignin content of grape stalk)
   - Limited seasonal availability of feedstock/ poor continuity throughout the year
   - Legislative issues
   - Other _____________
6. How could these challenges be overcome? (Q36)

Block "current structures"

7. When you provide your agricultural by-products for this valorisation pathway, how much do you get paid (*important: ask exactly for which unit the price applies, e.g., per ton wet material, per ton dry material, per cubic meter, etc.)*? Who organizes the transport of the by-products? Who pays for the transportation of the by-products? (Q29)
8. How satisfied are you with your current valorisation of apple-/tomato-/grape-/potato processing/brewer's grains (see Table 1)? Why? (Q8.1) E.g., regarding
   - Profitability
   - Legislation
   - Traditional reasons
   - Personal relationships
   - Effort
   - Other _____________
9. Are you aware of other alternative valorisation pathways that might be better than the current one? (Q8) Yes – No if Yes: Which ones?

Block "expectations"

10. Which would be your ideal solution for the valorisation of your by-products of apple-/tomato-/grape-/potato processing /brewer's grains (see Table 1)? Could you explain, why? (Q8.2) *(Internal remark: if interviewee does not know any other pathways, give examples like conversion in plant proteins, re-use as manure on the farm, produce mulch-films for application on own farm, etc.)*
11. What kind of support would you need for this ideal valorisation of the by-products of apple-/tomato-/grape-/potato processing /brewer's grains (see Table 1)? (Q8.3) E.g.,
    - Financial support
    - Organizational support

- Supportive legislative framework
- Support regarding contact persons/ network/ supply structures
- Other _____________

12. What are your expectations regarding the valorisation of by-products from apple-/tomato-/grape-/potato processing /brewer's grains (see Table 1)? (Q8.4) E.g., regarding
    - Effort
    - Benefits
    - Other ___________

Block „Outlook and perspectives"

13. Do you observe any new interesting solutions in the area of valorisation of by-products from apple-/tomato-/grape-/potato processing /brewer's grains in your professional environment? (Q8.5)
14. In your opinion, where is the development going regarding the use of the by-products from apple-/tomato-/grape-/potato processing /brewer's grains? (Q8.6)

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II. Questionnaire 2 for traders, processors, converters of the end-product PHA

Block "Introduction and ice breaker":

1. To begin with, please briefly describe your company and your position within the company.
2. Which type of residue stream (apple, tomato, grape, potatoes or brewer's grains) do you deal with in your company? OR Which material/ end products (mulch films, horticultural pots, twines, growth protectors, greenhouses, nets, grow/seedling bags from PHA) do you manufacture in you company?

Block 1: Market opportunities

3. How do you assess the market potential of mulch films, horticultural pots, twines, growth protectors, greenhouses, nets, grow/seedling bags from PHA; see Table 2? How do you assess it compared to conventional materials? (Q9)
4. Which factors determine market potential of mulch films, horticultural pots, twines, growth protectors, greenhouses, nets, grow/seedling bags of PHA predominantly? (Q10), e.g.:
    - Logistics
    - Price
    - Legislation
    - Availability of by-products
    - Etc.
5. In how far do you think that mulch films, horticultural pots, twines, growth protectors, greenhouses, nets, grow/seedling bags (Table 2) are the best application of PHA in agriculture? (Q12)
6. Which other applications of PHA are attractive in terms of functionality (e.g., mulch films, horticultural pots, twines, growth protectors, greenhouses, nets, grow/seedling bags, etc.)? (Q13)
7. For which agricultural applications is PHA not suitable? Why? Which functions are missing? (Q14)

Block 2: Stakeholders' expectations

8. Which functions does PHA as material has to fulfill for use in agricultural applications like mulch films, horticultural pots, twines, growth protectors, greenhouses, nets, grow/seedling bags (Table 2)? (Q23)
    - material description:
    - The way consumers use it:
    - Its expected service life:
    - Key features appreciated by consumers:
    - Key features appreciated by industries:
    - Ability to print on the material; example: Printability is key.
    - Etc.
9. Which expectations to mulch films, horticultural pots, twines, growth protectors, greenhouses, nets, grow/seedling bags of PHA do you have regarding its quality? (Q24)
10. In how far is contamination of the material an issue?
11. In case you produce composite products: Which degree of purity do clients ask for mulch films, horticultural pots, twines, growth protectors, greenhouses, nets, grow/seedling bags? Does it have to consist from 100% PHA? Could it partwise be supplemented with, e.g., cellulose? (Q25)
12. How do you assess price development of PHA applications for agriculture, in this case for mulch films, horticultural pots, twines, growth protectors, greenhouses, nets, grow/seedling bags (Table 2)? On which factors does the price development depend? (Q28)

Block 3: Limits and barriers

13. Please describe the challenges regarding the application of mulch films, horticultural pots, twines, growth protectors, greenhouses, nets, grow/seedling bags (Table 2) from PHA, e.g.:
    - seasonal availability of agricultural by-products

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- regional distribution of agricultural by-products
- prices
- transportation
- allocation of feedstock
- availability of feedstock
- processing difficulties
- scalability, etc. (Q34)

14. How could these challenges be overcome? (Q36)
15. How fast could scalability of PHA applications from agricultural residues like mulch films, horticultural pots, twines, growth protectors, greenhouses, nets, grow/seedling bags take place in your opinion? (Q38)

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III. Questionnaire 3 for arable farmers/ horticulture businesses as users of the end-product PHA applications (mulch films etc. according to Table 2)

Block "Introduction and ice breaker":

1. To begin with, please briefly describe your company and your position within the company.
2. Which products made of plastic (mulch films, horticultural pots, twines, growth protectors, greenhouses, nets, grow/seedling bags) do you use in your farm/ business?

Block 1: Market opportunities

3. In how far are bio-based and bio-degradable mulch films, horticultural pots, twines, growth protectors, greenhouses, nets, grow/seedling bags (Table 2) from agri-residues a better solution than products from petrochemicals for you? (Q3)
4. Which further advantages do bio-based and bio-degradable mulch films, horticultural pots, twines, growth protectors, greenhouses, nets, grow/seedling bags from agri-residues have for you?(Q4)
5. Which disadvantages do they have? (Q5)
6. In how far do you think that bio-based and bio-degradable mulch films, horticultural pots, twines, growth protectors, greenhouses, nets, grow/seedling bags (Table 2) are the best application from agri-residues in agriculture? (Q12)
7. Which other bio-based and bio-degradable applications from agri-residues are attractive to you in terms of functionality (like, e.g., mulch films, horticultural pots, twines, growth protectors, greenhouses, nets, grow/seedling bags; see Table 2)? (Q13)
8. For which agricultural applications are applications from agri-residues not suitable for you? Why? Which functions could not be fulfilled compared to conventional materials? (Q14)

Block 2: Stakeholders' expectations

9. Which functions do bio-based and bio-degradable mulch films, horticultural pots, twines, growth protectors, greenhouses, nets, grow/seedling bags from agri-residues have to fulfill for you? (Q23 ff) (e.g., resistance to weather conditions/ snow/ humidity/ high solar radiation, material must last at least 6 months, etc.)
    - material description:
    - expected service life:
    - expected resistance of the material; example: resistance at all point of the value-chain (production, logistics, home storage)
    - Technical requirements related to appearance; example: transparency is not an issue.
    - Etc.
10. In how far is contamination of the material an issue? (Q26)
11. Which degree of purity do you need for mulch films, horticultural pots, twines, growth protectors, greenhouses, nets, grow/seedling bags? Does it have to consist from 100% PHA as material? Could it partwise be supplemented with, e.g., cellulose? (Q25)
12. Under which circumstances would you be willing to pay a higher price for bio-based and bio-degradable mulch films, horticultural pots, twines, growth protectors, greenhouses, nets, grow/seedling bags from agri-residues than for conventional materials? (Q27)

Block 3: Limits and barriers

13. Please describe the challenges for the use of bio-based and bio-degradable mulch films, horticultural pots, twines, growth protectors, greenhouses, nets, grow/seedling bags from agri-residues for you. (Q34)
14. How could these challenges be overcome? (Q36)

Block 4: Outlook and perspectives

15. Do you observe any new interesting solutions in the area of bio-based and bio-degradable mulch films, horticultural pots, twines, growth protectors, greenhouses, nets, grow/seedling bags from agri-residues in your personal surrounding? (Q8.5)

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16. In your opinion, where is the development going with regard to the application of bio-based and bio-degradable mulch films, horticultural pots, twines, growth protectors, greenhouses, nets, grow/seedling bags from agri-residues? (Q8.6)

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IV. Questionnaire 4 for feed traders and processors of the end-product extracted and microbial proteins

Block "Introduction and ice breaker":

1. To begin with, please briefly describe your company and your position within the company.
2. Which type of residue stream (apple, tomato, grape, potatoes or brewer's grains) do you deal with in your company? OR Which material/ end products (mulch films, horticultural pots, twines, growth protectors, greenhouses, nets, growth/seedling bags from PHA) do you manufacture or trade in you company?

Block 1: Market opportunities

3. To which extent could extracted/ microbial proteins fulfill the same purpose as conventional proteins? (Q16)
4. Which functions could extracted/ microbial proteins not fulfill compared to conventional proteins? (Q17)
5. What do you consider to be the best use of extracted/ microbial proteins regarding their functionality (e.g., feed for aquaculture)? (Q18)
6. Which other applications (besides feedstuff) of extracted/ microbial proteins are attractive to you in terms of functionality? (Q19)
7. Which applications are inappropriate for the use of extracted/ microbial proteins? (Q20)
8. In which markets can these proteins be applied? (Q21)
9. How do you assess the market potential for extracted/microbial proteins? (Q22)

Block 2: Stakeholders' expectations

10. Which expectations to extracted/ microbial proteins do you have regarding quality, e.g. regarding:
    - microbial risks
    - contamination
    - toxicity
    - anti-nutritional factors
    - minimum quantities of certain ingredients
    - etc. (Q31)
11. How do you assess the qualities of extracted/microbial proteins compared to conventional proteins? (Q32)
12. Which expectations regarding the qualities of agri-residues as feedstock for processing of extracted/ microbial proteins do you have? (Q32.1)

Block 3: Limits and barriers

13. How does the geographical distribution of agricultural residues (Table 1) influence the production of extracted/microbial proteins? (Q39)
14. How could this logistical challenge be overcome? (Q40)
15. Which other factors limit the market potential of extracted/microbial proteins, e.g.:
    - availability of extracted/microbial proteins as feedstuff
    - legislation
    - consumer acceptance
    - price
    - processing technology
    - infrastructural issues
    - logistics
    - allocation of feedstock
    - competition

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- scalability, etc.? (Q45)

16. How do you assess the costs of conventional proteins compared to extracted/ microbial proteins? (Q41)
17. On which factors does the price of extracted/ microbial proteins depend? (Q42)
18. How do you assess the future development of prices for extracted/ microbial proteins? (Q43)
19. How do you assess the legislation regarding approval of extracted/ microbial proteins as feed (e.g., preferential treatment of extracted/ microbial as feed, impediment of extracted/ microbial as feed, etc.)? (Q44)
20. How do you assess the scalability of extracted/ microbial proteins from agricultural residues? (Q46)
21. What does the scalability depend on? (Q47)
22. How does scalability limit today's market success of extracted/ microbial proteins? (Q48)

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V. Questionnaire 5 for potential users of the end-product extracted/ microbial proteins (=livestock farmers and aquaculture)

Block "Introduction and ice breaker":

1. To begin with, please briefly describe your company and your position within the company.
2. Which types of extracted/ microbial proteins do you use in your farm/ business?

Block 1: Market opportunities

3. Which proteins do you currently use for your purpose? (Q15)
4. To which extent could extracted/ microbial proteins fulfill the same purpose? (Q16)
5. What do you consider to be the best use of extracted/ microbial proteins regarding their functionality? (Q18)
6. Which other applications (besides feedstuff) of extracted/ microbial proteins are attractive to you in terms of functionality? (Q19)
7. Which applications are inappropriate for use of extracted/ microbial proteins? (Q20)
8. How do you assess the market potential of extracted/ microbial proteins (Q22)?

Block 2: Stakeholders' expectations

9. Which expectation to extracted/ microbial proteins do you have regarding quality, e.g.:
    - regarding microbial risks
    - contamination
    - toxicity
    - anti-nutritional factors
    - nutritional qualities
    - amino acid profile
    - digestibility
    - feed conversion ratio
    - minimum quantities of certain ingredients, etc. (Q31)
10. How do you assess these qualities compared to conventional proteins? (Q32)
11. Under which circumstances would you be willing to pay a higher price for extracted/ microbial proteins than for conventional feedstock? (Q33)

Block 3: Limits and barriers

12. Which factors limit the market potential of extracted/microbial proteins, e.g.:
    - availability of extracted/microbial proteins as feedstuff
    - legislation
    - consumer acceptance
    - price
    - processing technology
    - infrastructural issues
    - logistics
    - allocation of feedstock
    - competition
    - scalability, etc.? (Q45)
13. How do you assess the costs of conventional proteins compared to extracted/ microbial proteins? (Q41)
14. On which factors does the price of extracted/ microbial proteins depend? (Q42)
15. How do you assess the future development of prices for extracted/ microbial proteins? (Q43)
16. How do you assess the legislation regarding approval of extracted/ microbial proteins as feed (e.g., preferential treatment of extracted/ microbial as feed, impediment of extracted/ microbial as feed, etc.)? (Q44)

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Block 4: „Outlook and perspectives"

17. Do you observe any new interesting solutions for the use of extracted/ microbial proteins in your personal surrounding? (Q22.1)
18. In your opinion, where is the development going with regard to the use of extracted/ microbial proteins? (Q22.2)

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Last page for all of the interview guidelines above

We are already approaching the end of our interview. I only have some last organizational questions for you.

1. Are there aspects about the topic of the interview that are relevant for you but that we did not consider in our interview? Could you specify them please?

2. Do you know further experts about the topic of the interview who would be interested to participate in the survey?

3. Are you interested in receiving a summary of the results of this study? This document will of course not disclose any confidential information. If yes, I would need your e-mail address, please: ___________________________

The interview is now over. We thank you for your participation.

Postscript of the interview
Anything particularly noticeable during the interviews? E.g. Interruption, tense discussion atmosphere? Did the interviewee give relevant information after the official end of the interview? If so, please note it in the postscript section

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