agriloop

high-value products from agricultural residues through sustainable chains

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Abbreviations

Abbreviation	Term / Definition
B2B	Business-to-Business
B2C	Business-to-Consumer
BSG	Brewer's spent grains
BTBU	Beijing Technology and Business University
CIP/SIP	Clean-in-Place / Sterilise-in-Place
CO_2	Carbon dioxide
CP	Crude protein
Cp/Cpk	Process capability indices
D	Deliverable (project deliverable)
DSS+	DSS+ (consulting partner)
DoA / DOA	Description of Action of AgriLoop Project
EFSA	European Food Safety Authority
EU	European Union
EUG	End-User Group
EPR	Extended producer responsibility
EWR	Evidence-weighted rating / score
FCR	Feed conversion ratio
FCAC	Federació de Cooperatives Agràries de Catalunya
GDPR	General Data Protection Regulation (DSGVO)
GMO	Genetically modified organism
GMP	Good Manufacturing Practice
HACCP	Hazard Analysis and Critical Control Points
HPLC	High-performance liquid chromatography
IAA	Indispensable amino acid
ICP-OES	Inductively coupled plasma – optical emission spectrometry
INRAE	French National Research Institute for Agriculture, Food and Environment
IPR	Intellectual property rights
KPI	Key performance indicator
LCA	Life-cycle assessment
LC/MS	Liquid chromatography–mass spectrometry
LLM	Large language model
ML	Machine learning
MP	(Extracted/) Microbial proteins
MRL*	Market readiness level (*project-internal usage)

Mt	Megaton
NER	Named entity recognition
NLP	Natural language processing
OPEX	Operating expenditure
PE	Polyethylene
PHA	Polyhydroxyalkanoate
PHB	Polyhydroxybutyric acid
PLA	Polylactic acid (also: Polylactide)
POPs	Persistent organic pollutants
PP	Polypropylene
PPO	Polyphenylene oxide
PPA	Power purchase agreement
QDA	Qualitative data analysis
R&D	Research and development
RQ	Research question
SDS	Safety data sheet
SDU	University of Southern Denmark
SKU	Stock-keeping unit
SPC	Statistical process control
SSbD	Safe and Sustainable by Design
TEA	Techno-economic analysis
TRL	Technology readiness level
WP	Work package
WR	Wageningen Research
aw	water activity

1 Executive Summary

The objective of Task 1.1 (Work Package 1) is to analyse the current management of agricultural residues and capture stakeholder expectations for innovative circular value chains. The aim is to identify promising residue streams, regional focus areas, business-to-business (B2B) markets, and Safe and Sustainable by Design (SSbD) criteria and prioritised pathways. This deliverable (D1.3) brings together the desk study and market scoping from D1.1 with evidence from three Delphi rounds to provide an integrated view of opportunities and constraints.

The desk study in D1.1 identified the most promising residue streams by mapping processing hubs, estimating residue volumes via product-to-residue ratios and assessing technical suitability for extraction and fermentation processes. In Europe, the most promising streams identified were tomato, apple, potato, wine grapes and brewer's spent grains; in China, the most promising streams were peanuts, potato, apple, soybean, wine, brewer's spent grains, citrus and corn. Across the portfolio, the priority target products for valorisation remain polyhydroxyalkanoates (PHAs) and microbial proteins (MPs), as these are within the scope of the AgriLoop project.

A clear hierarchy of constraints emerges from synthesising the results from three Delphi rounds (Delphi I-III). Regulation is the dominant constraint, especially for residue-based routes (e.g. eligibility, hygiene and traceability) and for novel foods in human applications, with timing, classification and evidence requirements (such as food safety, migration testing e.g.) being the main considerations. Scalability (reliable, relevant tonnage at tight, reproducible specifications) and price follow as near-equal second-order barriers. When co-location, hub-and-spoke pre-conditioning and dry outbound formats with stable specifications are in place, geography and logistics become design variables rather than hard blockers. Energy is a key lever for both operating expenditures (OPEX) and Life-cycle assessment (LCA), with drying being the main hotspot. Site energy strategy and formulation/equipment choices can significantly impact price per kilo and grams of CO_2 equivalents per kilogram (gCO_2e/kg). Feedstock classification (waste versus by-product) and traceability determine front-end eligibility for food and feed uses, and therefore the feasibility of downstream dossiers.

For microbial proteins, the near-term market path is as follows:

(i) aquafeed first, conditional on protein tier and a fishmeal-adjacent indispensable amino acid profile with high digestibility, with palatability managed via staged inclusion;

(ii) pet food, as a bridge for pricing and dossiers (digestibility, palatability, and simple health markers); and

(iii) human food, once sensory parity, 'as-processed' techno-functionality, cost-in-use, and authorisation are aligned.

For PHA, stakeholders emphasise application fit (i.e. material properties against target use), reducing costs through scaling up and reducing process complexity, and clearer regulatory and end-of-life frameworks to enable broader substitution.

These findings have practical implications. A regulatory-operations track involving early scoping, dossier templates and coordinated expert endpoints should run in parallel with market development. Pilots should remain within eligible inputs and contexts while broader approvals are finalised. Supply chain design should secure affordable, stable residues via multi-year contracts, minimise 'water miles' through co-location and hub-and-spoke preconditioning, and transport dry, free-flowing stock keeping units (SKUs) with defined physical and chemical specifications. The energy strategy should be co-designed with the formulation and equipment to lower added moisture, ensure suitable dryer architectures, provide clean/low-cost heat and power and integrate waste heat. This should be tracked via kilowatt-hours per kilogram (kWh/kg) and gCO_2e/kg. Adoption is evidence-led: claims-ready packages (for food, as-processed functionality and safety; for feed/pet food, digestibility/palatability and handling; and for both, site-specific LCA/energy Key performance indicators (KPIs)) should be tied to transparent cost-down milestones and capacity increases. Taken together, the programme converts residue availability and stakeholder interest into bankable offtakes while staying within SSbD guardrails.

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2 Introduction

2.1 Description of Work Package 1

The tasks and results that are the object of this Deliverable Report are embedded in Work Package 1 “Foundational circular & strategic flows” that is led by partner Wageningen Research (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 agricultural residue 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 deliverable report describes the methodology that we applied, provides final results as well as an outlook for the next steps.

2.2 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 description of action (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 MP from agricultural 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, AgriLoop project partner 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 End-User Group (EUG) and the main targeted value-chains were interviewed using qualitative research methods to investigate the market potential. The preliminary results led to the previous progress report (D1.2). This report (D1.3) of Task 1.1 includes the final results of the stakeholder assessment of the market and business potential.

3 Applied methods

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

More detailed information about the methods for data collection are given 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.

3.1 Desk research

As the conduction of the first stage survey is aspired at the 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 agricultural residues biorefineries etc."
- "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 preparing the expert interviews like descriptions of the market for agricultural residues, challenges of promising end-products like PHA and MP, current structure of valorisation of agricultural residues.

3.2 Identification of practical opportunities: promising residue streams, regional focus areas, relevant applications and B2B markets assessment in Europe

The promising residue streams, regional focus areas and relevant applications, as well as the assessment of B2B markets in Europe, were evaluated in D1.1, Chapter 2.2, and are therefore summarised briefly in this report. More detailed information can be found in D1.1.

The qualitative analysis indicates that Europe's agri-food system produces significant quantities of predictable by-products that are concentrated in a few processing hubs. While agricultural production is spread across different climates and soils, processing is concentrated in specific areas. For example, tomatoes are processed in Mediterranean regions, potatoes in the north-west, apples in Central Europe's juice industry, wine in the Italy–France–Spain area, and beer in Central and Western Europe. This creates reliable sources of raw materials for biorefinery processes targeting proteins and peptides, polyphenols, cutin/suberin, carotenoids, and fermentation-ready carbohydrates. Methodologically, we focus on industrial side streams rather than primary field residues, and on processing rather than production. This is because fresh-market dynamics and trade flows decouple where crops are grown from where residues arise. For each stream, we estimate the processed volumes by country using industry statistics or a proxy main product. We then apply literature-based product-to-residue ratios and cross-check the totals against independent sources to enable like-for-like comparisons. This approach also clarifies regional anomalies, such as Germany's leading role in apple juice processing despite ranking only fourth in apple cultivation, due to inflows of Polish apples and concentrates.

Several recurrent patterns shape opportunities across streams. Breweries provide the largest continuous solid flow in terms of scale and regularity—about 7 megatons per year (Mt/year) of wet brewer's spent grains (BSG) across the EU—on a near-daily basis that is amenable to local aggregation, drying or direct wet use. Similarly large in aggregate, wine residues (pomace, stems and lees) are seasonal, but cooperative centralisation in Italy and Spain reduces collection complexity. The potato processing industry generates approximately 1.7 Mt/year of peels and starch-rich fines, primarily concentrated in Belgium, the Netherlands, Germany and France. Tomato pomace is smaller in volume (0.43–0.50 Mt/year), but it is attractive in terms of its composition (carotenoids and oil-bearing seeds), and it is produced in tightly clustered Mediterranean processing plants. Apple pomace from juice production is comparable in volume (0.8 Mt/year), and Germany and Poland dominate once concentration dynamics are considered. The feasibility is then determined by logistics: moisture and seasonality dictate whether near-site wet valorisation (e.g. BSG), stabilisation by drying/ensiling or campaign processing during the wine and tomato seasons is optimal. Incumbent offtakes (e.g. biogas for potato peels) set floor prices that can anchor higher-value extractive layers. The composition of the pomace determines its value: BSG's arabinoxylans and proteins enable food and materials applications and can be used in fermentation processes after pretreatment; grape pomace contains market-ready polyphenols and seed oils with hydrolysable sugar fractions; tomato pomace contains lycopene-class carotenoids, fibre and seed oil, which can be used for on-site valorisation as processors currently pay for its removal; potato peels contain phenolic compounds and starch fines, which can be used for dual extractives-plus-energy applications; and apple pomace is polyphenol-rich but microbiologically unstable, requiring rapid stabilisation and cascading designs that prioritise extracting the polyphenols before the energy/ other materials.

Market entry is business-to-business and specification-driven. Buyers expect clear specification tiers (e.g. protein, moisture and particle size), evidence of processability through conditioning, extrusion and drying (including pellet durability and fines where relevant) and trial packages that demonstrate the link between inclusion and performance (e.g. intake, feed conversion ratio, growth, survival, palatability and health markers). Feed-oriented regulatory documentation (e.g. Hazard Analysis and Critical Control Points (HACCP)/Good Manufacturing Practice (GMP), contaminant screens and residue-route traceability) usually reduces the time taken to adopt a product relative to the food industry. Prioritisation therefore emerges at the intersection of volume, centralisation, and product fit. BSG is the most immediate pan-EU opportunity, given its scale and cadence, as well as its multiple outlets (feed, ingredients, fermentation and biomaterials). Grape pomace follows, thanks to cooperative logistics and its high-value polyphenols and oils. Potato peels in the north-west corridor offer scale, with existing energy offtakes that can be upgraded via extractives. Tomato pomace in Italy, Spain and Portugal is well suited to co-located carotenoid and seed oil recovery. Finally, apple pomace in Germany and Poland is attractive where stabilisation or dryer co-location exists. However, two caveats qualify this outlook. Firstly, many streams already have incumbent uses (e.g. feed and biogas), which cap near-term margins but de-risk supply and cash flow. Secondly, in a subset of countries, processing volumes required proxy estimation; however, triangulation with independent totals yielded close agreement. Overall, Europe's processing clusters offer large, reliable and compositionally rich side streams whose centralisation aligns with biorefinery and fermentation value chains. A pragmatic approach — starting with low-risk outlets and rapidly adding extractives and materials where the composition allows for a premium — balances logistics with achievable specifications, positioning side-stream valorisation as environmentally and commercially compelling.

3.2.1 Examined end-products

Based on the desk research and the analysis of promising residue streams in chapter 3.2.2 promising end products were identified. Due to the aim to demonstrate the possibility to produce at integrated pilot scale, PHAs as well as MP are examined in pilot plants. The high-value agricultural 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

With the help of the stakeholder interviews the industry's expectations and needs, as well as their assessments on the examined end-products will be identified. The Delphi interviews will also help to identify bottlenecks.

3.3 Research and surveys on expert level

In the following chapter the methodology of the Delphi survey is described in detail. We describe the general methodology of Delphi and the process of Delphi surveys in AgriLoop, as well as the development of research questions, hypotheses and questionnaires. We also discuss the selection of the Delphi panel and describe its representativeness. Finally, the collaboration with INRAE to optimise the synergies and interaction between the iterative interviews and the innovative computational methods is described.

3.3.1 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. 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 complex to investigate (Bui et al., 2021; Conchin and Carey, 2018; Haber and Schärli, 2021).

A first round of interviews ("Delphi I"), characterized by mainly open questions 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 stir 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 3 rounds in total. This is shown in Table 1.

Table 1: *Overview of the framework for Delphi expert survey (Own compilation by Ecozept).*

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	Data collection finished
Delphi III	May-Sept 2024	Qualitative	Validation, consolidation and supplementing of results	Phone interview	Data collection finished

3.3.2 Development of research questions hypotheses

To develop the hypotheses for Delphi, we have compiled research questions based on the desired results in the description of action[1], desk research on the latest scientific publications and taking into account the target stakeholder groups. The research questions (RQ) 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 used them to formulate hypotheses. The hypotheses relate directly to the research questions and operationalize and concertize them. The answer to the hypotheses is given by the answer to the questions within the questionnaire and the answer to the hypotheses in turn answers the overall research question. The formulated research questions are listed below:

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

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.

MP

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

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.

[1] Description of Action of the AgriLoop project.

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

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.

3.3.3 Development of the questionnaires

Subsequently to the creation of the research questions and hypotheses, Ecozept drafted a questionnaire with corresponding topics for the experts' assessment of the market potential of the innovations, the experts' expectations regarding the AgriLoop innovations and the experts' needs regarding implementing innovations. In the following the main thematic fields that were explored in the questionnaires are presented. The aim of the third round of stakeholder interviews was to confront interviewees with pre-formulated hypotheses forged in previous interview rounds or derived from literature to verify these results (Frewer et al., 2011; Okoli and Pawlowski, 2004; Padel and Midmore, 2005). The questionnaire will, inter alia, also include those topics that did not reach consensus during the second round. The final version of the guidelines and questionnaires are attached in the Annex of this deliverable deport:

Delphi I:

Valorisation:

Current valorisation of agricultural by-products, strengths and advantages in the current valorisation, challenges regarding the valorisation, 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 agricultural residues as feedstock for processing of MP, willingness to pay; influence of geographical distribution agricultural residues, logistical challenges, other factors limit the market potential, assessment of the costs compared to conventional proteins, price, future development of prices, legislation regarding approval of microbial proteins as feed, scalability.

Delphi II

Valorisation:

Current valorisation of agricultural by-products, financial compensation for providing your agricultural by-products, importance of agricultural by-products to the current value chains, satisfaction with the current valorisation, assessment on PHA as an alternative pathway, assessment on positive effects through valorisation, benefits of PHA and MP as an alternative pathway, validation of identified challenges, solutions to existing challenges, expectations on ideal valorisation, assessment on valorisation of residues to PHA as an ideal valorisation process, assessment on crucial factors for ideal valorisation, specification of financial support, expectations in terms of input and output generated, assessment on PHA applications for agriculture, willingness to pay, promising valorisation pathways.

PHA:

Assessment on market potential, validation of previously identified determining factors for market potential, validation of best applications for PHA in agriculture, Perception on competitiveness of PHA compared to conventional alternatives, further attractive applications for PHA, inappropriate applications for PHA, expectations on functional requirements, expectations on specific features for practical usability, Assessment on issue of contamination, validation of previous assessment on supplementation of PHA, Assessment on price development, identification of price factors, validation of previously identified main challenges to the market potential, solutions to current challenges, assessment on scalability.

Extracted/ microbial proteins:

Validation of previous assessment on market potential of MP, assessment on suitable markets, identification of specific functionalities or characteristics of MP, identification of not-existent functionalities, best practical usage of MP, identification of promising applications for MP, expectations on quality and functional requirements of MP, qualities of MP compared to conventional proteins for feed / food, expectations on the qualities of agricultural residues as feedstock for processing of MP, assessment on influence of geographical distribution of agricultural residues on the production of MP, validation of previously identified challenges to the market potential of MP, Identification of factors influencing the price of MP, willingness to pay, assessment on price development, assessment on legislation regarding MP, assessment on scalability of MP, Identification of factors influencing the scalability of MP.

Delphi III

PHA:

Validation of mulch films and horticultural pots as key applications, framed process to produce PHA from residues, standards for reliability of mulch films and clips, key characteristics for leaving PHA in soil, blending/supplementation for PHA applications, factors to ensure proper biodegradation, contamination assessment of raw material/end-application, ranking and justification of barriers for PHA market potential, assessment on production by-products/waste, assessment on production maturity, assessment on legislation: importance and effects, assessment on price competitiveness of PHA, end-user understanding of PHA.

Extracted/ microbial proteins:

Assessment on market potential of MP and suitability for food, aquaculture and/or poultry; other potential applications; inappropriate applications, arguments for price justification & advantages, specifications for formulation needs, specifications on functional requirements (ranking of essential properties), assessment on amino-acid priorities for target species, comparative assessment vs conventional proteins, process & quality control: routes to homogeneous MP, assessment on price drivers, assessment on legislation & approval, energy hotspots and reduction options, health & environmental risks from using agricultural by-products, ranking and justification of barriers for PHA market potential

3.3.4 Selection of Delphi panel and representativeness of the stakeholder group

The Delphi method is a research technique used to obtain a consensus from a panel of experts in the relevant field through several rounds of questioning. One of the most important phases of the Delphi technique is constituting a Delphi panel by identifying individuals who have the knowledge and expertise on the subject-matter of the study. This phase is essential because the validity of the results depends on the competence and knowledge of the panel members. (Brady, 2015; Habibi et al., 2014; Sablatzky, 2022). In other terms, the Delphi method seeks representativeness less through quantities or size of the sample than through the method that helps to achieve 'representativeness of ideas'. One of the greatest qualities of the Delphi method is its iterative nature, which allows new issues to be raised and for participants to evaluate and compare their own knowledge, opinions and responses with those of others. Consequently, the Delphi methodology itself allows the results of the previous round to be verified. The experts check and verify the statements of their colleagues in the same stakeholder group (Lilja et al., 2011). This principle is applied within the stakeholder interviews of the AgriLoop project. Through iteration and the type of questions asked, the survey goes beyond the group of respondents and thus allows a representative assessment of the real market needs. Indicators for achieving representativeness are:

(1) The statements start to repeat themselves.

(2) Consensus is reached in the iteration.

Within AgriLoop, the target group of stakeholders is clearly defined in the Grant Agreement, more precisely in the Description of Activities: farmers, residue traders, feed, food, biochemical and material producers and users, investors, legislators, policy makers, consumers. The experts in the fields of interest were identified by the consortium partners, as they are experts in their field, have excellent networks within the industry and have targeted contacts. The list of experts was supplemented by the results of the desk research. The experts were selected according to their area of expertise. Experts were also identified from across Europe in order to identify regional differences in expert judgements. Finally, the snowball sampling technique was used during the Delphi rounds. Snowball sampling is one of the most common approaches to sequential sampling. This type of sampling is a non-probability method that is also randomly selected. This method is suitable when the members of a group or community cannot be easily identified. In this method, the researcher first identifies some people and after receiving the information, he/she wants them to introduce other people (Habibi et al., 2014).

The research questions and hypotheses were formulated according to the Delphi method and taking into account the identified target stakeholders. In order to best address the target stakeholders, the questions to answer the research questions and hypotheses were divided into 5 questionnaires. Each questionnaire is aimed at specific target groups:

Table 2: Overview on questionnaires and their specific target groups (Own compilation by Ecozept).

Questionnaire	Target group	Stakeholders of target group
Questionnaire 1:	Suppliers of residual streams	Farmers, residue traders, plant production, food processors
Questionnaire 2	PHA industry	Traders, processors, converters of the end-product PHA, investors
Questionnaire 3	Users of the end-product PHA	Arable farmers/ horticulture businesses as users of the end-product PHA applications
Questionnaire 4	Feed and Food industry	Feed traders and processors of the end-product extracted and microbial proteins & food producers
Questionnaire 5	Potential users of the end-product extracted/ microbial proteins	Livestock farmers and aquaculture, protein producers

The first round of Delphi interviews focused on farmers and end users of PHA applications. The second round focused on producers, traders and processors of PHA, as well as producers of extracted and microbial proteins, since many topics had been identified as areas of disagreement during the first round, and new topics had also emerged.

The third and final round further deepened the research within the target group of producers, traders and processors of PHA, as well as producers of extracted and microbial proteins, in order to reach a consensus on topics of interest. The target group of farmers was not included as no increase in knowledge was expected without presenting product briefs to farmers to obtain assessments of the final products (WP4, task 4.4). Finally, as described above, is that the overall aim of the Delphi method is to ensure that all target groups are adequately and equally represented, thus achieving representativeness of ideas and consensus for the targeted stakeholder groups.

3.3.5 Conduction and analysis of the stakeholder interviews

The conduction of the Delphi method can be divided into three phases.

The **first phase** is the preparation of the interviews. In this phase, the research questions described in 3.4.2 were formulated on the basis of the research objectives in the description of the action[2], desk research of recent scientific publications and consideration of the target stakeholder groups. On this basis, hypotheses were formulated, and questionnaires were designed to evaluate the hypotheses. The Delphi I and II guidelines contain the questionnaires presented in Annex I and Annex II. The Delphi II guideline was adapted on the basis of the Delphi I results and aimed at validating these results. In addition, the format of the survey was determined in preparation for the Delphi survey. For Delphi I and II, a qualitative survey format was defined in the form of open questions within a semi-directive questionnaire. The questionnaires were tested in two staged pre-tests. The first test was carried out internally with the research team. The second test was carried out with an external expert. Phase 1 did not end until the questionnaires had been validated twice.

As a first step in the **second phase**, 'Conduction', the experts for the panel were then identified as described in 3.3.4. The experts in the areas of interest were identified by the consortium partners as experts in their field, with excellent networks within the industry and targeted contacts. The list of experts was supplemented by the results of the desk research. The next step was to make initial contact with each expert by telephone. They were briefly informed of the aim of the project and asked if they would be willing to participate in an interview. We decided to motivate the experts non-monetarily by promising them early access to the results. If they agreed, further information about the project was provided in a short email. Participants had to agree to take part in the interviews by completing a consent form on a self-administered online form. The interviews were conducted using a phone/visio conferencing tool and the interview language was English, French, German and Spanish. The interviewees' answers to the interviewers' questions were transcribed directly into a Microsoft Word document and served as the basis for the analysis.

Finally, in the **third phase** 'Analysis', the results of the qualitative interviews were analysed by Ecozept using the MAXQDA software. The approach is a thematic qualitative text analysis to reduce the large amount of qualitative data. The analysis is based on a defined code system, which structures the data according to codes derived from existing literature (deductive codes) and codes derived directly from the interviews (inductive codes). In Delphi I, a code system was created by one researcher and then validated internally by a second researcher. After this, each interview transcript was encoded using the code system. The codes were then combined into summaries. In the main analysis step, the individual codes and summaries were used to compare the assessments, expectations and needs of each expert for each question. The aim of the analysis is to identify consensus, analyse disagreement and sentiment, interpret the results and draw conclusions for recommendations for action in preparation for the second round of stakeholder interviews. Table 3 gives an overview of the Delphi approach used in AgriLoop.

[2] Description of Action of the AgriLoop project.

***Table 3:** Overview of the Delphi approach carried out in AgriLoop (Own compilation by Ecozept based on* (BEIDERBECK ET AL., 2021)*).*

Preparation *(Phase One)*

Desk research
- *Screening and analysing scientific papers*

Initial conceptualization
- *Research goal: practical contribution*
- *Research setting: future based*
- *Delphi questionnaire: context-related*

Formulation sessions
- Formulation of research questions, hypothesis, questions based on research
- Iterative refinement
- Question formats (e.g. flexible, fixed, multiple dates), related information, and additional questions

Project pre-test
- *Pre-test with research team*
- *Pre-test with external experts*

Conduction *(Phase Two)*

Software selection
- *Technical Delphi requirement*
- *Selection of MAXQDA software*

Expert selection
- *Expert selection: Expert nomination, desk research and snowball sampling*
- *Selection criteria: Areas of expertise*
- *Expert motivation: non-monetary*

Conduction of survey
- *Survey format: Qualitative, context related survey*
- *Format of questions: Open questions within a semi-directive questionnaire*
- *Survey conduction: time-related, consensus-related*

Expert follow-up
- *Appreciation for participation*
- *Invitation for follow-up discussion, meetings*

Analysis *(Phase Three)*

Descriptive statistics
- Qualitative analyses
  - *Definition of code system*
  - *Validation of code system*
  - *Syntax and content analysis*
- Quantitative analyses (planned for third round)

Sentiment analyses
- *Experience and expertise*
- *Level of confidence*
- *Level of optimism*
- *Positive and negative affect*

The interviews in the first round of Delphi with an overall number of 17 experts were conducted from June until August 2023. The interviews of the second round of Delphi with an overall number of 17 experts were conducted from May to September 2024. The interviews of the third round of Delphi with an overall number of 13 experts were conducted from May to October 2025. The survey sample comprised a large spectrum of different kinds of experts. The different characteristics of the participants are depicted in Table 4.

Table 4: *Study sample for Delphi I- III (Own compilation by Ecozept).*

Expertise	**First round of Delphi interviews (Delphi I)**	**Second round of Delphi interviews (Dephi II)**	**Third round of Delphi interviews (Dephi III)**
	Number of interviews	Number of interviews	Number of interviews
Total	17	17	13
Residual streams/ valorisation	9	3	
Bio-engineering/ Biopolymers	2	4	3
PHA/PHB	4	4	3
Extracted/ microbial Protein	2	6	7
Country			
Germany	3	1	3
Spain	7	3	2
Belgium	1	1	2
France	3	4	1
Netherlands	1	3	/
Australia	1	/	/
Switzerland	1	/	/
Ireland	/	1	/
Denmark	/	1	/
United Kingdom	/	1	/
Norway			4
Canada			1
Type of company			
suppliers of residual streams	9	2	/
traders, processors, converters of PHA	3	8	6
users of the PHA applications	3	1	/
feed traders and processors of extracted and microbial proteins	2	6	7
Position of the interviewee			
Management	7	5	3
CEO	2	3	3
Coordinator	1	3	1
Production manager/ director	2	2	2
R&D manager	4	3	4
Chief New Business Officer	1	1	

3.3.6 Set up of the product brief

As the first, second and third round of the Delphi method are aimed at identifying the market potential and readiness of agricultural-residue-based products, there is no specific product brief. The product briefs are developed and adapted during work package 4, task 4.4, in order to present them to participants in the B2B market study. The B2B market study will be based on the results of DL 1.3.

3.3.7 Outlook: B2B market studies

In anticipation of WP4—Task 4.4 (B2B market studies for specific end-products), the outputs of Task 1.1 will be directly incorporated into the design and execution of the market studies. The segmentation, SSbD guardrails, evidence architecture, and price per function framing developed in this study have already been distilled into product briefs (use case, service window, target end-of-life, grade/formulation hypotheses, and required evidence pack). These briefs will serve as the foundation for buyer interviews and procurement decision criteria in Task 4.4, thereby ensuring a seamless transition from early opportunity mapping to the validation of investable demand. In summary, Task 1.1 provides the analytical foundation and the standardised briefs that inform and structure the B2B studies in WP4.

3.3.8 Collaborative approach with INRAE - Annotation-supported coding for criteria identification and preference aggregation

In the course of the work undertaken in WP1, task 1.1, there was intensive cooperation between INRAE and Ecozept. The collaboration facilitated the optimisation, facilitation and validation of the qualitative research conducted during the stakeholder interviews. The subsequent section delineates the outcomes that have been accomplished. The work completed thus far is to be further developed by all parties, as it has not yet been finalised.

3.3.8.1 Automation of interview response categorization

Data coding is a core step in qualitative data analysis (QDA), in which interview responses are annotated using a dedicated coding system (see Figure 1). Grouping segments with the same code then facilitates subsequent analyses outlined above. In this project, coding is performed manually in MAXQDA. Due to the AgriLoop hierarchy comprising 145 codes organised across five levels in Delphi I, manual coding is labour-intensive and therefore a candidate for automation. Accordingly, a methodology that supports annotation has been developed and is now being applied within the project. This methodology can also be transferred to other projects (Koptelov et al., 2025)

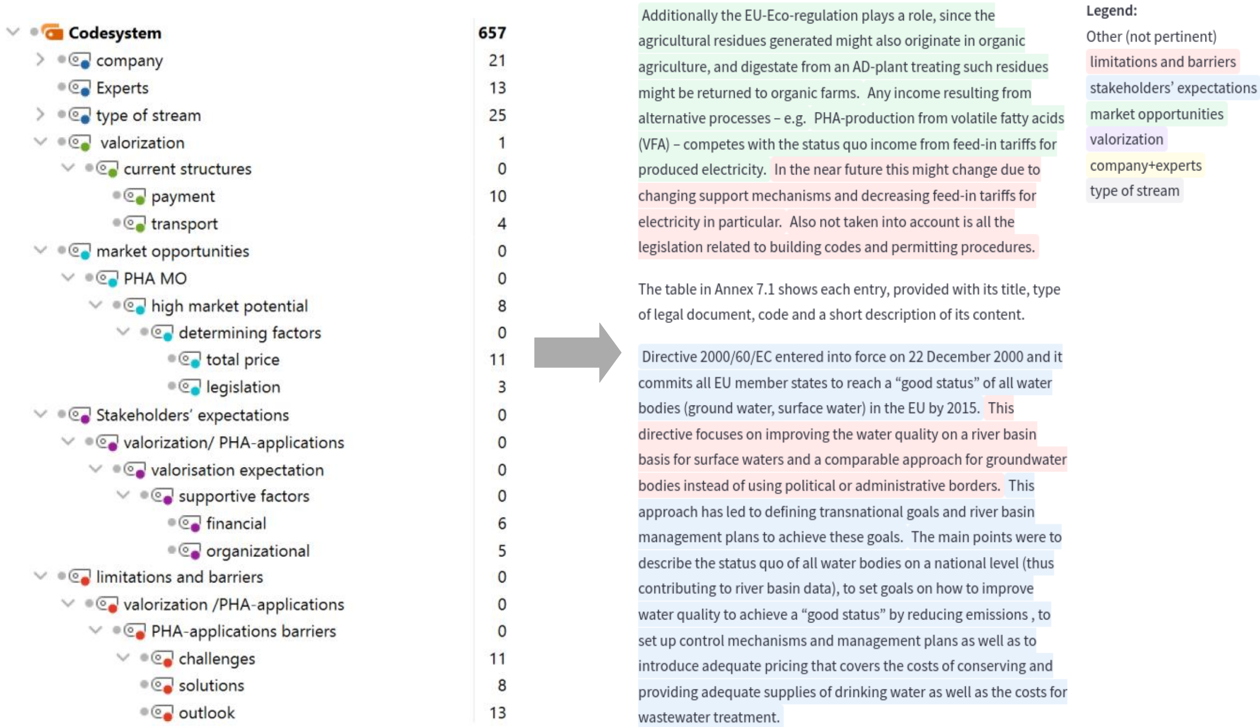


Figure 1: *Example of a code system (left) and text annotated at the sentence level using some of the codes from this system (right).*

The methodology proceeds in two stages. First, a subset of the Delphi I material is manually annotated to provide sufficient training examples for a machine-learning classifier. The trained model is then used to provide annotation support. Where annotations are insufficient, additional labelled data is generated synthetically using a large language model (LLM) together with relevant corpora from other projects and/or public databases (see Figure 2). In this study, material from the NoAW (No Agricultural Waste) project was used to produce further examples. This approach is domain-agnostic and can be transferred to other automated text-coding contexts.

To demonstrate its applicability, a graphical interface tool (AgriCode) was developed for the automatic categorisation of interview responses. AgriCode can predict Ecozept's taxonomy at Level 1 (seven categories) and at Levels 1–2 combined (15 categories), with inference at paragraph or sentence granularity (see Figure 1). On Delphi I data, accuracies reached 87% (paragraph) and 79% (sentence). Fine-tuning using synthetic data generated by LLMs and external sources improved performance by up to 3%. Evaluation on Delphi II data showed accuracies of up to 80% (paragraph) and 61% (sentence), demonstrating promising transferability (Koptelov et al., 2025).

Current limitations include a restriction to two taxonomy levels, as well as lower performance for finer-grained classes. These issues can be resolved through methodological refinements. A key area for future research is the development of a fully LLM-based coder that can map interviews and other texts to arbitrary hierarchical taxonomies using a small number of examples per category.

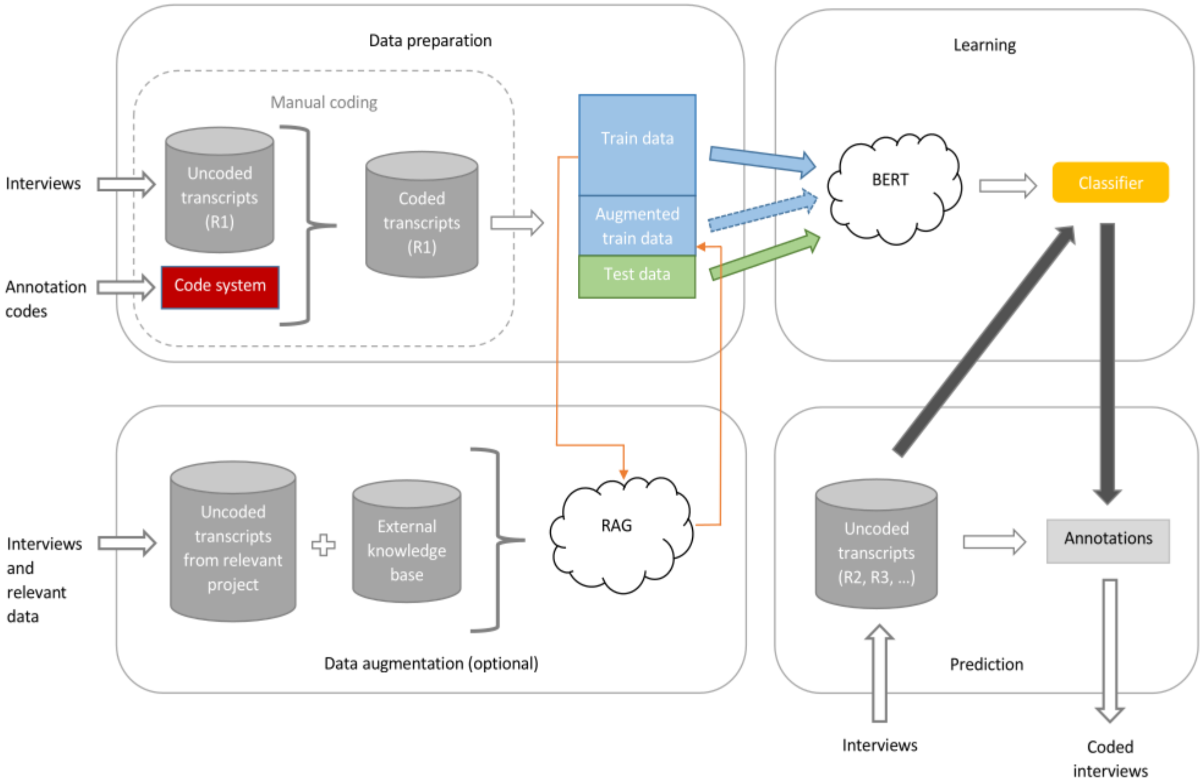


Figure 2: *Workflow of our methodology for annotation support in QDA illustrating the various phases and their interactions.*

3.3.8.2 Criteria identification and ranking

Once the interview responses have been coded, important criteria can be identified. This step is performed manually by analysing the most important arguments and excluding responses that are not relevant to the research question. For example, in response to the research question 'What are the main issues and challenges for PHA applications?', the following criteria were identified as the most frequently mentioned responses in Delphi I: 'Availability of by-products', 'development', 'legislation' (administrative barriers) and 'price'. Once the criteria have been identified, they need to be ranked to determine the most and least important ones. The simplest frequency-based approach can serve as a baseline for this ranking. Criteria ranked in this way by an expert produce a result, as illustrated in Figure 3.

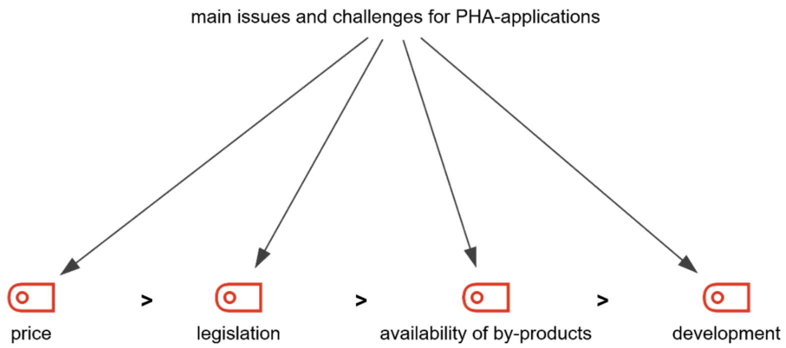


Figure 3: *Main issues and challenges for PHA applications and their ranking as determined by an expert based on Delphi I interview responses.*

3.3.8.2.1 *Frequency based criteria ranking*

Another specialised tool has been developed to automate this process. Our ValoNER tool is based on text mining and searches expert responses for entities associated with the user-entered criteria. It highlights these entities in the text and counts their frequencies (Figure 4).

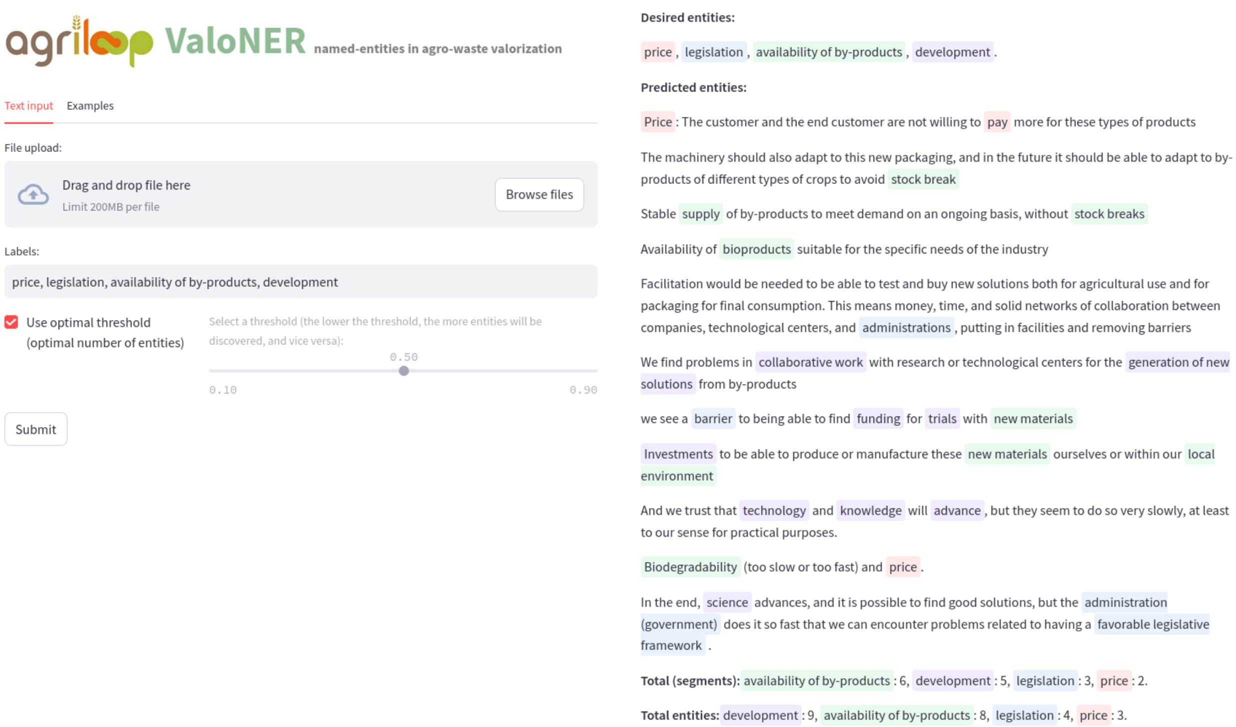


Figure 4: *The ValoNER interface: uploading the file with interview responses and entering criteria (left), highlighted entities found (right), and the final criteria ranking (bottom right).*

To develop this tool, seven documents covering different research questions (three from Delphi I and four from Delphi II) were annotated and several state-of-the-art Named Entity Recognition (NER) models were evaluated. A named entity typically refers to a real-world object such as a person, location, organisation or product identifiable by a proper name. The present task, however, departs from this standard definition by targeting broader conceptual categories rather than conventional named entities. Accordingly, a universal NER approach was selected, capable of recognising user-defined concept types beyond geopolitical or domain-specific taxonomies.

Three models—UniversalNER, Gliner and NuNER—were assessed on the annotated corpus, with the best-performing model achieving up to 51% F1-score (performance indicator used to measure model accuracy). To improve performance, synthetic data were generated because the manually annotated material alone was insufficient for fine-tuning (Appendix 3). An LLM-based procedure, seeded with the first three documents as examples, produced additional labelled data for training. Fine-tuning on this augmented set increased F1-score to as much as 80% on the three seed documents used for data generation and up to 66% on four test documents that were previously unseen by the model (Appendix 4). The best-performing model was subsequently adopted for implementation.

ValoNER is intended to support manual criteria ranking and error detection in qualitative data analysis for projects with contexts similar to AgriLoop. As with AgriCode, the workflow is portable to other domains. Development is ongoing, and further gains are expected through methodological refinements, for example by optimising model hyperparameters during fine-tuning.

3.3.8.2.2 *Criteria ranking based on explicit ranks and justifications*

In order to achieve a more advanced ranking that takes into account not only frequencies of responses but also explicit ranks and reasons given by respondents, we develop another approach. This approach would improve collective decision making in the current project, automate preference aggregation, and increase the transparency and interpretability of the whole methodology.

For this purpose, respondents in Delphi II and III were asked to explicitly rank the criteria and provide justifications for their choices. The first aggregated, collaborative ranking can be computed without considering justifications, for example by using the Borda count method (Young, 1974). Table 1 illustrates the rankings identified by industry experts in Delphi II and the process of calculating the Borda ranking. This results in the following final ranking (without taking justifications into account): *Price of PHA (17) > Scalability of PHA (14) > Production of PHA (9) > Durability of PHA (8) ≈ Availability of feedstock (8) > Logistics in PHA (2)*. This approach provides a more accurate result because it relies on explicit expert rankings and a deterministic, fully reproducible mathematical model. In other words, the final ranking will always be the same if the same method is applied.

Table 5: *The main barriers to the market potential of PHA and PHA end-products, their ranks as identified by industry experts in Delphi II, and the aggregated ranking computed using the Borda method.*

N	Criterium	Stakeholder	Rank (1-6)	Borda count (w/o justifications)		
				Score	Total	Rank
1	Scalability of PHA	Stakeholder 1	1	5	14	2
		Stakeholder 2	2	4		
		Stakeholder 3	4	2		
		Stakeholder 4	3	3		
2	Price of PHA	Stakeholder 1	3	3	17	1
		Stakeholder 2	1	5		
		Stakeholder 3	1	5		
		Stakeholder 4	2	4		
3	Production of PHA	Stakeholder 1	2	4	9	3
		Stakeholder 2	6	0		
		Stakeholder 3	5	1		
		Stakeholder 4	2	4		
4	Durability of PHA	Stakeholder 1	4	2	8	4
		Stakeholder 2	3	3		
		Stakeholder 3	3	3		
		Stakeholder 4	6	0		
5	Availability of feedstock	Stakeholder 1	5	1	8	4
		Stakeholder 2	4	2		
		Stakeholder 3	2	4		
		Stakeholder 4	5	1		
6	Logistics in PHA	Stakeholder 1	6	0	2	5
		Stakeholder 2	5	1		
		Stakeholder 3	6	0		
		Stakeholder 4	5	1		

A key limitation of the classical Borda count is that it disregards the reasoning behind experts' rankings, meaning that contradictory arguments can produce inconsistent outcomes. To address this issue, a conflict-resolution methodology is required to reconcile arguments and compute final rankings. The workflow, which was previously developed in a related context (Bisquert et al., 2025), involves capturing expert inputs in the **DAMN** tool, performing structured reasoning by identifying and evaluating arguments with the **ELDR** engine, and feeding the

ELDR results back to the DAMN tool to visualise the argumentation graph (areas of agreement and disagreement). A Rank Sliding procedure then adjusts the individual rankings accordingly to produce updated, justified ranks (see Figure 5).

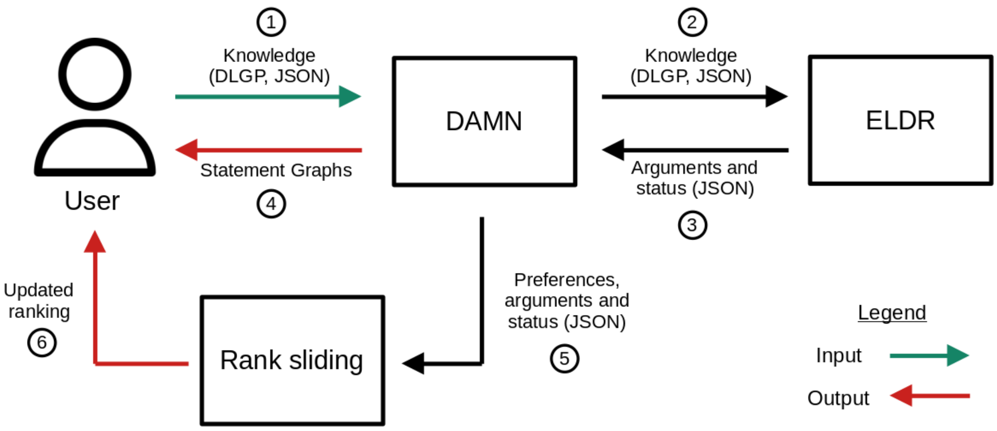


Figure 5: *Workflow for updating rankings by taking justifications into account.*

The main bottleneck of this approach is that justifications must be represented in a special logical language (in the form of conjunctions and implications) adapted for input into DAMN. For instance, "Logistics in PHA is not important criterion because it is more complex than in fossil alternatives" can be represented as the following implication:

isMore(logistics_in_PHA,fossil_alternatives,complex) -> importance(logistics_in_PHA,low).

In the ranking aggregation framework, this conversion is performed manually, which is highly labor-intensive. To automate the process, we developed an AI-based pipeline that converts justifications written in natural language into the logical language required by our methodology (Figure 6).

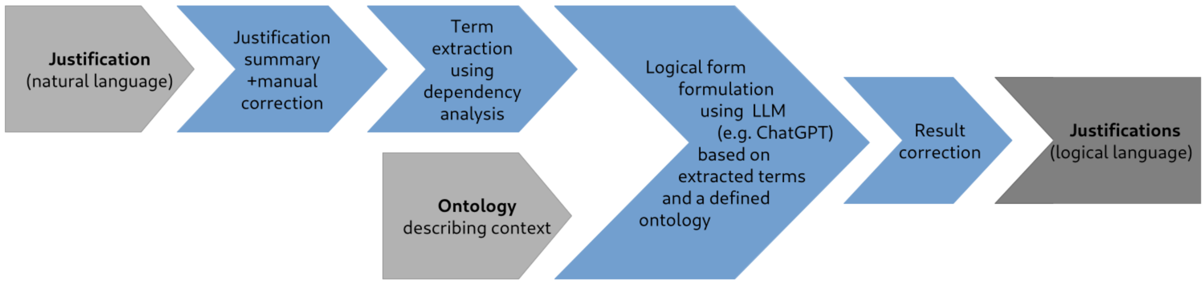


Figure 6: *Pipeline illustrating the steps in converting justifications from natural to logical language (blue shapes indicate actions, while grey shapes indicate inputs and outputs).*

The pipeline begins by preprocessing expert justifications: long arguments are summarised and very short comments are expanded with minimal context to increase informational value. For example, the brief note “No production yet in Europe” for the criterion *Production of PHA* (ranked 2/6) is reformulated as “Production of PHA is an important criterion because it is not yet developed in Europe.” Conversely, multi-sentence justifications are condensed. Additional examples are provided in the project dataset.

In the next step, a term-extraction module based on dependency analysis (Jaiswal, 2021) identifies the variable values and constants needed for logical representation. Sixteen predefined linguistic patterns are applied (e.g., nouns, adjective–noun combinations). From the sentence “Logistics in PHA is more complex than in fossil alternatives," the module extracts "logistics in PHA," "complex," and "fossil alternatives." An LLM then composes conjunctions of atoms using the extracted terms, a predefined ontology, and few-shot examples. The ontology defines the admissible relationships among terms and atoms used in the logical input. The AgriLoop ontology was developed following practices from the NoAW ontology (Bisquert et al., 2025) reusing existing relations (Huguet Cabot and Navigli, 2021) and adapting them to the present context (Appendix 5). A final validation step then reviews the LLM-generated logical representations; a data engineer corrects outputs where necessary, as LLMs may produce invalid constructs (e.g., relations with arities not supported by the ontology).

Table 6: *The main barriers to the market potential of PHA and PHA end-products, their ranks as identified by industry experts in Delphi II, and the aggregated ranking computed using the Borda method.*

N	Criterium	Stakeholder	Rank (1-6)	Justification status	Borda count (considering justifications)		
					Score	Total	Rank
1	Scalability of PHA	Stakeholder 1	1	ambiguous	4	12	2
		Stakeholder 2	2	accepted	4		
		Stakeholder 3	4	rejected (unjustified)	0		
		Stakeholder 4	3	ambiguous	4		
2	Price of PHA	Stakeholder 1	3	ambiguous	4	16	1
		Stakeholder 2	1	ambiguous	4		
		Stakeholder 3	1		4		
		Stakeholder 4	2	accepted	4		
3	Production of PHA	Stakeholder 1	2	accepted	4	12	2
		Stakeholder 2	6	ambiguous	4		
		Stakeholder 3	5	rejected (unjustified)	0		
		Stakeholder 4	2	accepted	4		
4	Durability of PHA	Stakeholder 1	4	ambiguous	0	0	5
		Stakeholder 2	3	ambiguous	0		
		Stakeholder 3	3		0		
		Stakeholder 4	6	ambiguous	0		
5	Availability of feedstock	Stakeholder 1	5	accepted	1	6	3
		Stakeholder 2	4	accepted	2		
		Stakeholder 3	2	ambiguous	2		
		Stakeholder 4	5	accepted	1		
6	Logistics in PHA	Stakeholder 1	6	accepted	0	2	4
		Stakeholder 2	5	accepted	1		
		Stakeholder 3	6	accepted	0		
		Stakeholder 4	5	accepted	1		

The validated logical justifications are passed to the DAMN tool, where the Rank Sliding procedure updates justification status and computes the final ranking (Bisquert et al., 2025). As shown in Table 2, justifications marked **accepted** retain the score from the baseline (ranking without justifications); **rejected** justifications receive a score of 0; **ambiguous** justifications assume the score of the nearest accepted rank (and receive 0 if no accepted justifications exist). In the illustrative example, this yields the final order: *Price of PHA (16) > Scalability of PHA (12) ≈ Production of PHA (12) > Availability of PHA (6) > Logistics in PHA (2) > Durability of PHA (0)*. This outcome diverges from the initial frequency-based ranking and is considered more accurate and equitable because it incorporates expert reasoning and provides an explicit conflict-resolution mechanism. The process is transparent and reproducible, which is critical for collaborative decision-making on environmentally and economically sensitive topics.

A key limitation of this approach is data dependency. In the current small-sample case (three Delphi II stakeholders and one external expert), ties can occur (e.g., “Scalability of PHA” and “Production of PHA”), and some criteria may fall to the end when all justifications are classified as ambiguous (e.g., “Logistics in PHA”). Expanding the dataset is expected to mitigate these effects by enabling more decisive reasoning and reducing ambiguity. Accordingly, additional material from Delphi III will be processed to produce more reliable rankings that reflect a broader evidence base.

4 Results of market assessment in Europe

The following section presents the European market assessment that forms the foundation for AgriLoop's deployment choices. The methodology employed integrates stakeholder consultations (Delphi rounds) with desk-based analytics to delineate promising pathways under SSbD and B2B readiness. This chapter contains three sections. Firstly, the current practices, economics, and enabling templates of valorisation of agricultural residues are discussed. Secondly, the application envelope, barrier taxonomy, and cost-down/action modules of residue-derived PHA are reported. Thirdly, the use-case quality, plant-fit guardrails, and scale/price drivers of extracted and microbial proteins are described. Replicable implementation modules (offtake/price-floor models, factory-gate pre-conditioning with specification windows, and co-location or hub-and-spoke collection) are introduced. The objective is to provide a neutral decision basis that translates European residue maps and converter realities into checkpoints for feasibility and readiness, preparing the ground for the detailed analyses in Sections 4.1–4.3.

4.1 Valorisation of agricultural residues

This section outlines options for the valorisation of agricultural by-products, based on stakeholder input and aligned with SSbD and business-to-business (B2B) readiness. It defines evaluation criteria for viable pathways that combine profitability with limited added complexity, fit with existing logistics and assets, and the potential to extract higher-value fractions. Operational constraints are made explicit, including moisture-driven transport and drying needs, hygiene and storage windows, feedstock heterogeneity, seasonality, and fragmented authorisations. The section then introduces the enabling conditions and templates used throughout this deliverable: offtake and price-floor models, logistics responsibility options, factory-gate pre-conditioning with specification windows, co-location, hub-and-spoke collection, and compliance templates aligned with current rules. The aim is to provide a neutral basis for decision-making that supports a shift from disposal-led handling to repeatable, higher-value utilisation within the SSbD framework.

4.1.1 Current practices across commodities

Experts describe heterogeneous valorisation practices depending on residue type and region. Nuts, shells (almonds/hazelnuts) are pressed/collected and sold as biomass or milled as shell flour; in other cases, shells are returned to fields or fed to cattle. In fruit processing, “second category” fruit is transformed into concentrates for juice. In olives, by-products are used to extract pomace oil; additional streams (e.g., pinyol, dried pomace) are traded. A minority channel all waste into their own biogas plants; a few collaborate with charities.

Tomato residues consist mainly of skins and seeds and account for about 3–5% of processed weight. Many companies store the residues in large trailers and donate them for animal feed without payment, which creates an operational and market unreliability regarding acceptance, quality and costs of tomato residues during the peak season (June–September). Innovative routes exist but remain uncommon: fermentation to compost (e.g., reported from California), extraction of lycopene and tomato seed oil (e.g., a French example for cosmetics), and biogas use, which firms perceive as more reliable than relying on farmers for collection.

Payments vary widely by stream and are often minimal or zero (e.g., tomato waste frequently given away; some nut/olive by-products have set prices as cited in Delphi I). Responsibilities for transport vary. Processors often cover the inbound leg (from the field to the processor), while buyers may cover the outbound leg (from the supplier’s gate to the buyer’s site). Some firms handle collection, transport and disposal themselves. Occasionally, subsidies apply. Centralised collection at farm/cooperative level is seen as environmentally beneficial but is practically constrained by moisture, hygiene, and short storage windows.

4.1.2 Stakeholders' expectations – General expectations and ideal solution for the valorisation of by-products

Across all Delphi rounds, experts expect higher profitability and added value from residues, enabling better farmer remuneration and viable new business lines. An acceptable solution should show a favourable cost–benefit ratio with minimal additional complexity, fit existing logistics, and—where possible—extract high-value compounds for agri-food or other sectors. Suggested pathways include organic fertilisers (e.g., using wastewater with sorghum), protein-derived products (subject to sufficient protein content), green hydrogen, and authorised animal-feed additives.

In tomatoes, efficient lycopene extraction (potential re-introduction into tomato products) and tomato seed oil were highlighted; however, adoption depends on economics and operational simplicity. Companies decide between in-house processing and outsourcing primarily on perceived profitability. A small subset is satisfied with current arrangements (e.g., seamless waste removal to on-site biogas or nearby service providers), but most signal that current efforts are not adequately compensated.

Support structure and factors

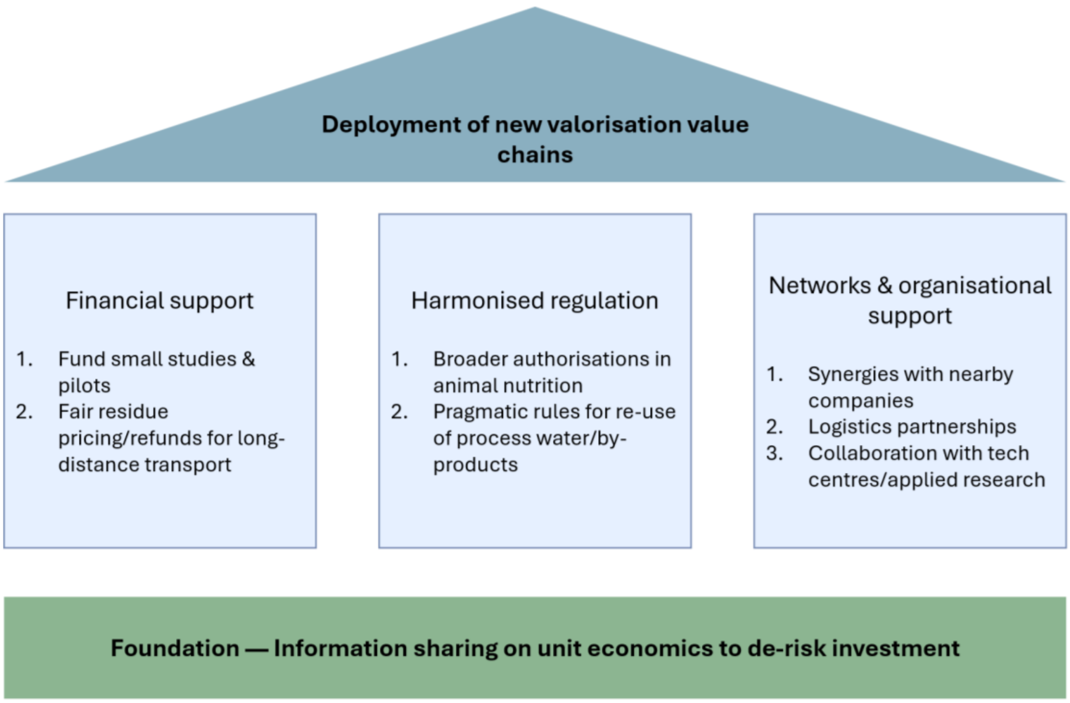


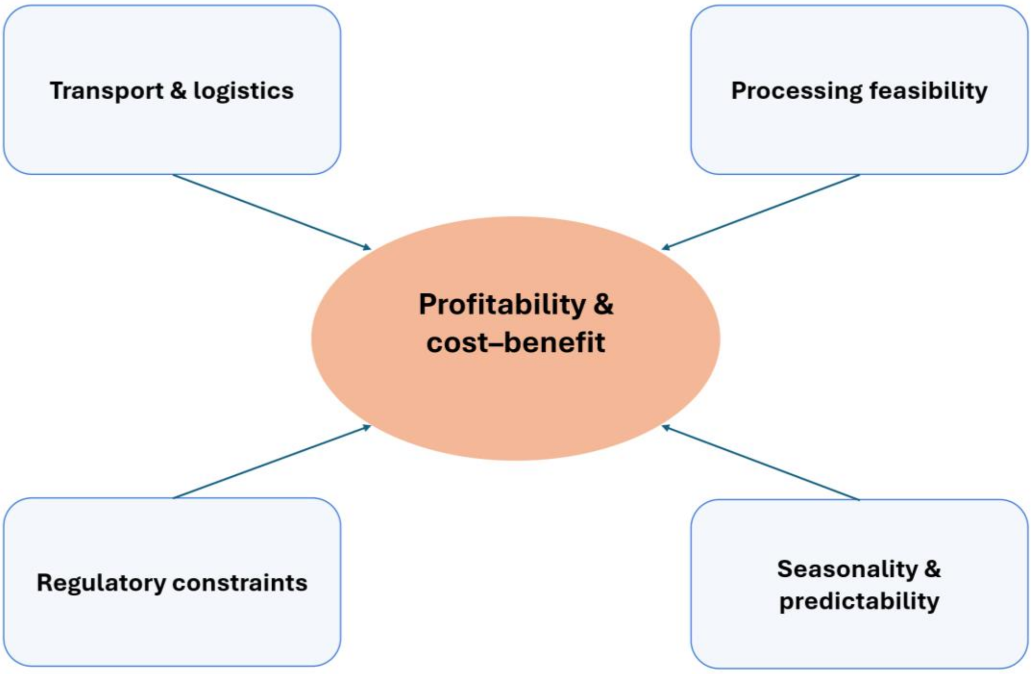
Figure 7: *Support structure for deploying new valorisation value chains—financial support, harmonised regulation, and networks/organisational support on a foundation of unit-economics transparency ((Own compilation by Ecozept, based on Delphi interviews).*

Experts highlight three main enablers: targeted finance for small-scale studies and pilot projects, including fair residue pricing and refunds for long-haul transportation; a supportive, harmonised regulatory framework that is aligned with industrial reality, such as broader authorisations for animal nutrition and pragmatic rules for reusing process water and by-products; and strong organisational support and networks via local synergies, logistics partnerships and collaborations with technology centres and applied research. Transparent, cross-cutting sharing of unit economics is essential for investment decisions, and deployment should focus on factories rather than farms, since factories generate processable residues. The supportive structure is summarized in Figure 7.

4.1.3 Main barriers and limitations to the market potential of agricultural residues

This section summarises the determinants that ultimately affect the viability of residue-valorisation projects at a plant level. Drawing on Delphi evidence and desk analysis, we have grouped the drivers into four clusters: transport and logistics; processing feasibility; seasonality and predictability; and regulatory constraints. These clusters jointly feed into the central cost–benefit analysis. Figure 8 illustrates this process: each outer driver exerts upward or downward pressure on unit cost, risk, and revenue potential, and the net effect determines investability under SSbD and B2B readiness.

Figure 8: *Determinants of residue-valorisation economics: transport & logistics, processing feasibility, seasonality/predictability, and regulatory constraints feeding into a central cost–benefit (Own compilation by Ecozept).*



Profitability and cost–benefit.

Experts identify profitability as the overarching constraint. Many residues are given away or fetch only token compensation; once logistics, drying and compliance are factored in, cost–benefit assessments frequently fail. Without a credible business case, companies prioritise core products and defer investment in residue valorisation.

Transport and logistics.

High moisture content raises weight and transport cost, while drying is energy-intensive and often uneconomic. Hygiene requirements, short storage tolerances and uneven campaign volumes increase coordination effort; feasible local offtake radii limit partner options. Centralised platforms are viewed critically due to food-grade and handling constraints.

Processing feasibility.

Heterogeneous compositions (e.g., lignin-rich fractions; high-moisture streams) complicate processing and standardisation. Quality variability—partly linked to climatic effects—affects extract yields and process stability. SMEs in particular face financing/know-how gaps for higher-value extraction or pre-treatment.

Seasonality and predictability.

Short, intense campaigns restrict annual asset utilisation and dampen investment appetite for equipment such as dryers. Rapid degradation risks require swift processing, while accurate volume forecasting remains difficult. Some plants mitigate with winter diversification or propose small in-factory units, yet these are context-dependent and not universally established.

Regulatory constraints.

Experts describe the framework as restrictive and fragmented (regional versus national or international), with narrow authorisations (e.g., in animal nutrition) and barriers to certain reuse options (e.g., process water). Experts request clearer, harmonised rules that reflect industrial reality and do not impede market entry of compounds derived from residues.

4.1.4 Valorisation of agricultural residues – Key findings

Key takeaways:

- Economics and operability take precedence over tech choice. Companies will act when a stable offtake, credible price floors and clear logistics responsibilities are in place. High moisture content, short hygiene windows and fragmented permits set hard boundaries, and local solutions outperform centralised schemes in practice.

Decision rule (when to move):

- Only proceed if the total cost of ownership remains positive once the costs of moisture-driven transport, drying, storage, quality assurance and authorisation have been factored in.
- A green light is given when there is a contracted buyer, a price floor and a defined logistics risk split (i.e. who pays for trucks, buffers and rejects).

Non-negotiables at the factory gate:

- Specification window: moisture percentage, contaminants/foreign matter, temperature, microbiology and packaging/handling.
- Time-bound: maximum dwell times during the campaign and hygiene standard operating procedures.
- Traceability and classification: by-product versus waste, batch tagging and certificates of analysis.
- Fallback outlet: pre-agreed (e.g. biogas) to mitigate downtime risk.

Logistics and storage (design variables):

- Short wet haul only. Press, screen and dewater on site where possible.
- Use a hub-and-spoke system for pre-conditioning (pressing, blending and pasteurisation/acidification, where justified) to stabilise quality before any longer-distance transport.
- Buffers should be sized to accommodate campaign peaks, and cold/covered storage should be used to protect hygiene.

Processing pathways (what works where):

- Robust, low-complexity outlets (e.g. biogas, where nearby capacity exists) are operationally dependable.
- Higher-value extraction (e.g. lycopene or tomato seed oil) requires consistent feedstock and operator capability. SMEs face capital expenditures (CAPEX)/ OPEX and know-how gaps.
- Attempting to dry or store wet residues without the necessary infrastructure will usually render the business case unviable and compromise hygiene.

Seasonality playbook:

- European tomato campaigns (July–October) result in a compressed operating period and a weak ROI for large, stand-alone assets.
- Mitigation strategies include small, factory-integrated units, winter product switches, shared equipment and staffing models aligned to peak weeks.

Regulation and authorisation:

- Fragmented regional and national permitting shapes what can be reused, when, and under which codes.
- Authorisations need to be adopted faster where they align with industrial reality (clear categories, time-bound reviews and harmonised hygiene rules).
- Treat classification and permits as critical to the project, not just paperwork.

Collaboration and risk sharing:

- Local networks (comprising nearby processors, biogas plants, extractors, third-party logistics providers and technology centres) stabilise flows, reduce the risk of pilot projects and provide benchmark economics.
- Pool volumes to reach minimum efficient scale and share quality assurance and logistics assets.

Risks and mitigations (execution view):

- Moisture: transport/drying costs can be mitigated through on-site dewatering, shortest wet miles and concentrating before shipping.
- Short hygiene window: rapid intake quality control; defined maximum dwell time; sanitation plans.
- Quality heterogeneity (climate/crop): specification bands, seasonal blending and at-line analytics/ Statistical process control (SPC).
- Permit friction: early scoping with the relevant authorities; template dossiers; staged approvals.
- Operator/SME gaps: standardised modules, service contracts and shared utilities.

4.2 PHA from agricultural residues

This chapter presents a concise deployment framework for residue-derived PHA under SSbD, based on stakeholder consultations. It clarifies the application scope, establishes an evidence ladder linking lab, mesocosm and field tests to article geometry, and outlines the necessary governance to ensure quality and safety. The aim is to establish clear go/no-go criteria and readiness checkpoints for transitioning from the feasibility stage to the offtake stage.

4.2.1 Stakeholders' expectations

4.2.1.1 Function of PHA

Stakeholders came to a consensus on a two-stage functional brief: First, maintain mechanical performance under real operating conditions across the intended service window. Second, relinquish properties in the intended environment without leaving behind persistent micro-/nanoplastic residues. For agricultural use, the duty cycle is aligned with crop calendars and field operations. Articles must survive installation stresses and peak loads during the early season (e.g. UV exposure, moisture, temperature fluctuations and abrasion/handling) and then disintegrate within a timeframe relevant to the field once their agronomic role has been fulfilled.

<u>Application-specific envelopes:</u>

The application envelope is governed by two criteria: first, whether the article must disappear in the soil after use, and second, if so, whether it can provide a service life of up to one season at a low polymer mass per hectare. Thin, soil-exposed formats qualify when both criteria are met: mulch films that survive lay-down and one crop cycle before rapidly disintegrating in soil; the gauge of which is tuned to the crop and climate (recognising that down-gauging aids decay, but can compromise lay-flat handling and early-season robustness); clips and twines that provide around six months of UV/load capacity during cultivation, before disintegrating within two to four months in compost or soil; and plant-through/plant-with pots that retain their shape throughout propagation, logistics and planting, before biodegrading under agronomic conditions. Where soil disappearance is required, but the one-season/low-mass criteria cannot be met, the article should either be redesigned or deferred. If soil disappearance is not required, the focus shifts to durability. Transport trays and reusable pots have a lifespan of 6–60 months and are evaluated based on stability, opacity, colourability and dimensional control. However, greenhouse films requiring 7–8 years of UV stability and transparency are not within the scope of neat PHAs in the near term. Figure 9 introduces a application selection scheme based on the previously mentioned criteria.

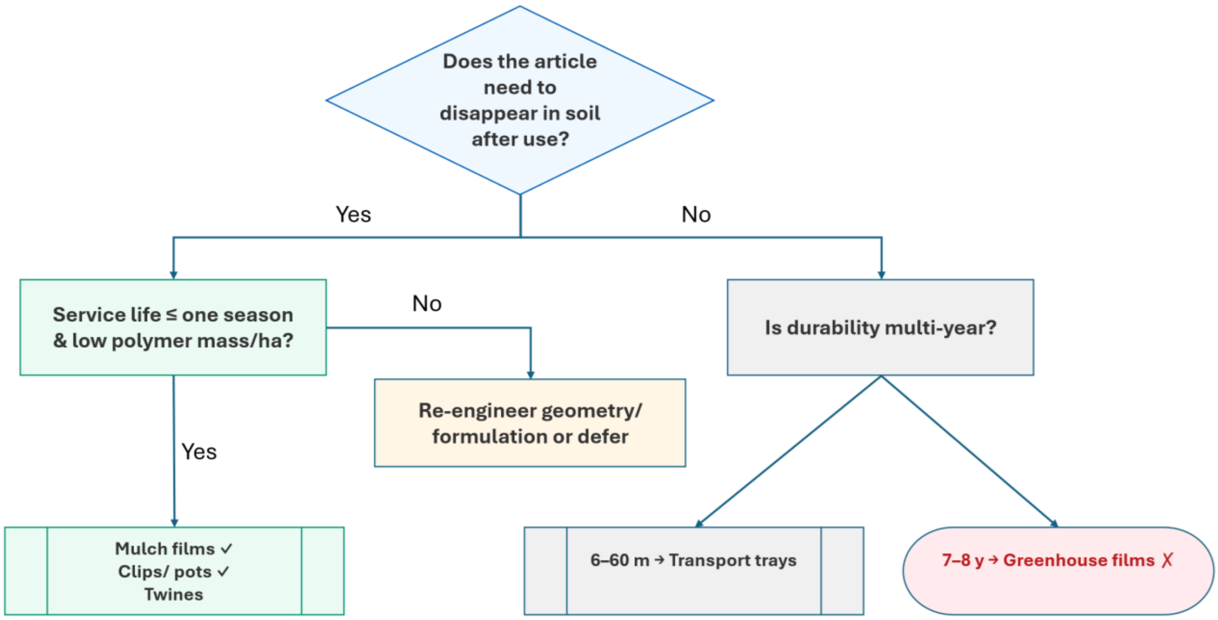


Figure 9: *Application-selection flowchart for residue-based PHAs: end-of-life and service-life gates route soil-disappearing, thin-gauge uses (mulch films, clips/pots, twines) versus technical items (transport trays) and exclude greenhouse films. (Own compilation by Ecozept).*

<u>Design trade-off: retain function, then allow controlled degradation.</u>

Experts stress that the degradation rate must be programmed. Too much stabilisation (thickness, higher crystallinity, robust geometries, UV/antioxidant packages) extends service life but adds mass/cost and risks persistence beyond agronomic need. Too little stabilisation protects end-of-life performance yet can truncate the service window under UV, moisture and mechanical stress. The practical rule is to specify a time-bounded retention window (target property retention under defined exposure) and a matched end-of-life trigger (disintegration/biodegradation under defined conditions), then tune thickness, crystallinity and part geometry to hit both.

This has implications for fit-for-purpose use. PHAs are most effective where the service life is naturally limited (to a maximum of one year) and verified soil degradation provides operational or environmental benefits (e.g. eliminating the need to retrieve film or enabling plants to be grown in pots). Long-life outdoor applications remain incompatible with neat PHAs. Where such applications are explored, they would require multilayer engineering and explicit, credible end-of-life solutions.

4.2.1.2 Processability

Experts describe processability as the hinge between molecular design and manufacturability. The non-negotiable benchmark is drop-in runnability on incumbent assets—blown and cast/flat film extrusion, thermoforming, and injection moulding—without wholesale retooling. Processors expect a usable melt window, predictable crystallisation kinetics, and reproducible rheology that deliver low start-up scrap, stable weld/knit strength, and tight batch-to-batch consistency. Where early PHAs placed melting too close to onset of decomposition—producing odour and brittleness—current practice shifts the window by controlling co-monomer ratios and molecular-weight architecture and by using nucleation strategies that stabilise crystallisation.

Operationally, converters look for steady viscosity profiles and bubble stability on film lines, dimensional control in thermoforming, and reliable filling/weld integrity in injection moulding. Experts repeatedly ask for clear, grade-specific standard operating procedures—drying protocols, temperature profiles, screw and die settings, and nucleation guidance—to avoid post-crystallisation embrittlement and to keep in-line behaviour predictable across jobs and seasons. Several voices underline that flexibility can be tuned at the formulation level, but acceptance on the shop floor is ultimately evidenced by smooth start-ups, stable throughput, and reproducible part quality.

Because many high-volume agricultural articles (e.g., mulch films) are produced on standard lines, "runs on existing assets with near-equivalent operability to polyolefins" is the first acceptance criterion. Experts also highlight that processors need practical support to adapt to differences in melting behaviour versus incumbents; concise processing windows, troubleshooting guides, and consistent certificates of analysis are seen as enablers of qualification. In sum, processability is defined by predictable melt behaviour and crystallisation, robust standard operating procedures that prevent brittle drift after processing, and lot-to-lot consistency that allows converters to treat PHA grades as dependable, drop-in materials on current equipment.

Processor priorities:

- Stable viscosity and bubble; minimal die-line instability (film).
- Clear standard operating procedures for drying, temperature profiles, nucleation to avoid post-crystallisation embrittlement.
- First acceptance criterion: runs on existing assets with near-equivalent operability to polyolefins.

4.2.1.3 Stability (thermal/UV; property retention)

Experts define stability as retention of required properties over the declared service window under UV, heat, and moisture—followed by a deliberate release of properties thereafter. PHAs should be engineered for this outcome: stability is delivered by molecular architecture, crystallisation control, and targeted stabiliser packages, and it must be bounded so that what protects use-phase performance does not delay post-use decay in the intended environment.

For outdoor and warm/moist contexts, the expectation is explicit UV and thermal resistance for the duty cycle at hand (single-season vs. multi-year). Articles should maintain tensile/elongation and impact profiles, dimensional form, and surface integrity through that period and then decline. Environmental conditions strongly modulate results: higher soil moisture and temperature accelerate decay; shade slows UV-driven change; and thickness is first-order—thin sections retain properties for shorter periods than thick ones under otherwise similar exposure.

Two failure modes dominate if left unmanaged:

(1) Post-processing crystallisation and partial crystallinity can lead to embrittlement over time; experts therefore expect stabilisation and crystallisation control that keep ductility and toughness within the use-phase envelope.
(2) Hydrolytic and microbial onset in soil/wet exposure can shorten life markedly; neat PHAs are viewed as unsuitable for long, multi-year outdoor durability without significant intervention, which some consider incompatible with credible end-of-life in soil.

Further, Experts describe a pragmatic set of tools: controlled crystallisation and nucleation to prevent early brittleness, minimal UV and thermal stabilisation to withstand the declared timeframe, and choices of geometry and thickness that balance in-service robustness with timely post-use decay. Opinions differ mainly on how much stabilisation is appropriate. One group argues for more robust films to ensure short- and medium-term retention, while another group prefers 'robust enough, but no more', citing the risk that heavier films could slow down the desired degradation process after use.

Experts want property-retention data obtained under realistic stressors (UV exposure, thermal cycling and humidity) within the specified timeframe, rather than just the initial datasheet values. Several caution that common laboratory standards may underestimate or overestimate field behaviour because they do not fully capture seasonality, moisture dynamics, or soil heterogeneity. Consequently, they expect stability claims to be supported by scenario-specific protocols that bridge the gap between laboratory conditioning and representative outdoor exposure over the intended timeframe.

4.2.1.4 Biodegradability and compostability and End-of-life

Experts treat biodegradability and compostability as environment-specific performance requirements rather than generic labels. Claims should be specific to the actual article in question, taking into account its composition (including additives, pigments and fillers), thickness and geometry, and must demonstrate that the item is fit for purpose within the stated timeframe, after which it will disintegrate and fully biodegrade without leaving persistent small-particle residues in the intended setting. As standard laboratory protocols can under- or over-predict behaviour in the field, evidence is required that bridges the gap between controlled tests and representative exposure conditions (e.g. soil type, seasonal moisture/temperature, microbiome, shading/placement and agronomic practice). While certificates are useful, they are insufficient on their own. Credibility rests on a transparent chain of proof that links harmonised laboratory methods to mesocosm and field validation. This should include particle-size analytics to confirm true biodegradation rather than mere fragmentation, as well as baseline ecotoxicity checks relevant to soil organisms.

Route-use alignment is non-negotiable. If the declared end-of-life is composting, the specifications should reflect the actual practices of the facility: many industrial plants operate 6–8-week cycles (some up to 12 weeks) and impose practical limits on the thickness and shape of articles. Where municipal organics collection dominates, evidence of industrial composting should form the basis of the dossier. Where in-field degradation is intended (e.g. mulch films or pots that can be planted in), field-linked data takes precedence over composting certificates. Experts should note that market acceptance can lag behind certification, as some operators still refuse compostable materials regardless of labels. Therefore, deployment plans should document how product claims align with the actual waste pathway in the target geography.

Expected evidence follows a three-tier 'ladder'. First, laboratory testing establishes disintegration and CO_2 evolution (mineralisation), as well as baseline ecotoxicity, under defined conditions. Secondly, mesocosm studies reproduce the wet–dry and warm–cool phases that are representative of the relevant soil's seasons. Thirdly, multi-site, multi-season field trials confirm the results across the target agro-climatic zones. Throughout the tiers, endpoints couple mass and disintegration with time-resolved particle size distributions that trend towards disappearance rather than plateauing at small sizes. Boundary conditions must be explicitly defined (e.g. soil type, moisture/temperature ranges, placement, gauge/surface area), observed timelines should be linked to the declared service window and, where relevant, at least one full seasonal cycle should be captured. Testing should use the commercial formulation and thickness, not surrogate coupons.

Documentation and labelling are expected to adhere to a performance-first, SSbD logic. Dossiers should state the intended environment (soil, home compost or industrial compost), the validity window of the claim and the boundary conditions. They should also link the composition and provenance (including residue-based traceability) to the evidence set, noting any restrictions (e.g. maximum gauge). Gatekeeping before release typically proceeds through four waypoints: laboratory conformity; mesocosm confirmation across seasonal cycles; multi-site field confirmation; and a documented absence of persistent small-particle residues and adverse ecotoxic outcomes. After release, experts favour monitoring at sentinel sites (periodic sampling of surfaces and soils for particle size distributions, plus simple mass and CO_2 checks) to verify that in-market performance remains within validated bounds and to trigger corrective action where local conditions deviate.

Finally, transparency regarding limits and usage instructions is expected. Since standard tests cannot represent all soils and climates, evidence packs should disclose any uncertainties (e.g. soil diversity not covered, or narrower moisture ranges) and provide operational guidance where appropriate (e.g. thickness caps, or caution for cool, arid soils without irrigation). In short, end-of-life is a design specification that must be engineered, evidenced and labelled for the specific context. Only environment-matched, method-linked documentation is regarded as credible and ready for procurement.

4.2.1.5 Colour and printability

Experts consider colour and printability secondary but application-relevant factors, the importance of which is dictated by the intended use. Visible branding packaging demands tight chromatic control, managed transparency/opacity and reliable print receptivity. By contrast, B2B agricultural products (e.g. mulch films) prioritise function; simple opacity or a high-contrast tint for field handling is sufficient, and printing is often unnecessary.

PHAs are not colour-neutral substrates. Two recurring phenomena should be engineered for: a natural yellow cast (observed in certain medium-chain-length grades) and thermal colour drift during extrusion, thermoforming or moulding. The approach is to co-design appearance and processing stability rather than 'painting over' it afterwards. Compliant masterbatches and pigment systems are selected and dosed to deliver predictable hue, opacity and gloss, while maintaining reproducible crystallisation kinetics, rheology and dimensional control. In this context, colour stability becomes an operational specification: formulations are expected to resist yellowing or browning over realistic periods of time and reprocessing cycles, with simple metrics (e.g. Yellow Index) remaining within defined limits from one batch to the next and before and after typical thermal exposure.

The same pragmatism is applied to printability. Where brand or regulatory communication is required, the surface should accept ink cleanly and consistently (regardless of the surface treatment or ink system used), without compromising the robustness of the polymer/additive stack. Therefore, several voices downplay the importance of print for soil-contact films, favouring thin-gauge integrity and minimalist pigmentation over graphics that add unnecessary complexity.

End-of-life expectations set hard boundaries. Pigments, fillers and print additives must be compatible with the claimed end-of-life route, and the dosage levels should not impede field-relevant disintegration or leave behind persistent residues. For soil-degrading products, pared-back pigmentation is often favoured to reduce the burden of demonstrating fragment-free outcomes. At the same time, the appearance must be protected sufficiently to meet the service window. This creates a managed trade-off: stabiliser and pigment packages should guard against in-service discolouration to the required extent but not be so aggressive as to complicate or delay post-use decay. Opinions differ on the 'right' margin of protection; the solution is to provide application-specific proof that the chosen package meets both in-use and end-of-life expectations.

4.2.1.6 Quality & purity (SSbD governance emphasis)

Experts do not equate 'quality' with a single purity figure. Instead, they expect a fit-for-purpose, auditable specification stack embedded in SSbD governance. This involves documented inputs, targeted pre-treatment where necessary, robust bioprocessing, calibrated downstream polishing and release analytics. This chain of processes makes claims traceable and inspection-ready by linking what was input, what was removed and what remains at shipment.

Across European markets, quality baselines include genetically modified organism (GMO)-free biology and feedstocks, non-toxicity and traceable additive identity and provenance. Where intended use involves food contact or near-food use, experts expect compliance with migration regulations and full documentation of composition, additives, and residuals.

Application-class acceptance thresholds: Purity targets are use-dependent rather than universal.

(1) For food contact/near-food applications, there must be consistent evidence of high purity, migration testing against the intended context, an absence of hazardous substances at relevant limits, and full traceability of inputs and additives.
(2) For agricultural B2B applications (e.g. mulch and plantable items), functional performance and evidence of the absence of hazardous residues in soil and water are decisive, and ultra-purity is not required if safety is assured and documentation is sound.

Additives (e.g. stabilisers, plasticisers, nucleators, compatibilizers, fillers and pigments) are treated as governed substances. Their identity and provenance must be documented, restricted substances must be excluded, and dosing must be controlled within declared ranges that are aligned with sectoral norms. Declarations should match the release specification and downstream compliance needs.

Each batch should be shipped with coherent evidence pack (Certificate of Analyis, Declaration of Conformity (DoC)) covering batch identity and traceability, GMO-free declarations, additive declarations, and targeted residual/contaminant panels appropriate to the feedstock and route. These should include ash, residual protein/lipid/cell debris, heavy metals, relevant pesticide/mycotoxin screens, and solvent traces where applicable. For food-adjacent uses, migration data for the stated use conditions should also be included. Experts emphasise that testing and documentation incur significant costs and time and must be incorporated into the business model.

While there is a general agreement on the governance architecture, companies differ in terms of where they allocate their efforts. Some rely on strict sourcing and targeted detoxification to keep the downstream process light, while others accept heavier pre-treatments to accommodate heterogeneous residues. In all cases, comprehensive documentation and critical analytics are required, and quality system controls (including HACCP-style elements in sensitive contexts) ensure that 'quality' can be demonstrated, is proportional to use and conforms to SSbD.

4.2.1.7 Composition and blends

PHAs are not a single resin, but rather a compositionally engineered family. Their performance is determined at an early stage through the choice of co-monomers and molecular-weight architecture and then finalised through blends and additives. The co-monomer ratios and molecular weight distributions are adjusted to create a workable melt window, stabilise crystallisation and deliver consistent rheology, enabling extrusion, thermoforming and injection moulding to be carried out using existing equipment. Blending then reconciles the core trade-offs: stiffness versus toughness, process stability versus biodegradation, and cost versus compliance. PHB-rich chemistries are used where stiffness and heat resistance are required, while softer PHA copolymers, starch and selected bio-polyesters (PBAT and PBS) widen the melt window and reduce brittleness. Mineral and natural fillers (e.g. chalk, eggshell and cellulose fibres) increase modulus and enable down-gauging, provided that moisture is controlled and fibre–matrix adhesion is engineered. Practitioners report that PHA–starch blends can reduce costs and, in certain scenarios, enhance compostability, while enzyme-assisted formulations can accelerate degradation when desired. By contrast, PLA-forward blends favour industrial composting at the end of life and complicate claims for soil degradation. While bio-based, lignin is repeatedly judged to be mechanically limiting and unsuitable for food contact. Table 8 further describes the blend palette for PHA formulations.

Additives are essential to the composition process, not an afterthought. Nucleators, plasticisers, compatibilizers, stabilisers and pigments are selected and dosed to ensure melt stability, dimensional control and surface quality on standard production lines. Governance is on a par with performance, with the following features: documented identity and provenance; exclusion of restricted substances; dosing controls aligned with sectoral quality systems; and compatibility with end-of-life claims. Over-stabilisation (UV/thermal) can slow degradation, whereas under-stabilisation can lead to embrittlement during use (e.g. due to post-crystallisation).

The same 'fit-for-service, then let go' logic applies to fillers and copolymers: blends must protect the intended properties and then disintegrate and mineralise along field-relevant trajectories, leaving no persistent micro-/nanoplastic residues. Compounding practice reinforces this: purity and uniformity are important because residual cell debris or poorly conditioned fibres cause brittleness and variability. In some cases, nutrient-bearing fillers may assist biodegradation by supporting microbial activity.

Expectations regarding GMO-free organisms and feedstocks, and food-contact safety where relevant, need to be designed in from the outset. The focus remains consistent: engineer a forgiving melt by designing the molecular architecture; use blends and compatibilisers to achieve application-specific mechanics on existing equipment; and select additives and co-materials to ensure end-of-life performance remains demonstrable in the target environment and timeframe.

Table 7: *Blend palette for PHA formulations—comparative effects on stiffness/heat resistance, machinability/runnability, cost/down-gauging and decay/compost route. Symbols: ✓✓ strong contribution; ✓ moderate; — limited/neutral. (Own compilation by Ecozept).*

Material	Stiffness & heat resistance	Machina-bility & runnability	Cost/ down-gauge	Accelerated decay or compost route	Comment

PHB-rich	✓✓	—	—	—	Provides stiffness and heat resistance
Starch / PBAT / PBS	—/✓	✓✓	✓	compost bias	Widens the melt window and reduces brittleness
Natural/mineral fillers	✓	—	✓✓	—	Increases modulus and enables down-gauging, but requires moisture management and compatibilization
Enzyme-assisted	—	—	—	✓✓ (faster decay)	Accelerates degradation
PLA blends	✓	—	—	✓ (industrial compost)	have a bias towards industrial composting and can complicate soil-degradation claims
Lignin (non-food)	—	—	✓ (cost niche)	—	mechanically limiting and not suitable for food contact

4.2.1.8 Material strategy — from polymer platform to application-ready formulation

This section sets out a concise, stage-gated path to turn PHA from a platform polymer into application-ready grades. Rather than repeating technical detail from earlier chapters, it ties formulation choices to the governing envelopes already defined—processability (see 4.2.1.2), in-use stability (4.2.1.3), end-of-life and biodegradation (4.2.1.4), and SSbD governance/quality (4.2.1.6)—and uses composition and blends (4.2.1.7) to meet them. The stage-gated workflow is summarised in Figure 10.

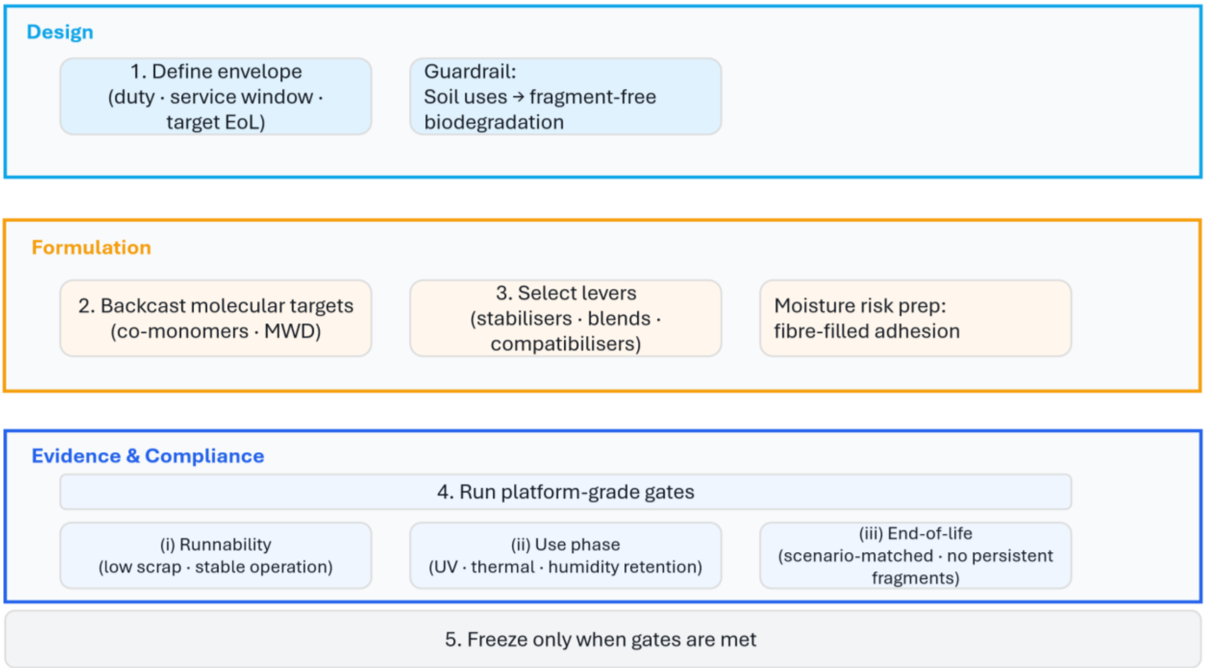


Figure 10: *Stage-gated pathway turning formulations into bankable dossiers: envelope definition, molecular backcasting, lever selection (incl. moisture management), platform-grade testing, and freeze on gate pass. (Own compilation)*

The starting point is the definition of the application envelope, which includes the use case, the required service window, the intended end-of-life route (soil, home composting or industrial composting) and the regulatory/contact class. These boundaries then inform the process of 'backcasting' at the molecular level: the co-monomer ratios and molecular-weight architecture are set to open a usable melt window, stabilise crystallisation, and deliver consistent rheology on existing assets. Once this platform is in place, the formulation levers are selected under explicit end-of-life constraints. Stabilisers (thermal/UV), nucleators, plasticisers, compatibilisers, fillers and pigments are added using a simple low/medium/high scale — robust enough to ensure retention during use, but not so aggressive as to impede post-use decay. Any change in the dose of a material or the supplier re-opens the end-of-life gate.

Conversion to production then hinges on establishing a processing window and standard operating procedures for existing equipment. Grade-specific standard operating procedures, such as drying protocols, temperature profiles, screw and die settings and nucleation guidance, are fixed alongside acceptance criteria including low start-up scrap, stable viscosity, bubbles on film lines, consistent knit/weld integrity and constancy from one lot to another. In parallel, in-use retention is verified by showing that tensile, elongation and impact properties, as well as dimensional form and surface integrity, remain within bounds over the declared period under UV, heat and moisture, with crystallisation control preventing post-processing embrittlement.

The end-of-life stage is evidenced through a laboratory-mesocosm-field ladder using the commercial formulation and gauge. Disintegration and mineralisation are coupled with time-resolved particle-size distributions that trend towards disappearance rather than plateauing at small sizes, and with ecotoxicity checks that are relevant to the target setting. The boundary conditions — soil type, moisture/temperature cycles, placement and thickness — are made explicit so that the dossier links the method to the context.

Release is governed by SSbD. Each batch is shipped with an inspection-ready evidence pack that covers traceable inputs and additives, GMO-free declarations where applicable, targeted residual/contaminant panels and, for food and near-food uses, relevant migration data. This is all aligned with CoA/DoC requirements.

Change control is integral. Triggers include changes to the formulation or supplier, shifts in the additive dose, detectable drift in the thermal history, or measurable shifts in rheology, colour, or degradation kinetics. When a trigger occurs, re-qualification runs through processing, in-use and end-of-life gates, and statistical process control is maintained on critical quality attributes. standard operating procedures and specification windows are also updated.

The application process is straightforward and follows a simple portfolio logic. Soil-exposed, thin-gauge films favour starch-based or soft-segment PHA blends with minimal stabilisation and restrained pigmentation. Field-relevant evidence of end-of-life takes precedence. Load-bearing or thermally stressed parts favour PHB-leaning matrices with controlled nucleation and, where necessary, compatibilised mineral or fibre reinforcement with engineered moisture interfaces. Higher retention is demonstrated prior to reconfirmation of end-of-life.

Overall, composition, formulation and documentation are co-designed: upstream molecular control provides a stable processing base, blends and additives are tuned within explicit stability and end-of-life limits, and governance verifies claims. This transforms PHA from a chemistry into bankable, application-ready grades without compromising environmental integrity.

4.2.1.9 Contamination and safety (residue-to-polymer)

Experts treat contamination and safety as an end-to-end discipline. As agricultural side streams can carry heterogeneous chemical and biological loads, assurance cannot rely on any single unit operation. Control begins with risk-stratified sourcing and continues through pre-treatment, fermentation, downstream purification and batch release. The operational objective is twofold: (i) to deliver resins that meet non-toxicity expectations for the intended use and (ii) to provide auditable and traceable evidence that contaminants remain within defined limits from intake to finished polymer.

Hazard landscape. Credible chemical risks include pesticide actives and metabolites, mycotoxins (particularly in straw-type lignocellulosics), heavy metals and pre-treatment derived inhibitors (furfural, HMF and phenolic compounds), as well as dissolved salts that accumulate from washing and pH control. Biological risks comprise wild microbes, bacteriophages and biofilms, which depress titres and destabilise batches. Only a few add downstream auxiliaries (e.g. residual solvents, flocculants) where stewardship is weak. Context matters: non-food agricultural articles are comparatively forgiving, whereas food-contact formats require stricter migration limits and documentation.

Control follows a HACCP-like architecture: (i) risk-stratified sourcing and intake analytics (targeted Liquid Chromatography–Mass Spectrometry (LC/MS) for pesticides/mycotoxins, Inductively Coupled Plasma – Optical Emission Spectrometry (ICP-OES) for metals, High-Performance Liquid Chromatography (HPLC) for inhibitors); (ii) selective detox/pre-treatment where warranted; (iii) robust, monitored fermentation (bioburden/phage surveillance, Clean-in-Place / Sterilize-/Steam-in-Place (CIP/SIP)); and (iv) calibrated downstream polishing with solvent recovery where applicable.

Table 8: *HACCP-aligned critical control points for residue-to-PHA: hazards, analytical measures, and thresholds/actions at intake, detox exit, fermentation, and release. (Own compilation by Ecozept).*

CCP	Hazard focus	Measure	Threshold / Action
Intake	Pesticides, mycotoxins, metals, inhibitors	LC/MS, ICP-OES, HPLC	Reject/segregate if above spec
Detox exit	Residual inhibitors/salts	Targeted analytics	Re-detox or blend down
Ferment	Bioburden/phages	Rapid microbiology	Abort/CIP if out-of-control
Release	Additive dosing; solvent residues; end-of-life-relevant composition	Certificate of Analysis /DoC cross-check + analytics	Hold until conform

Without traceability and defined release criteria, safety is not credible. Gate-to-gate documentation links feedstock analytics to batch release via named critical control points with explicit hazards, methods and accept/reject rules. Out-of-tolerance triggers result in quarantine, root-cause analysis and corrective and preventive action. The same governance applies to additives: identity, provenance and dosing ranges; exclusion of restricted substances; and DoCs that reference the supporting analytics. In sensitive contexts, HACCP-style controls must be ready for inspection. Table 9 summarizes the HACCP-aligned critical control points for residue-to-PHA.

The level of stringency depends on the application. With the above architecture, contamination risks can be managed for technical and agricultural uses. Food-contact formats require higher-resolution analytics, tighter migration limits and more exhaustive purification and documentation. Residue inputs remain possible if detoxification and quality assurance are scaled accordingly. For mulch films and similar soil-exposed articles, functionality should be demonstrated alongside evidence that no hazardous constituents are introduced into the soil, water or crops.

Residual risk, field safety and verification are key considerations. As many applications involve soil exposure, experts expect verification that contaminants will not be mobilised during use or after disposal. While certifications are valued, lab protocols may not replicate real-world moisture/temperature regimes and microbiomes. The prevailing stance is to triangulate evidence: standard release testing at the plant level plus scenario-specific verification where warranted (e.g. targeted pesticide/mycotoxin screens in representative soils after disintegration) with transparent method–context linkage. In parallel, when degradation is intended, analytics should confirm that neither polymer nor additive residues persist as problematic micro- or nano-fragments at the end of the product's life.

One approach relies on rigorous sourcing and selective detoxification, treating the downstream processing as a polishing step. Another approach highlights that heterogeneity can necessitate batch segregation and more extensive detoxification, resulting in increased costs and complexity. Both approaches converge on the same design rule: engineer robustness upstream through risk-stratified procurement, inhibitor-avoiding pre-treatments and tolerant biologies, and reserve the downstream process for confirmation rather than rescue. Where uncertainty persists (e.g. new residue classes or seasonal drift), define re-qualification triggers that are tied to shifts in contaminant profiles or critical quality attributes.

4.2.2 Main limitations and barriers to the market potential of PHA

The following chapter examines the main limitations and barriers to the market potential of PHA. The results of all three rounds of surveys are summarized and analysed.

4.2.2.1 Main limitations and barriers to the market potential of PHA– Ranking and justifications

This sub-chapter analyses the arguments experts provided for their rankings of key market barriers. For each criterion, we first report the cross-interview average rank (1 = very important barrier; 6 = least important barrier) and then provide a detailed analysis of the justifications leading to the ranking of the experts. Here we perform an analysis that synthesises the justifications per-interview, justifications and contrasts positions across interviews (consensus vs. divergence).

Table 9: *Ranking of market-entry barriers for PHA: mean expert ranks (1 = most important) and scores normalized to 100 (Price = 100). (Own compilation by Ecozept).*

Barriers	Mean ranking	Mean ranking scaled to 100
Price	1.00	100
Legislation	1.50	90,0
Scalability	2.83	63,33
Availability of feedstock	3.17	60,00
Production	3.25	56,00
Durability	3.80	56,66
Transportation & logistics	4.50	40,00

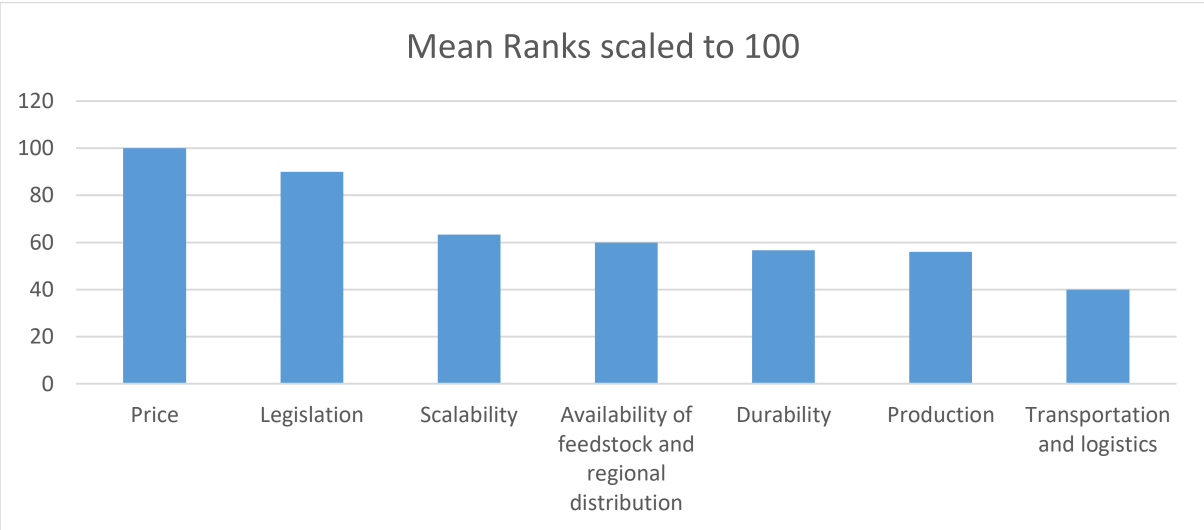


Figure 11: *Normalised mean ranks (0–100) of perceived barriers to PHA market entry; Price set to 100. (Own compilation by Ecozept).*

4.2.2.1.1 *Assessment on barrier – Price*

Price remains the dominant gatekeeper for market entry and expansion. Current transaction levels cluster around €6/kg, with a broader range of €5–10/kg depending on grade, geography and business model. Prices below €5/kg are generally not representative, unless high utilisation assets, favourable feedstocks and simplified downstream processing are in place.

Unit economics are process-dominated: Downstream processing, including cell disruption, extraction/purification and polishing to meet specifications, together with solvent handling/recovery, energy intensity and purity requirements, drives OPEX. Feedstocks account for around half of the total cost, but they are not the sole determining factor: low-cost residues often contain inhibitors that reduce yields and increase downstream processing costs. Variability in titres, productivity and purity lengthens cycles, increases scrap and the quality control (QC) burden, and increases the cost per kilogramme (€/kg). Factor costs (energy, labour and compliance) and asset utilisation further modulate outcomes.

Affordability is co-produced by industrial cadence. Residue-based plants are most feasible in the 5–25 kt/a range and are configured as standardised, automated, multi-reactor systems that operate continuously with inline analytics. This design enables improvements in heat and solvent integration and statistical control. First-of-a-kind facilities require hundreds of millions of euros and bankable offtake. Without volume, price per kilo remains high and, without lower €/kg, volume stalls.

The feedstock strategy is an economic boundary condition. Pretreatment-light, compositionally uniform streams (such as selected sugars, oils, and stable food industry side streams) protect yields and simplify downstream processing. In contrast, heterogeneous lignocellulosics (such as furans, phenolics, and salts) can eliminate nominal price advantages through detoxification and yield loss. There are incentives for biogas bidding on the same organics, which tightens availability and increases input prices. The practical response is specification-driven intake, including risk-stratified sourcing, densification hubs, seasonal blending and inhibitor-avoiding pretreatments, to ensure that any "savings" made upstream do not reappear downstream as costs.

Regional dynamics reinforce this picture. The expansion of Asian capacity exerts downward pressure on unit prices, which is supported by lower factor costs and access to conventional substrates. In some validated routes, non-sterile, salt-tolerant fermentations are also possible. Regions lacking investable policy signals and standardised assets face a persistent price per kilo disadvantage. Willingness to pay in B2B remains low: agricultural users typically accept a premium of only about 3–5% over incumbents, whereas consumer-facing niches may accept a premium of 10–20% when biodegradation is demonstrated and operational issues are resolved (e.g. mulch-film retrieval). However, such premiums rarely close the average price per kilo gap.

Policy can facilitate acceptance if it is outcome-based. Instruments that recognise verified, fragment-free biodegradation, such as eco-modulated fees, green-procurement eligibility and accounting towards circularity targets, increase tolerance for a moderate premium. In contrast, classification-centric bans and inconsistent acceptance of certified compostables suppress volumes and delay cost degression.

PHA price competitiveness

Price competitiveness is contextual rather than a single threshold. A pragmatic sequencing logic avoids head-to-head competition in ultra price-sensitive segments and builds initial revenue where performance is explicitly valued—biomedical and other certification-dense niches in which biocompatibility, controlled degradability and traceable supply command premiums. This is staging, not retreat: tight specifications focus R&D on verifiable outcomes, reference deployments build credibility, and premium margins buy time for the cost curve to bend. Where end-of-life is monetised through outcome-based procurement or eco-modulated fees, thin, soil-exposed formats can also act as early-scale anchors because verified biodegradation becomes compliance value rather than an unfunded attribute.

How circularity is counted shapes willingness to pay. If frameworks (e.g. PPWR or sectoral rules) allow bio-based/biodegradable polymers to contribute to recycling or broader circularity targets when verified in the relevant environment, PHAs shift from "costly alternatives" to compliance enablers, increasing tolerance for a price delta in procurement. Adjacent, low-friction fiscal nudges—reduced value-added tax for certified articles, eco-modulated extended producer responsibility (EPR) fees, targeted levies on non-conforming incumbents—narrow the gap without dulling incentives for process efficiency. Experts generally prefer technology-neutral, performance-based instruments over open-ended operating aid.

Regulation and scale form a feedback loop. Outcome-based eligibility or mandates consolidate demand, justify standardised, modular capacity (5–25 kt/y modules) and accelerate learning. Affordability emerges from industrial cadence—multi-reactor continuous trains using ≥50,000 Liters (≈50 m^3) reactors, solvent-lean or closed-loop downstream processing, heat/solvent integration and in-line analytics—so fixed costs and energy/solvent intensities fall. Many savings are learning effects only unlocked at scale; investors fund these steps against stable offtake, which makes securing outcome-based access and "doing cost reduction" strategically equivalent.

Cost concentration lies in downstream processing. Feedstock heterogeneity, slow microbial growth and solvent- or energy-intensive recovery extend cycles and raise OPEX. Two levers should be co-designed: (i) microbial/bioprocess gains (higher titre, productivity and purity) that compress purification effort and dampen variability across residue feeds; and (ii) engineering simplification (fewer unit operations, solvent-lean/solvent-free routes, tighter heat/mass integration). The translation gap from lap scale research to scaling up processes to pilot scale is a recurrent pitfall; lab successes stall unless microbiology and plant design meet on demonstration lines that surface scale artefacts (fouling, solvent closure, long-run stability) before capital is locked in.

Blanket subsidies are viewed as counterproductive. Experts ask instead for performance-anchored rules, credible labels and harmonised standards, interoperable test infrastructure and time-bound de-riskers for first-commercial assets—support that rewards verified outcomes without prescribing a technology path.

Table 10: *Composite playbook for price competitiveness (Own compilation by Ecozept).*

Lever	What to implement (DL1.3-consistent)	Key KPIs
Stage market entry	Target certification-dense niches; expand to thin, soil-exposed formats with verified, fragment-free biodegradation priced on €/function.	Share of outcome-priced SKUs; price per function delta vs. incumbents
Policy as economic mechanism	Enable counting towards circularity targets; apply eco-modulated fees / EPR modulation tied to environment-matched performance.	EPR modulation in place; procurement criteria adoption; offtake under GPP
Industrial cadence (corrected)	Multi-reactor continuous trains with ≥50,000 Liters reactors; first-commercial 5–25 kt/y modules, scalable to 30–50 kt/y; solvent-lean, standardised downstream processing; long campaigns; integrated utilities.	Reactor size (≥50 m^3 / ≥50,000 Liters); installed train volume; capacity (kt/y); OEE %; campaign hours; SEC (kWh/kg); solvent-recovery %.
Bio×Eng co-design	Raise titre/productivity/purity; reduce downstream processing intensity via counter-current/membrane steps; validate on demo to eliminate scale artefacts pre-FID.	Titre (g/Liter); qP (g/Liter·h); yield; solvent use (kg/kg); rework/scrap %
Bankable offtake	Multi-year, outcome-label-aligned contracts to load first trains and reduce cost of capital.	Contracted volume (kt/y); tenor (years); price indexation; utilisation %

4.2.2.1.2 *Assessment on barrier – Legislation*

Legislation is a decisive market shaper and, at present, a binding barrier because it sets the evidentiary threshold for use and end-of-life and determines whether the environmental value of PHA is recognised economically. Three frictions recur:

(i) classification-centred rules treat food-grade PHAs as generic plastics regardless of verified biodegradability, narrowing eligible applications and deterring converter qualification;

(ii) end-of-life incoherence—certified compostables are not reliably accepted in organic-waste systems—breaks declared disposal routes and undermines buyer confidence; and

(iii) cross-policy competition for feedstocks (notably biogas subsidies), together with unpriced externalities for incumbents, tightens residue markets and depresses the reference price PHAs must meet.

Regulatory tempo magnifies these effects. Slow, multi-year policy cycles and uneven implementation collide with 36–48-month product/asset timelines, raising approval risk, delaying offtake, increasing the cost of capital and deferring first-of-a-kind investments. By contrast, jurisdictions that explicitly recognise environment-specific, fragment-free biodegradation tend to accelerate adoption and cost learning.

Decision-makers and procurers therefore ask for performance-based proof in the intended environment (soil, home or industrial composting): time-bound, fragment-free degradation under transparent boundary conditions (moisture/temperature regimes, representative microbiology). Certificates are valued but are insufficient when field realities diverge from laboratory settings; dossiers that bridge standards with scenario-specific field verification carry disproportionate weight in permitting and public procurement.

The market impact of design choices is visible in practice. Experts cite Spain's single-use regime, where blanket exclusions have effectively shut PHAs out of high-volume packaging, slowing R&D and hardening the price gap; conversely, agronomic and some marine uses advance where field data and certifications are recognised. Rules that target proven performance in the relevant environment trigger procurement pull, while input- or origin-based framings raise search costs and distort incentives. Ambition without delivery capacity (transition pathways, test infrastructure, harmonised standards) risks compliance leakage, quality loss and forfeited learning curves.

A constructive redesign prioritises performance and recognises multi-track end-of-life—mechanical/chemical recycling where appropriate and biological degradation where demonstrably effective—anchored in harmonised, season- and field-relevant methods, standardised reporting and auditable chains of evidence. Outcome-based instruments should replace material-class regimes, with permissions or prohibitions hinging on demonstrable, time-bounded, fragment-free degradation and ecotoxicological safety; substitutions should be judged on functional equivalence and improved footprint, not origin labels. Most experts support refined classification and labelling that binds claims to use environments (soil, home/industrial compost, aquatic), states boundary conditions (time windows, temperature/moisture ranges, minimum biological activity) and links methods, thresholds, labels and enforcement so buyers can make binary, audit-ready choices.

Views on subsidies diverge. Many warn of distortion and leakage; a minority favour tightly scoped, temporary, technology-neutral enablers (standards harmonisation, shared test infrastructure). The sharpest debate concerns single-use rules: one camp supports conditional access when PHAs show application coherence (limited service window, secured end-of-life, fragment-free degradation) with mandatory labelling/disposal instructions and enforceable penalties; the other argues blanket bans depress volumes, flatten learning curves and delay cost reduction.

A pragmatic pathway for AgriLoop follows four tracks:

(1) advocate performance-based policy by curating complete evidence chains (timeframes, fragment freedom, ecotoxicity) from lab → mesocosm → field for priority use cases and feeding them into consultations;
(2) co-develop clear labels that encode environment- and time-bound claims to cut search, audit and greenwashing costs;
(3) scale first in receptive channels (soil-contact agricultural formats, defined B2B, green public procurement) while preparing targeted fixes for blocked, high-volume segments (e.g., single-use packaging); and
(4) link internal development gates to external regulatory milestones (e.g., formal recognition of field tests), using transition markets to pre-finance operational learning.

In short, the ambivalence of regulation — both catalyst and constraint — can be resolved through outcome clarity. Once policy measures what PHAs do rather than what they are, the route to investable scale becomes clearer.

4.2.2.1.3 *Assessment on barrier – Scalability*

Although experts agree that scalable routes to PHA exist, the binding constraints are multi-origin and should be solved in parallel. In terms of hardware and infrastructure, progress is hindered less by exotic technology than by the immaturity of assets: there are few open-access pilot-to-demonstration-to-industrial bridges, standardised unit operations are not widely adopted, and there is little learning from long continuous runs. The result is higher downtime, scrap and quality assurance costs than for existing facilities, which slows converter qualification. A pragmatic consensus favours modularity over gigantism, such as multi-reactor trains and parallel lines, because biological and heat/mass transfer realities constrain the size of single vessels. Where funding allows, the practical path is to expand capacity by increasing the number of bioreactors, a trend already visible in regions that have scaled rapidly.

On the biological/performance axis, PHAs are stress-response products. Titres, productivities and purities cap output unless strain engineering and process control continue to improve. Robust — sometimes non-sterile — salt-tolerant processes are a credible solution because they reduce the burden of sterility and cut contamination-related downtime. However, they still require disciplined CIP/SIP and rigorous in-line monitoring to keep variability in check across trains and sites.

In terms of feedstock and logistics, residue strategies imply decentralisation. Seasonality, low bulk density and compositional drift mean that 5–25 $kt{\cdot}a^{-1}$ units are realistic when feedstocks are sourced locally and preconditioned at hub-and-spoke densification sites through processes such as sorting, dewatering and inhibitor-lean pretreatments. Single-site concepts of 500 $kt{\cdot}a^{-1}$ or more are widely considered impractical for residues: the supply radius required to ensure a consistent organic supply would compromise both the economics and quality control. Siting near stable, homogeneous streams and seasonal blending to specification are considered structural requirements for industrial cadence.

The scale versus price feedback loop is clear: without sufficient volume, unit costs will remain high, and without credible cost trajectories and offtake, finance will not be available. Near-term feasibility is therefore anchored in:

(1) Modular capacity additions that can be financed against specific, evidence-based use cases.
(2) Fast progression to continuous operation in order to identify 'scale artefacts' (e.g. fouling, solvent closure and heat integration) before capital expenditure is locked in.
(3) Standardised quality assurance /analytics so that converters can accept multi-site output under one specification.

The first commercial EU plant could be commissioned by 2030 if offtake and permitting align. However, broader deployment remains contingent on stable feedstock contracts, harmonised end-of-life recognition in target markets and access to project finance.

4.2.2.1.4 *Assessment on barrier – Production (operations & flowsheet)*

Production is the structural link between diverse inputs and market-ready pellets. Residue streams are not 'fermentation-ready' by themselves; they require concentration and conditioning prior to reliable metabolism. Once intracellular granules have accumulated, the recovery process involves extraction and purification steps that dominate the unit cost. In most flowsheets, downstream processing—including cell disruption, phase separation, polymer purification, drying and pelletising—accounts for a disproportionate share of OPEX and CAPEX, with solvent handling and recovery, as well as utilities such as heat, electricity, chilled water and compressed air, being major contributors. Respectable titres alone do not yield competitive price per kilo unless downstream processing is simplified and better integrated.

Variability translation and batch stability are also important factors. When using residues as a carbon source, heterogeneity in the upstream process propagates into growth and PHA accumulation, and then into molecular weight distribution, rheology and crystallisation drift in the converter. Therefore, operators should

(i) maintain biological performance within tight limits despite compositional noise, and
(ii) prevent this noise from reappearing as variability between lots after extraction.

This pushes plants towards spec-driven preconditioning and in-line/at-line analytics to steer feeds and harvest points, as well as recovery trains that minimise the carry-over of cell debris and low-level inhibitors. Where this discipline is weak, converters report warpage, brittle failure, unstable melt windows and wider certificates of analysis scatter.

Further, solvent-based routes deliver high throughput and purity, but require near-closed loops with high recovery yields, low entrainment and in-line quality control to control cost and environmental impact. Aqueous, enzymatic or membrane-assisted options reduce the need for solvents but can compromise throughput or polishing completeness unless paired with intensified separations. The principle of 'purity to purpose' applies across all routes: deep polishing is justified for sensitive applications (e.g. food-related), whereas technical and agricultural grades should avoid over-processing that increases cost and produces by-products without providing any additional functionality.

In addition, Europe has many capabilities but lacks assets: high factor costs and a shortage of standardised, automated production lines reduce overall equipment effectiveness and magnify start-up and shutdown losses. Regions that have deployed modular multi-reactor trains with codified standard operating procedures report faster learning curves and tighter cost control. Persistent issues are not limited to biological processes: fouling, solvent closure, heat integration, salt management and water recirculation are all factors that influence sustained cadence and cost per kilogramme. While some believe that capacity will follow once prices drop, most regard production excellence — repeatable fermentation plus lean, integrated downstream processing — as the precondition for any durable price improvement.

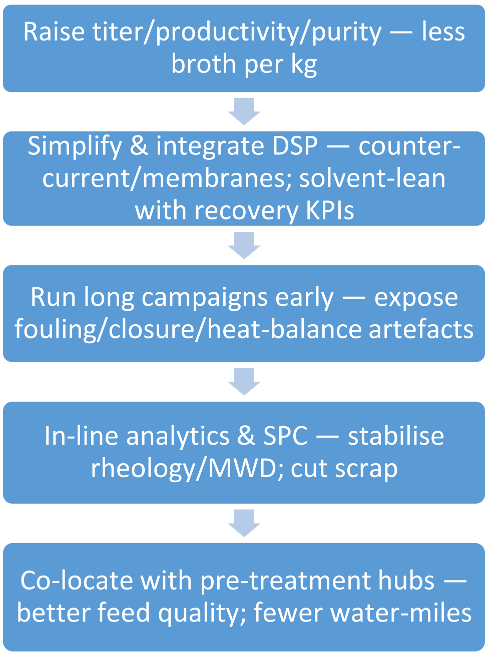


Figure 12: *Five-step operations-first playbook (Own compilation by Ecozept).*

<u>Production as a key limitation (scale & industrial maturity)</u>

Experts largely agree that production is the binding constraint on competitiveness—more a matter of site economics and industrial maturity than of chemistry. Europe is capability-rich but asset-poor: high labour, energy and compliance costs, coupled with a lack of large, standardised lines, yield price per kilo above Asian benchmarks and have contributed to past bankruptcies despite technical feasibility. A counterview holds that disciplined operations and reliable substrates can outweigh location, but even that camp concedes the region's factor-cost handicap should be managed through excellence.

Debate centres on maturity rather than possibility. The tools exist—fermentation and extraction are not exotic—but opinions diverge on what limits scale: resource costs, operational competence, or IP/licensing. Sceptics of the "tech is done" narrative point to the absence of long, continuous runs on standardised trains; without them, reproducibility, uptime and cost discipline lag polyolefin-style norms. Feedstock choice is a crucial nuance: scaling on conventional sugars/oils appears feasible; robust, reproducible performance at full industrial cadence using residue-based inputs has yet to be demonstrated.

Perceptions of homogeneity also split. Many practitioners still see property drift across chemistries and residue-borne fluctuations that unsettle fermentation, rheology and crystallisation; others report that consistent grades are already achievable and that remaining gaps are linked to extraction know-how, not to intrinsic material limits. Both camps converge on the same implication: treat cost as a system property and engineer consistency into variability.

The pragmatic path is clear: pair priced, detoxified, logistically sound residues with simplified, automated downstream processing to offset factor costs; move rapidly from demonstration to continuous operation so scale artefacts (fouling, solvent closure, heat integration) are exposed before capital is locked; enforce statistical process control and seasonal blending to narrow certificates of analysis scatter; document long-term stability to de-risk converter qualification; secure freedom to operate to avoid tollgates; and align output with policy value where verified biodegradation unlocks access or counts toward circular metrics, bridging today's price per kilo gap while scale and learning take hold.

4.2.2.1.5 *Wastes and by-products of production*

The "waste signature" of a PHA plant is a design variable shaped by feedstock and processing choices. Refined sugars yield simpler broths and low-load process waters; residue-based inputs shift the profile toward non-fermentables in liquors/solids (lignin fragments, ash, proteins, lipids, micronutrients) that should be separated, treated, or valorised. Downstream processing design then amplifies or dampens this profile: aqueous/enzymatic or membrane-assisted recovery keeps effluents recyclable, whereas poorly closed solvent extraction adds regulated organic loads. The governing rule is purity to purpose (see 4.2.2.1.4): medical/food grades justify deeper polishing; technical/agricultural grades should avoid over-processing that generates side streams without functional return. In all cases, downstream processing closure—high solvent recovery, water recirculation, and explicit salt management—aligns environmental and economic performance.

Even at good titres, complex agri-streams leave residual solids and solubles. Upfront characterisation (ash, lignin, proteins, lipids, inhibitor congeners) and selective pretreatment reduce this load. Where full conversion is unrealistic, outlets should be pre-planned so that non-converted material re-enters productive loops, for example via anaerobic digestion (AD) for energy, compliant soil amendments (subject to contaminant/ecotoxicity limits), or targeted recovery of enzymes/biochemicals where activity and purity justify it.

Beyond the obvious process steps, auxiliaries can quietly shape the waste profile. Flocculants, chelants, pH agents, stabilisers and nutrient feeds increase dissolved solids unless unit operations are integrated (e.g., counter-current washing, low-salt pH swings, membrane polishing) and targets are set to real specifications rather than "ultra-pure by default". Mineral nutrients and pH-control salts raise the salinity of mother liquors and wash waters; without deliberate bleed-and-recycle, crystallisation, or diversion to salt-tolerant uses, these impacts tend to surface late in permitting and in OPEX.

Where solvent extraction is used, solvent stewardship becomes a credibility test. The solvent mass balance should be treated as a KPI with audited recovery targets; volatile organic compounds (VOCs) are contained via high recovery, low entrainment and in-line QC. Aqueous or hybrid recovery is preferable where release specifications and throughput permit. "Next-generation" solvents (e.g., ionic liquids or lipid-based systems) should only be pursued with a demonstrated price per kilo advantage and near-quantitative recycling given current cost, corrosion, recovery-yield and environment, health and safety.

Lignocellulosic routes introduce inhibitors such as furfural, hydroxymethylfurfural (HMF) and phenolic compounds that suppress growth and polyhydroxyalkanoate (PHA) accumulation, extend batch times and increase side streams per kilogram of product. Formation can be minimised through selective, milder pretreatment with short residence times, supported by on-line inhibitor analytics to adjust conditions in real time, detox modules sized to measured loads (activated carbon, over-liming, targeted resins), and, where justified, tolerant strains to preserve titres/productivity.

Safe-by-design practice and transparent monitoring reduce permit risk and strengthen life-cycle assessment (LCA) quality. Strong acids, alkalis and oxidants can mobilise organics and mycotoxins and complicate effluent treatment; benign chemistries and proven detoxification methods are preferred. Evidence should be underpinned by LC/MS panels (liquid chromatography–mass spectrometry) and, where relevant, acute/chronic ecotoxicity assays.

In implementation, the emphasis is on flow-through discipline rather than add-on fixes: engineer the waste profile upstream via rigorous feedstock qualification and inhibitor-avoiding pretreatment; calibrate polishing intensity to purity to purpose and avoid additive overuse; prefer solvent-lean designs and, where solvents remain, manage recovery as a top-level KPI; valorise residuals by default through pre-planned outlets (AD, compliant soils, process-aid recovery); make inhibitors measurable with fast assays and tolerant biologies to hold productivity on residue feeds; and reflect minerals, inhibitors and other small toxic fractions explicitly in LCA inventories and permits, as these streams often determine both credibility and unit economics.

4.2.2.1.6 *Assessment on barrier – Availability of feedstock*

The issue is mobilisation, not mass. The constraint is converting dispersed, seasonal and compositionally variable residues into fermentable, specification-grade inputs at cost. Low bulk density and perishability increase transport and storage costs, while seasonality creates multi-month troughs that should be bridged without compromising quality. For sugar-bearing residues, pre-concentration to high sugar levels (tens of percent—up to about 60% reported for fermentation suitability) is typically required, immediately linking "availability" to local water/energy balances and on-site conditioning capacity.

Availability becomes economics through heterogeneity. Variability in moisture, ash, nutrient balance and inhibitor load means that "available" tonnes are not automatically processable. Stabilisation therefore relies on specification-driven pre-treatment and homogenisation (screening, washing, pH control, dewatering) plus seasonal blending to hold C:N ratios and inhibitor levels within tolerance. Without this normalisation, upstream noise propagates into fermentation instability and, downstream, into molecular-weight/rheology drift at the converter—both costly and acceptance-penalising.

Logistics determine the practical boundary. Cost-effective systems prioritise short-radius collection, hub-and-spoke pre-concentration/densification, and campaign operations modelled on established agri-industries (e.g., sugar). Shipping conditioned intermediates rather than raw residues buffers seasonality and reduces "moving water." Policy reshapes availability: biogas incentives compete for the same organics, setting a floor price and diverting streams; projects therefore co-locate with organics infrastructure to secure supply and protect margins.

Scale should match residue geography. For residue-only routes, credible plant sizes cluster around 5–25 $kt \cdot a^{-1}$. Larger single-site concepts face catchment-radius and logistics walls; modular replication aligned with local residue basins better fits seasonal supply and limits transport loss. A bankable intake requires multi-year, risk-stratified contracts; intake specifications (moisture, ash, inhibitor thresholds); quality assurance sampling with re-qualification triggers for new classes or seasonal drift; and blending databases to predict/correct composition before fermentation.

Practical playbook: favour inhibitor-lean, compositionally stable residues; install front-end densification and preconditioning to decouple seasonality from fermentation cadence; site and size from the residue map outward; and treat intake governance—specifications, sampling and blending rules—as operating infrastructure, not paperwork. While a minority downplays "availability" versus price and industrial maturity, they concede that without disciplined intake, biomass "on paper" does not translate into reproducible, economical feedstock in practice.

4.2.2.1.7 *Assessment on barrier – Durability*

Experts define durability as 'fit for service, then loss of properties'. Applications should retain their function within a defined timeframe, after which they lose their mechanical integrity to allow post-use degradation to proceed. The barrier arises when either side of the equation fails: premature loss of service or persistence beyond the declared timeframe. This constraint is most significant in outdoor, multi-season duty cycles. Neat PHAs lose properties too quickly for long-life formats because they have hydrolysable ester bonds and ready microbial access in moist or soil-contact settings. Silage films are not an option because microbes would consume the film, and any residual fragments would be unacceptable in feed. Likewise, greenhouse covers demanding 7–8 years of transparency and UV stability are incompatible without complex multilayers and stringent testing, placing them outside the near-term opportunity set.

Within the targeted agricultural sector, durability requirements are shorter and more varied and failing to meet them creates operational and reputational risk. Mulch films should retain their integrity throughout a growing cycle (often around six months) and then disintegrate in the soil. Horticultural twines should maintain line and knot strength, as well as modest UV stability, for a season (around six months), yet disintegrate in compost within two to four months. Transport trays and certain pots span a period ranging from months to a few years, depending on handling and storage. Beyond hydrolysis, an increase in time-dependent crystallinity can embrittle parts during storage or use. This undermines confidence in medium-term formats and perpetuates the perception of early brittle grades.

Designing the correct window involves striking a balance: stabilisation that protects against sun, heat and moisture can slow post-use breakdown, while minimal protection can lead to in-service failure. This trade-off can lead to conservative buyer behaviour and extend the qualification process. As degradation rates depend heavily on climate and soil moisture, credibility hinges on application-specific evidence demonstrating:

(1) retention of properties over the stated timeframe under representative exposure, and
(2) subsequent timely disintegration in the relevant environment without the formation of persistent fragments.

In practice, this means prioritising formats with a limited lifetime that are in contact with the soil, where durability can be programmed for the use phase and post-use breakdown is a functional advantage, while avoiding decadal outdoor exposure. In parallel, developers should close the trust gap by providing clear data trails that demonstrate the transition from stability to degradation under real conditions.

4.2.2.1.8 *Assessment on barrier – Transportation & logistics*

Finished PHA goods move through existing converter channels much like other polymers, but transportation and logistics are a structural constraint upstream. Seasonal, perishable, heterogeneous and low-density residues make the cost of delivered fermentable carbon—and the variation in input quality—logistics-driven rather than chemistry-driven. Seasonality, stability and density dominate outcomes: residues arrive in pulses; composition shifts with cultivar, weather and agronomy; high moisture and bioload raise risks of microbial spoilage, hydrolysis and inhibitor formation with every hour between harvest and conditioning; low bulk density increases transport cost per unit of carbon. If unmanaged, these factors translate into erratic fermentations and lot-to-lot variation downstream.

A robust control strategy is to co-locate fermentation with large, homogeneous side streams (e.g., food processors) and deploy regional densification/pre-conditioning hubs to "freeze" quality before transport. Hubs perform pressing, screening, partial dewatering and simple detox; operations run in harvest-aligned campaigns with storage buffers for inter-season continuity. This architecture shortens wet-haul distances, lifts payload density and turns seasonality into an operating calendar rather than a source of off-spec inputs.

Pre-conditioning should protect quality without over-processing. Rapid solid–liquid separation, moisture reduction and—where justified—pH adjustment suppresses growth and limit inhibitor formation prior to transport. Logistics doubles as a quality system: risk-stratified contracting, batch tagging and intake analytics at hubs enable segregation and blend-to-spec, reducing the chance that field-edge variability reappears as plant-scale instability.

Commercial cadence depends on disciplined contracting. Multi-year supply agreements with volume/tolerance bands and clear rejection or price-adjustment clauses are essential. Where residues compete with biogas/feed markets, forward contracts and take-or-pay structures secure availability; pricing is best indexed to auditable metrics such as moisture and ash. Long-distance wet hauling erodes unit economics and environmental claims, so projects favour short-radius collection for high-moisture streams and reserve longer hauls for pre-concentrated fractions. Leveraging existing organics infrastructure (e.g., utilities, storage and handling at anaerobic digestion sites) lowers capex and speeds ramp-up.

Overall, transportation and logistics are decisive enablers of residue-to-polymer reliability. Siting near stable supplies, adopting a hub-and-spoke pre-conditioning model and running campaign operations with traceable flows convert seasonal, low-density, perishable inputs into a managed, specification-grade supply that supports consistent processing and predictable costs.

4.2.2.1.9 *From raw rankings to weighted rankings:*

In order to achieve the objective of this study, expert rankings from a three-round Delphi (I–III) were combined with evidence-quality coding, following established Delphi guidance on iterative rounds, controlled feedback and convergence (Hsu and Sandford, 2007.; Linstone and Turoff, 1975; Okoli and Pawlowski, 2004). Ranks (1 = most important; 6/7 = least) were converted to Borda points (N+1−rank)

Each justification was coded against six criteria—specificity/mechanism, evidence/triangulation, contextual fit (Agri/B2B/residue-to-PHA), cross-round coherence, stakeholder relevance, and intensity—scored 0/0.5/1; their mean forms $J \in [0,1]$. We also captured dissent as $D \in \{0,0.1,0.2\}$. The coding logic aligns with established qualitative evidence appraisal and triangulation principles and consensus methods (Denzin, 2017; Fitch et al., 2001; Lewin et al., 2018; Miles et al., 2014).

For each {interview, barrier} we compute evidence-weighted points:

$$EP_{i,b} = BP_{i,b} \times \left(1 + 0{,}5 \cdot J_{i,b} - 0{,}5 \cdot D_{i,b}\right) \times w_i^{\text{round}} \times w_i^{\text{stake}},$$

Round weights are I=1.0, II=1.1, III=1.2 to reflect later-round convergence (Okoli and Pawlowski, 2004). Stakeholder weights follow topic relevance (e.g., Processor = 1.2 for production/processability; Regulator/Brand = 1.1 for legislation/market), in line with simple multi-criteria weighting practice (Belton and Stewart, 2002; Keeney and Raiffa, 1993).

Aggregating across interviews per barrier yields SumEP and SumBorda. The Evidence-Weighted Ratio $EWR =$ SumEP/SumBordashows how justification quality modulates raw ranks (>1 amplifies; <1 dampens). The final ordering metric is the Composite:

$$\text{Composite} = EWR \times \overline{\text{Borda}}.$$

For graphics, Mean Ranks are linearly scaled to 0–100 (1 → 100; 6/7 → 0). Composite is normalized to 0–100 by top-normalization (Composite/MaxComposite × 100). Sensitivity checks (±20% on coefficients/weights) left the Top-3 unchanged, indicating robustness. ((Belton and Stewart, 2002; Cohen, 1960; Miles et al., 2014)).

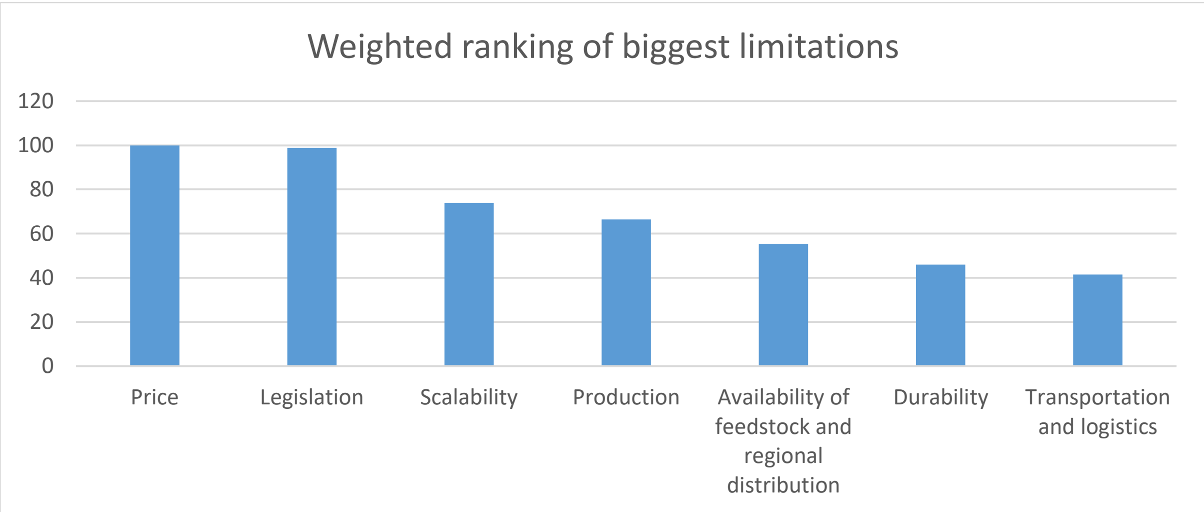


Figure 13: *Weighted ranking of the biggest limitations to PHA deployment (Own compilation by Ecozept,based on Delphi I–III)*

Price emerges as the top barrier, unequivocally. It ranks first on the mean rank scale (1–100) and leads the weighted view (composite-based 0–100), confirming that cost remains the main factor limiting market uptake. Strong, well-specified justifications linking price directly to downstream processing/extraction costs, economies of scale and process stability lift the evidence-weighting factor (EWR) above 1, thereby reinforcing the already high raw priority rather than diluting it. Legislation follows closely behind. Although its average rank is just behind that of price, triangulated arguments (specific country examples, alignment with microplastic restrictions and clear market-shaping logic) bring legislation even closer in the weighted view. This indicates that policy is not perceived as background noise, but as an active lever that can accelerate or stall adoption.

A second tier is formed by scalability and production. In the raw ranks, they are in the upper middle, but once weighted, both move up because experts consistently identify actionable mechanisms, such as access to open-access industrial capacity, demonstration-to-industrial scale pathways and, in production, the outsized role of downstream extraction (solvents and recovery steps) and standardisation gaps. This pushes their EWRs above 1, indicating that better mechanistic clarity and stakeholder relevance (processors addressing process hurdles) increases their priority compared to an unweighted reading.

The availability and regional distribution of feedstock is moderate. While the evidence acknowledges sufficiency in principle, it also highlights variability, pre-treatment requirements, density/moisture penalties and hygiene/seasonality. These factors are credible, yet they are heterogeneous across interviews. This keeps its EWR modest and limits upward movement. Durability and transportation and logistics remain lower-priority barriers in both scenarios. For near-term agri/B2B use cases, the operative design rule is 'fit-for-service, then let go'; long-lived endurance is rarely required, and many durability arguments remain generic. Logistics concerns appear real but conditional, becoming material at larger volumes or with unstable waste streams, so they remain subdued in the current analysis.

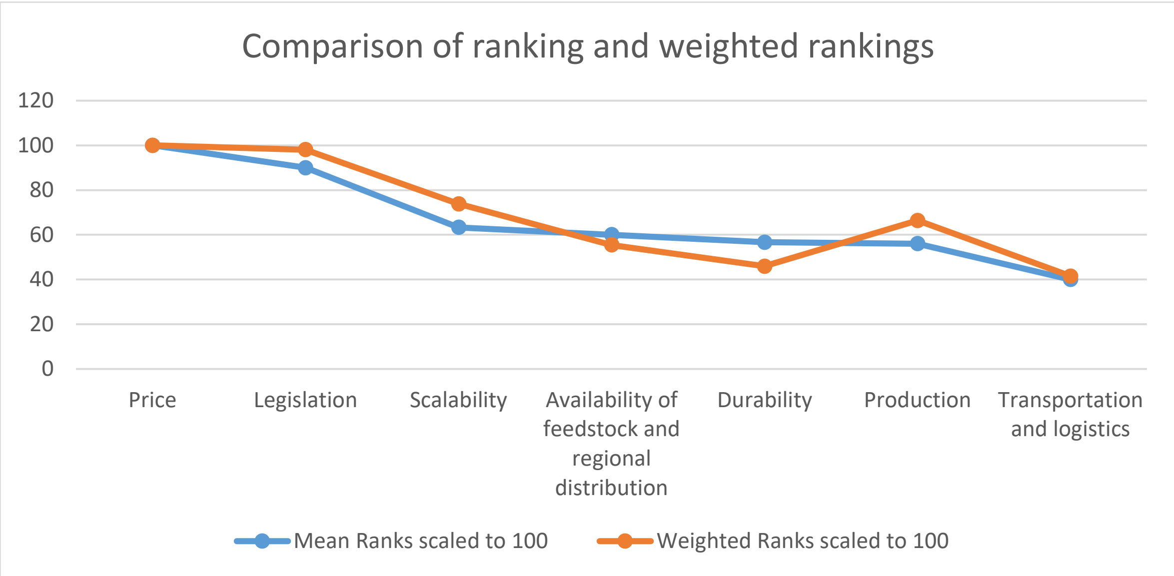


Figure 14: *Comparison of mean vs. respondent-weighted barrier ranks (both scaled to 100). Price and legislation lead in both methods; Production scores higher and durability lower in the weighted view, while transport & logistics remains least critical. (Own compilation by Ecozept).*

4.2.2.2 Additional barriers identified during Delphi III - Understanding of PHA functionalities among end-users as a barrier

Weak plastics literacy among consumers and, critically, professional buyers emerge as a structural barrier across interviews. Experts attribute this less to 'uninformed users' than to an industry communications deficit. For years, plain-language explanations of materials, trade-offs and environmental impact were lacking. In this vacuum, influencer soundbites take precedence over nuance, simplifying complex topics (e.g. microplastics) into memes. The result is a persistent perception–performance gap: even when PHAs deliver context-specific end-of-life advantages, scepticism shaped by half-truths raises adoption thresholds. Closing this gap requires evidence that travels: field data, case studies, third-party labels and simple visuals, routed through the channels where opinions are formed, not just technical papers.

A second durable hurdle is categorical oversimplification. Many buyers still treat 'PHA' as a single polymer rather than a tunable family, a misconception reinforced by legacy bias from the early, brittle grades. Although formulation science, molecular design (e.g. co-monomer ratios and molecular weight distributions) and quality assurance have improved markedly over the past 5–7 years, procurement often generalises the shortcomings of the past to the present day. The recommended remedy is structured re-qualification involving side-by-side benchmarking against existing products, transparent disclosure of formulation levers and tolerances, and application pilots demonstrating the following:

(1) runnability on existing equipment
(2) stable performance throughout the service life under relevant UV, thermal and moisture stresses
(3) fragment-free biodegradation in the stated environment and timeframe

Progress is real, but uneven. There is a shift in communication towards a problem–solution approach (linking grades to soil, home/industrial compost or marine-adjacent contexts with explicit time frames), and suppliers are adopting standardised tests and certifications to improve credibility with converters. However, myths persist, such as “biodegradable = litterable” and “bioplastics always contaminate recycling”, and awareness varies by sector and region. The emerging playbook has three parts:

(1) targeted buyer education that presents PHA as a formulated system rather than a pure polymer.
(2) 'Evidence ladders' (lab → mesocosm → field) that are translated into non-technical narratives; and
(3) visible reference deployments in applications where biodegradability is both functionally necessary and economically rational (e.g. well-matched agricultural uses).

The underlying principle is clear: improving end-user understanding is not just peripheral marketing — it is fundamental to the commercial infrastructure that determines whether technically sound PHAs become trusted and specified materials.

4.2.3 Expectations and limitations for PHA – Key findings

Key takeaways:

- Consider the co-engineering of function, stability and end-of-life, not sequentially. Near-term wins are bounded-lifetime, soil-contact articles (up to about 1 year).
- Manufacturability is the entry ticket: a stable melt window, predictable crystallisation and repeatable rheology on existing film/thermoforming lines.
- Claims should be article- and gauge-specific, with field-linked, fragment-free biodegradation going beyond certificates.
- Economics are downstream processing-led: currently €5–10/kg (≈ €6), with a path to €3–4/kg running through increased productivity, solvent-lean/closed downstream processing, modular trains and pretreatment-light feeds.
- SSbD = auditable spec chain (inputs → downstream processing → release), GMO-free biology/feeds, non-toxicity and additive traceability.

Entry criteria (non-negotiables):

- Evidence passport: laboratory → mesocosm → field; demonstrate disintegration, CO_2 evolution and time-resolved disappearance of particles under the declared boundary conditions (soil type, climate, season and placement).
- Service life → 'let go': property retention over the declared use window, followed by rapid, fragment-free decay in the intended environment.
- Article specificity: claims are tied to real geometry and gauge; there are no generic 'biodegradable' shortcuts.
- Manufacturability: stable bubbles/welds and gauge control, with standard operating procedures in place to prevent post-crystallisation embrittlement.
- Quality and safety (SSbD): GMO-free organisms/feedstocks, contaminant controls, full additive/migration dossiers, traceability and documented analytics at the time of release.

Functional and material insights (what to engineer).

- Functional envelope: mechanical integrity under UV, moisture, temperature and handling, followed by decay without the persistence of micro/nanoplastics.
- Processability: a usable melt window, predictable crystallisation kinetics and reproducible rheology for an uneventful drop-in on extrusion and thermoforming assets.
- Bounded stability: 'Robust-enough' stabilisation via architecture, nucleation and minimal stabilisers; thickness and climate govern lifetime.
- End-of-life: certificates do not constitute proof; evidence ladders are required.
- Optics/printability: manage intrinsic tint and thermal drift using compatible masterbatches and inks; favour minimalist pigmentation for B2B films.
- Composition/blends:
    - PHB-rich compositions offer stiffness and heat resistance.
    - Softer PHAs, starch, PBAT and PBS → processability and toughness.
    - Fillers → modulus tuning (watch out for moisture and adhesion).

Near-term core vs. deferred

- Core now (≤ about 1 year, soil contact): mulch films, plant-through/plant-with pots and horticultural twines.
- The second wave/conditional category includes thin thermoformed trays and coated articles with route-compatible systems.
- Deferred/out of scope (for neat PHAs): long-life outdoor products (e.g. 5–8 year greenhouse covers) and thick-section parts without multilayer re-engineering or dual proofing (service and end-of-life).

Economics and scale:

- Today, the cost is €5–10/kg (approximately €6), with downstream processing dominating OPEX/CAPEX (extraction, purification, solvent handling and drying).
- Cost-down levers: Increasing the title, productivity and purity; solvent-lean or near-closed recovery (KPIs on balance); counter-current/membranes sized according to the required level of purity; standardised, modular, multi-reactor trains (5–25 $kt \cdot a^{-1}$); and pretreatment-light, inhibitor-lean feeds.
- Monetising performance: outcome-based signals (eco-modulated fees, GPP) shift buying from price per kilo to €/function.

Operations & feedstock:

- The primary constraint is residue heterogeneity (moisture, ash and inhibitors) leading to variability in fermentation, MWD and rheology.
- Control measures: spec-driven pre-conditioning; in-line and at-line analytics and SPC; membrane polishing; long-campaign operations; solvent-recovery KPIs; and side-stream valorisation.
- Supply design: hub-and-spoke densification; short wet haul; campaign scheduling; risk-stratified contracts; sites selected from the residue map.

Regulation and market design (enablers):

- Outcome-based, SSbD-aligned frameworks define fragment-free, time-bounded and environment-matched degradation, which is then taken into account in fees and procurement.
- Harmonised labels and methods lower audit costs and speed up the qualification process.
- Re-qualification and literacy: structured protocols and visible reference deployments in coherent soil-contact use cases.

Risks and mitigations (execution view):

- Price/downstream processing OPEX: intensify upstream biology; close solvents; polish to the required level of purity; automate and standardise processes.
- Address durability window mismatch by engineering 'just-enough' stabilisation and linking property-retention curves to field data by climate/gauge.
- Feed variability: hub preconditioning, seasonal blending and inhibitor-lean intake, as well as at-line analytics and SPC.
- Logistics: minimise wet miles, establish quality-freezing hubs, implement batch traceability and pre-agree fallback outlets.
- Authorisations and competing incentives: conduct early scoping, provide technology-neutral support and align with GPP to secure initial volumes.

Table 11: *Barrier-to-lever map for PHA market deployment. Summary of key obstacles, their underlying importance, and actionable levers identified across Delphi rounds. (Own compilation by Ecozept).*

Barrier	Importance	Levers
1. Price (about €6/kg avg; €5–10 band)	downstream processing-heavy, low WTP in B2B	↑ titre/productivity/purity; solvent-lean/closed downstream processing; modular trains; pretreatment-light feeds; price per function policy
2. Legislation (fragmented/classified)	Slow/unclear pathways; competing incentives	Outcome-based eligibility; harmonised labels; tech-neutral fiscal tools; GPP anchors
3. Scalability/asset maturity	Few demo→industrial bridges	Standardised multi-reactor topology; early long-campaign runs; shared standard operating procedures/analytics
4. Production & downstream processing	Variability; solvent/utilities drive OPEX	Spec-driven pre-conditioning; in/at-line analytics; purity-to-purpose; solvent KPIs; automation
5. Feedstock availability/quality	Seasonal, low-density, perishable	Hub-and-spoke densification; risk-based contracts; seasonal blending DBs; inhibitor-lean prioritisation
6. Durability window	Over/under-stabilisation risks	“Robust-enough” stabilisation; lifetime models linked to field; focus ≤ about 1-year soil uses
7. Logistics	Cost & hygiene penalties	Co-located biorefineries; quality-freezing hubs; batch traceability; long-term supply frameworks

4.3 Extracted and microbial Proteins (MP)

Based on stakeholder consultation (Delphi I–III), the chapter provides a practical frame for extracted and microbial proteins in food and feed. It sets decision gates for feedstock quality and plant fit, clarifies as-processed performance and safety documentation, and specifies format/handling expectations. The aim is to define the minimum, SSbD-aligned evidence package required for B2B qualification.

4.3.1 Stakeholders' expectations

4.3.1.1 Expectations on critical qualities and functionalities of MP

Across interviews, "quality" is defined as a layered construct rather than a single number. In feed, buyers start with the nutritional core—crude protein, high digestibility and real biological utilisation—then enforce palatability as the non-negotiable intake gate. In food, the bar rises to include techno-functional performance under process-relevant conditions (gelation, emulsification, water/oil binding that survive hydration, shear and heat) and explicit allergenicity assessment. Safety is evaluated on two parallel tracks. Product/animal safety is certificate-driven: every lot should clear HACCP/GMP controls with contaminant panels (heavy metals, pesticides/Persistent organic pollutants (POPs), microbiology) documented by lot-specific certificates of analysis. Process/worker safety is about physical fit in factories: material should arrive dry, free-flowing and low-dust so it won't bridge hoppers or foul lines; pelletised or lightly fat-coated formats are preferred for dust suppression and predictable flow. Put simply, a "safe" microbial protein is both chemically clean for animals/humans and physically benign for mills and operators. Several experts add a production-side nuance: compared with extracted plant proteins, some MPs are more demanding to ferment and handle upstream, which elevates the importance of disciplined hygiene, in-process controls and release testing to keep lot-to-lot behaviour tight as volumes scale.

4.3.1.2 Functional requirements for food

Experts frame MP less as a commodity input and more as a functionality toolkit whose value is proven "as processed," not in abstract. In food, acceptance starts with sensory neutrality—clean flavour and acceptable colour—and then turns on a targeted techno-functional profile that survives the real unit operations of the product (hydration → shear → thermal ramps such as extrusion, cook–hold, pasteurisation/retort, and freeze–thaw). The required behaviours recur gelation/texturization for bite, elasticity and juiciness; stable, clean emulsification; controlled flow and reliable water/oil binding. No single MP excels everywhere: proteins that gel decisively can overset delicate systems, while great emulsifiers contribute little to fibrous texture. Consequently, high-MP products are almost never 100% MP. Formulators co-blend MP with complementary plant proteins and a lean, purpose-built binder/structurant stack (hydrocolloids/starches/protein binders) to close gaps in cohesion, juiciness and shape retention while meeting label and cost of goods sold constraints. The workable inclusion range is bounded by the MP's own functional envelope (gel–emulsion–viscosity trade-offs) and by process conditions—hydration time, shear history, salts/pH, and thermal profile.

Experts require standardised, application-bound ("as processed") functional data for microbial proteins (MP)—quantified read-outs for gelation and emulsion performance, water- and oil-holding, and viscosity/shear behaviour—together with practical specifications and documentation (lot-to-lot consistency; dry, free-flowing formats suited to plant handling; function-oriented specification windows and Certificates of Analysis, certificates of analysis). Processability also matters operationally: predictable dispersion and hydration with low dusting (agglomeration/instantisation where helpful) and physical specifications for dry formats (particle-size bands, flow indices) to ensure consistent plant behaviour.

Nutrition and safety are treated as baseline gates benchmarked to incumbents (e.g., soy). Experts expect declared crude and digestible protein with a full indispensable amino-acid profile, and evidence that these attributes persist through the intended process. Allergenicity requires explicit assessment and a labelling plan; anti-nutritional factors should be minimised and documented; for high-nucleic-acid single-cell protein intended for human use, suppliers are expected to set a purine limit and show a validated reduction method. Chemical safety is certificate-driven (contaminant panels consistent with food-grade sourcing), while shelf-life depends on moisture/aw control and oxidative stability where fats are present, supported by clear storage/handling standard operating procedures.

In practice, MP "wins" in food when it couples good-enough nutrition and clean flavour with an application-fit functional profile that holds up under process, delivered with quantified, as-processed specifications and toolkits—at cost-in-use near parity and, ideally, with a cleaner-label formulation than the incumbent alternative.

4.3.1.3 Functional requirements for feed

Experts converge on a clear standard for MP in feed: MP must behave predictably in the mill, perform nutritionally at line, and arrive physically fit for plants and operators. On the processing side, MP is expected to disperse and hydrate reliably, move cleanly through conditioning and extrusion, and retain "as-processed" functionality that supports pellet durability (low fines) and clean post-extrusion oil-coating. Buyers ask for compatibility maps that flag pH and salt sensitivities and interactions with common co-proteins and binders, because small shifts in ionic strength or calcium can tip viscosity, gelation, or water-holding. Enzymatic hydrolysis can lift digestibility but may induce stickiness in pelleting/extrusion unless binder selection and dryer set-points are tuned to protect pellet integrity.

Nutritionally, MP is judged on crude protein (CP), digestibility, and biological utilisation—with palatability as the intake gate. To count as a protein ingredient (not a filler/binder), CP should reach about 50–60%; 60–65% is preferred for routine use, and ≥65–75% is the credible fishmeal tier. High protein must be matched by high digestibility—≈85% or higher for protein and key indispensable amino acids (IAA)—reported with species- and life-stage-relevant coefficients and protected in process design (avoid excessive Maillard/crosslinking; ensure cell-wall disruption so lab numbers translate at line). The IAA profile should be fishmeal-adjacent: lysine is typically first-limiting and methionine often trends low, both managed at diet level via complementary proteins and, where permitted, crystalline amino acids.

Further, species nuances matter. Arginine strengths can be leveraged in salmonids; histidine sufficiency links to cataract control; carnivores expect low fibre and lipid-led digestible energy, so excess carbohydrate depresses performance and should be capped. Palatability is the gate before all others: yeasts are often well accepted; some bacterial MPs need pallets or off-note management. Adoption is evidence-led with staged intake/feed conversion ratio (FCR) checkpoints and predefined stop criteria (e.g., more than 10–15% intake drop or sustained FCR deterioration).

Formulation is specification-led and empirical. Most programmes start around 10–15% total MP inclusion and set ceilings via species- and life-stage-specific trials with early intake/FCR checkpoints. Product grades are positioned by CP tier (<50–55% CP for functional/binder roles; 50–60% CP as secondary protein with constrained inclusion; ≥65% CP as fishmeal-adjacent concentrates). First-limiting amino acids are corrected through blends and, where allowed, crystalline amino acids. Digestible protein is balanced against digestible energy (lipids carry most dietary energy), with small additions of hydrolysed carbohydrate used to protect pellet integrity without over-carbing carnivores. Practically, MP qualifies as a feed protein when it couples high CP, high digestibility, and a complementable amino acids profile with managed palatability, evidence-based inclusion by species/life stage, and a mill-ready, low-dust physical form—underwritten by lot-level cleanliness and quality systems that keep throughput predictable and operators protected.

Safety is managed on two fronts. Product/animal safety is documented under HACCP and GMP. Buyers expect certificates of analysis at lot level covering macro-composition (protein, lipid, carbohydrate, ash), a full IAA profile and, for feed, species- and life-stage digestibility coefficients; contaminant panels (metals, pesticides/persistent organic pollutants, POPs, and—where relevant—mycotoxins); microbiology; and explicit disclosure of nucleic-acid (purine) content plus any reduction method for sensitive uses. Process/worker safety is physical: materials should arrive dry, free-flowing, and low-dust. Granulated, pelletised or lightly fat-coated formats are preferred. Suppliers typically state particle-size distribution, bulk density, flow indices/angle of repose, moisture (typically 5–12%) and water activity (aw, typical ranges< 0.7), dustiness ratings and—where lipids are present—an antioxidant strategy (e.g., tocopherols), together with validated shelf-life and storage/transport humidity controls. Safety data sheets (SDS) and practical personal protective equipment /handling guidance are expected, and flow should be validated at typical plant humidity/temperature, as MP dusts can be immunostimulatory. Quality systems round this out with full traceability and hold/rework/reject protocols and change-control notices.

4.3.1.3.1 *Assessment on essential requirements for aquaculture:*

Table 12: *Ranked acceptance gates for microbial protein in feed formulations (Own compilation by Ecozept).*

Priority rank	Requirement	Importance level	Non-negotiables / stop criteria
1	Digestibility	CRITICAL gate	≥ 85% protein digestibility; process avoids Maillard/crosslinking; effective cell-wall disruption.
2	Nutritional value / Protein level	HIGH	≥50% CP minimum; 60–65% preferred; about 65–75% to credibly compete with fishmeal tier.
2	Amino-acid profile	HIGH	Manage lysine first-limiting and low methionine via blends/crystalline amino acids (where permitted); ensure species-specific arginine/histidine adequacy.
3	Palatability	MEDIUM	Terminate trial if intake decreases more than 10–15% or FCR worsens; stabilise intake with palatants/blends.

Experts rank **digestibility** as the first bottleneck (see Table 12): if indispensable amino acids are not bioavailable, nutrients are wasted, FCR worsens and faecal loading rises. Consequently, MP must demonstrate 'as-processed' protein and IAA digestibility of ≈85% or higher under the real thermal and shear histories of conditioning/extrusion—not just bench assays. Process design is part of the brief: avoid Maillard/crosslinking artefacts and ensure effective cell-wall disruption so laboratory coefficients survive the line.

For **nutritional value**, to qualify as a protein ingredient rather than a binder/filler, CP should meet the ranges defined in 4.3.1.3. Formulation balances digestible protein with digestible energy (lipids carry most dietary energy), and excess carbohydrate is capped in carnivores to prevent performance loss. Inclusion is typically phased in (starting at about 10–15% total MP) with early intake/FCR checkpoints to establish species- and life-stage-specific ceilings.

The **amino-acid profile** sits close behind. The target is a fishmeal-adjacent pattern: lysine is commonly first-limiting and methionine often trends low; both are managed at diet level via complementary proteins and, where permitted, crystalline amino acids. Species nuances matter: arginine strengths can be leveraged in salmonids, and histidine sufficiency is monitored for cataract control.

Finally, **palatability** is the intake gate. It is usually tuneable—via blending, palatants/flavours and upstream off-note reduction—with yeast MPs often well accepted and some bacterial MPs needing more support. Programmes proceed evidence-led: staged preference/intake trials, allowance for a short adaptation period, and predefined stop criteria (e.g., more than 10–15% intake drop or sustained FCR deterioration).

4.3.1.4 Ensure a stable raw material and a homogeneous MP

Experts converge on a simple premise: stable MP production starts at the intake gate. The cheapest and most reliable path is to anchor on traceable industrial side streams with predictable composition; heterogeneous household wastes require heavy pre-processing (hydrolysis/fermentation, filtration/membranes) that generates residues and quickly inflates costs. A compliance nuance is decisive for human food routes: the legal classification of inputs matters—materials deemed “waste” are generally ineligible, while “by-products” can proceed under HACCP/traceability, so eligibility must be secured before economics are meaningful. Operationally, stopgaps such as freezing and shipping small volumes can standardise supply in pilots but become inefficient at scale. The preferred architecture is co-location of substrate supply and fermentation (or at least first-stage downstreaming) to minimise water miles, tighten inflow specifications, and stabilise outputs.

The experts set out a simple intake-to-delivery control plan. This ensures a secure year-round supply in line with clear specification windows (C:N range, dry solids, fermentables and inhibitor limits), and rapid QC verifies this at the gate. The target C:N is then blended to stabilise fermentation. Where variability persists, convert upstream materials into organism-ready intermediates (e.g. sugars, glycerol or, on whey routes, lactic acid) to decouple plant uptime from seasonal drift. At the other end of the process, supply a dry, free-flowing ingredient that mills can handle, such as powder or granules rather than wet slurries. Physical specifications should be considered alongside nutritional ones, such as moisture content of about 5–12%, aw which typical ranges around <0.7, defined particle size bands, and bulk density and flow/angle-of-repose parameters, to ensure clean dosing and consistent behaviour on commercial lines.

Homogeneity is hardest with whole-cell products. While amino-acid profiles are relatively stable, macro fractions (protein/fat/carbohydrate) can swing with substrate, and fat content/profile is a recurring hotspot with downstream implications. The pragmatic response is to treat output like a recipe problem: publish tight spec windows, monitor lot-by-lot macro composition, and apply predefined corrective blends (e.g., buffer high-fat lots or top up protein with complementary sources such as wheat/corn gluten). Where SKUs demand narrower variance, partial concentration of biomass can tighten specifications without full, cost-heavy isolation. Shelf-life and transport round out the design: proteins travel more easily than fats but still need humidity control and, where lipids are present, antioxidants (e.g., tocopherols) to protect quality over more than 12 months. On the inbound side, it is often cheaper to convert residues to more stable, denser intermediates than to haul low-density wet streams over distance.

Taken together, the expert playbook is consistent: co-locate where it saves water and variability, qualify and standardise feedstocks up front, and ship a dry, spec-tight ingredient that mills can handle. Do that, and upstream variability is translated into homogeneous, formulation-ready MP with protected unit economics and a cleaner path through regulatory gates.

4.3.2 Main limitations and barriers to the market potential of MP

This chapter summarises the results of all three Delphi rounds in order to identify and analyse the main barriers to the adoption of MP in the food and feed sector, paying special attention to aquafeed. First, we rank the barriers using the mean of the interview scores (1 = most important, 6 = least important), and then we explore the justifications and practical implications in more detail (compare with 4.2.2).

4.3.2.1 Main limitations and barriers to the market potential of MP– Ranking and justifications

4.3.2.1.1 *Main limitations and barriers to the market potential of MP – Food:*

Table 13: *Ranking of market-entry barriers for MP in food: mean expert ranks (1 = most important) and scores normalized to 100 (Own compilation by Ecozept).*

Barrier	Mean rank (n=interviews)	Scaled 0–100*
Price	1.3	94
Scalability	1.5	90
Legislation/regulatory	2.0	80
Geography (siting vs. residues)	3.2	56
Consumer acceptance & comparability	3.3	54
Logistics	4.0	40

Assessment on barrier – Price

Price is the dominant barrier to MP in food and is tightly coupled to scale: at pilot/early volumes price per kilo is too high, and only larger, high-uptime lines bring costs down. Sensory and techno-functional fit is necessary but not sufficient; sustainability alone rarely earns a premium. Small, conditional uplifts happen only when MP improves cost-in-use (e.g., simpler recipes, lower quality risk). Broad adoption hinges on cost-down via stable, low-cost inputs, solvent-lean downstream, and smart energy strategy—until then, MP wins mainly where parity or near-parity on cost-in-use is achievable.

Assessment on barrier – Scalability

Scalability emerges as the decisive cost-reduction lever and adoption gate. At sub-scale, the cost per kilogramme (€/kg) and variability remain high, so offtakes are tentative. At industrial scale, with high uptime and continuous production runs, fixed and semi-fixed costs are diluted, and price parity becomes plausible. Major players require relevant, reliable tonnage and tight, reproducible specifications over time for routine inclusion (see 5.2.2.2 for indicative thresholds). In practice, 'scaling' requires capacity and control: stable feedstocks, SPC-driven process discipline and solvent- and energy-efficient downstream processing to keep specifications and costs on track.

Assessment on barrier – Legislation/Regulation

Legislation and regulation are primary barriers and pacing items for MP, especially for human food, regardless of technical fit. Approval regimes are rigorous and slow, adding time, cost and uncertainty. Progress hinges on clear classification, evidence-based documentation and smart sequencing (e.g. feed/pet first; faster jurisdictions) while food filings are processed. In practice, experts need a regulatory operations plan (including pre-submission alignment, templates and HACCP/traceability for residue routes) and should treat approval timelines as the critical path for market entry and financing.

Food (EU Novel Foods):

Experts welcome the Novel Foods regime for the trust it confers, yet decisions routinely exceed the nominal about 2-year timeline (see Section 5.2.2.1 for order-of-magnitude benchmarks). Bottlenecks are practical rather than legal: inconsistent guidance, limited use of standard templates, opaque milestones, and too little structured regulator–applicant interaction. The recommended response is a regulatory-operations plan: pre-submission alignment on scope and toxicological endpoints; submission-ready dossiers mapped to agreed endpoints; internal templates/checklists to cut iterations; early scheduling of critical studies; and project/financing plans that assume more than 24 months. In parallel, sector engagement for non-legislative improvements—public templates, clearer guidance notes, predictable milestones and feedback loops—can shorten time-to-decision without diluting rigour.

Assessment on barrier – Geography

Rather than being seen as a structural blocker, geography is framed as a design variable. Experts emphasise location choices that convert distance into economics, such as co-locating fermentation and the first stage of downstream processing with wet, variable residue streams to avoid transporting water, using hub-and-spoke aggregation and light preconditioning to buffer seasonality, and reserving long transport for stable, dry, free-flowing outputs. In practice, experts identify regions with high residue density, secure multi-year supplies with defined specification windows and model routes to minimise 'wet miles' and maintain time-definite deliveries. As geography is interlinked with cost, scale and feedstock stability, it is managed through planning: co-location where it reduces inbound mass and volatility; contracted lanes and buffer stocks where it does not; and outbound formats engineered for flow and shelf life. When integrated in this way, logistics becomes a lever for price per kilo and reliability rather than a stand-alone barrier to market entry.

Assessment on barrier – Logistics

Logistics is treated as an executional variable rather than a structural barrier. For food applications, standard industry playbooks are followed, and it is closely linked to geography and feedstock location. Mitigation is straightforward in practice: locate near residue hubs to minimise 'water miles', use hub-and-spoke aggregation to buffer seasonality and secure time-definite, contracted lanes via established third-party logistics providers. Risk can be further reduced by using inventory buffers and safety stock (but only for the cold chain if the product requires it) and by shipping in stable, mill-ready formats, such as dry, free-flowing powders or granulates with defined moisture/aw and particle size bands. In short, with sensible location, optimised routes, and tightly specified product formats, logistics becomes manageable and secondary to higher-impact barriers such as price, scale, and regulation.

Assessment on barrier – Consumer acceptance & comparability

Consumer acceptance is considered to be conditionally sufficient rather than a primary gatekeeper. The presence of existing microbial products on the market is seen as proof of baseline acceptance, with price, scale and regulation being seen as the more significant hurdles. As retail prices converge and products reach parity in terms of taste, texture and process-relevant functionality, confidence is expected to deepen. The practical focus is therefore on execution: achieving sensory parity, emphasising clear value cues such as credible nutrition and verified sustainability, and leveraging in-market precedents and familiar formats to reduce perceived risk. Under these conditions, acceptance is considered more manageable than the structural barriers that directly govern uptake.

4.3.2.1.2 *Main limitations and barriers to the market potential of MP – Feed:*

Table 14: *Ranking of market-entry barriers for MP in feed: mean expert ranks (1 = most important) and scores normalized to 100 (Own compilation by Ecozept).*

Barrier	Mean ranking	Mean ranking scaled to 100
Legislation/regulatory	1.1	98
Scalability	1.5	90
Price	1.7	86
Logistics	2.7	66
Geography (siting vs. residues)	3.4	52
Consumer acceptance & comparability	3.6	48

<u>Assessment on barrier – Legislation/Regulation</u>

Regulation is described as a primary constraint for feed applications—especially aquafeeds for fish destined for human consumption—when MP is produced from residual or "waste" streams. Under current EU legislation, many of these materials are not generally eligible for use in feed, so the first milestone is to ensure that the feedstock is eligible (in terms of hygiene, traceability, HACCP and contaminant control). Without the residual inputs being approved in advance, the ingredient dossier cannot progress. Once this has been secured, the pathway for ingredient authorisation depends on classification (ingredient vs. additive/functional component), the GMO status of the production organism and the intended dietary function. If claims are made, the additive framework applies, and EU feed catalogue inclusion and quantitative, species-specific digestibility data are often required.

Although procedures exist, including for GMO routes, the administrative pace is widely viewed as too slow, sometimes taking up to a decade, which places Europe at a disadvantage compared to faster jurisdictions. Another issue is the fragmented nature of expert reviews: different disciplines, such as toxicology and immunology, may interpret microbe-related immune modulation differently, resulting in inconsistent judgements and delays.

Experts therefore recommend practical upgrades that preserve safety while improving efficiency: early, joint scoping meetings with all relevant expert disciplines to pre-align endpoints and data needs; framing submissions in the use context so immune modulation is assessed as an intended functionality (or bounded risk) rather than a blanket hazard; and clear categorisation (ingredient vs. additive; with/without functional claims) to route dossiers to the correct legal framework from the outset. At policy level, they advocate time-bound reviews and integrated expert panels that issue coordinated opinions. Where timing is critical, some experts diversify scale-up geographically while EU approvals are underway to avoid stalling learning and supply development. More broadly, a policy–innovation gap remains: frameworks written for legacy inputs do not yet fully accommodate modern processing controls or circular side streams; until clarified or updated, regulation will continue to hinder scale and timing.

Early engagement with the relevant authorities and the European Food Safety Authority (EFSA) to clarify data requirements, as well as conducting pilot studies using already-eligible inputs to build safety and performance evidence, are considered pragmatic ways to maintain programme progress while broader approvals are being finalised.

Assessment on barrier – Scalability

Experts consistently rank scalability as a top barrier for microbial protein (MP) in aquafeed. Without the ability to deliver relevant tonnage reliably, MP cannot meet industrial needs or achieve cost competitiveness. Buyers emphasise that scale underpins cost reduction and stable pricing; insufficient volume keeps price per kilo high and limits inclusion to niches.

For the main European species—salmon, trout, seabass, seabream—manufacturers require large, steady volumes before routine inclusion is considered. Experts cite indicative thresholds of ≥10,000 t/year as a minimum, with 30,000–50,000 t/year preferred to be relevant for major players. Crucially, volume growth must come without sacrificing specification consistency, supply reliability, or quality/safety controls; otherwise MP remains a niche ingredient regardless of technical merits.

There is room for niche/functional SKUs at smaller volumes to generate early references and revenue, but broad adoption hinges on security of supply and a credible pathway to steadily scale output while keeping specifications tight. As indicative gates for fermentation scale-up, several interviews referenced pilot thresholds on the order of about 50,000 Liters.

Assessment on barrier – Price.

Experts consider price to be a decisive factor in the adoption of MP for aquafeed. In the pilot and early market phases, unit costs are high, which limits their use. The working assumption is that economies of scale and operational learning will reduce the cost per kilogramme. Buyers judge MP strictly in terms of cost versus fishmeal/soy, taking into account amino-acid top-ups and palatability aids, and only accept limited premiums where there is demonstrable performance or risk-reduction value (e.g. improved feed conversion ratio/survival rate, or supply/price stability). Most experts rate price as one of the main barriers today, even those who consider it "moderate" until costs normalise with scale.

The price is determined by the total cost of ownership across the following stages: intake, pre-conditioning, fermentation, downstream processing and logistics. Two factors dominate. Firstly, processing intensity varies with feedstock quality and consistency. Clean, specification-stable side streams require lighter conditioning and polishing, whereas heterogeneous inputs necessitate additional steps, increased energy and water usage, and rework. Secondly, sustained throughput and asset utilisation determine overhead dilution: standardised, automated, long-campaign/continuous processes reduce the cost per kilogramme, whereas small, stop-start processes do not. Other factors include residue/side-stream pricing and eligibility, energy/labour/compliance costs, and wet-haul logistics. Experts caution against optimising a single step (e.g. faster fermentation or shipping intermediates) only to see the cost reappear elsewhere. The key principle is to optimise the entire system to meet specifications at the lowest possible total cost of ownership. Within OPEX, energy is repeatedly cited as the main cost driver (e.g. aeration/agitation, thermal steps and drying). However, switching to low-carbon power can increase the short-term cost per kilogramme, even though it improves the life cycle assessment (LCA), so scenarios should make this trade-off explicit.

In practice, the pricing strategy involves two key elements: a feedstock strategy and a cadence strategy. The former involves securing long-term contracts for low-cost, specification-stable residues, while the latter involves enforcing tight intake windows and supplier qualification to minimise purification load. Other elements include reducing 'wet miles' via co-location or hub-and-spoke densification/dewatering, and running standardised multi-reactor trains with in-line analytics to stabilise cycles and reduce scrap. To make the price trajectory investable, experts recommend creating a scale-up roadmap linked to guaranteed sales, by aggregating demand across feed, pet food and (where applicable) food, increasing capacities from pilot level to about 10 kt/y and then to 30–50 kt/y, and tracking price per kilo against throughput targets. This makes cost convergence visible and reduces adoption risk.

Assessment on barrier – Geography

Experts treat geography (residue location versus plant siting) as a design variable, not a hard blocker (ranked from lower-priority to moderate across interviews). Both centralized hubs (scale/cost efficiencies) and local/decentralized plants (shorter, simpler inbound for wet streams) are feasible; the choice sets supply-chain complexity and euro per tonne-kilometre. The task is to align residue hubs, transport, and storage/preservation so a reliable, year-round inflow reaches the plant at acceptable cost. In practice, geography interlocks with logistics and sourcing strategy rather than determining viability on its own. A common rule of thumb is 'wet short, dry far': minimise inbound transport of water-rich residues and ship dry, specification-stable outputs longer distances.

Assessment on barrier – Consumer acceptance & comparability

Interviews indicate that end-consumer resistance is generally low: buyers tend to rely on labels/certifications and trust in producers, and fish fed with MP provokes less aversion than insect-based feeds. Acceptance issues are therefore mostly upstream—with feed formulators, farmers, brands/retail and regulators—where MP must be comparable to incumbents on performance, safety and lot-to-lot spec stability to secure use. Where products are safe and well specified, experts expect acceptance to be achievable; however, unfamiliarity can still trigger aversion without clear, proactive communication that situates MP within familiar food-fermentation practices. Overall, compared with price, scalability and consistent specifications, consumer acceptance is viewed as a secondary barrier in aquafeed. Finally, experts noted regional differences in acceptance, with some countries more cautious about 'waste-derived' inputs and others more permissive.

Assessment on barrier –Logistics

Logistics ranges from top-tier (Rank 1/6) to moderate (Rank 2–3/6) depending on context. For aquafeed, responsive, predictable delivery to feed mills is mandatory; delays or variability disrupt production schedules, inventory planning, and cost-in-use. In the EU, robust networks make logistics manageable with planning: placing production near wet/waste feedstock and shipping the finished, concentrated (dry/pelletized) product farther reduces inbound haulage of water and improves economics. Where feasible, converting residues into more stable, higher-density intermediates upstream can reduce inbound tonne-kilometres and improve unit economics. The barrier is also design-dependent: centralized hubs offer scale but widen collection radii and inbound complexity, while local/decentralized plants simplify inbound flows but may raise unit costs. Outside the EU, conditions vary by region, which can raise the logistics hurdle.

Assessment on barrier – Others

Experts consistently flag energy intensity/power price as an immediate, dominant constraint for MP—LCAs often show energy use as the main driver, so the energy source and consumption set the floor for price per kilo price per kilo and adoption. In parallel, while the amino-acid profile is generally stable, the macro composition (protein/fat/carbohydrate)—especially the fat profile—varies with heterogeneous residue feedstocks, which complicates formulation and spec stability. Experts therefore treat variability as a "recipe problem": normalize lots through blends and compensatory additions to protect performance. Overall, the challenge is to extract value from mixed wastes while controlling energy footprint and spec variability; where power costs are high, this category becomes the top-ranked barrier.

4.3.2.1.3 *From raw rankings to weighted rankings:*

As specified in Chapter 4.2.2.1.1, we calculated weighted rankings using mean rank and an evidence-weighted score (EWR). Below, only the weighted rankings for barriers to MP in feed are shown, as the food data sources did not allow for a detailed analysis. Consequently, the following section refers exclusively to MP in feed.

Figure 15: *Weighted ranking of the biggest limitations to MP deployment (Own compilation by Ecozept, based on Delphi I–III)*

Legislation emerges as the dominant gate across all interviews: it ranks first on both scales (mean = 100; EWR = 2.06; composite ≈ 12.36), due to consistent, well-triangulated concerns regarding approvals (feed/food safety dossiers and EFSA assessments), GMO/hygiene rules and the policy lag for side-stream inputs. Scalability follows closely behind (weighted = 93.53; EWR = 2.04; composite = 11.56), reflecting a consensus on the need to achieve secure and repeatable industry tonnages (10–50 kt·y^{-1}) while maintaining specification consistency, supply reliability and quality assurance /QC. These conditions directly underpin routine inclusion and cost convergence.

A second tier consists of price and logistics, which are essentially tied (weighted ≈ 72.81 and 72.49; mean ≈ 73.33 for both). Price pressures largely reflect penalties associated with pilot/early-scale production and the dependency of price per kilo on scale (EWR ≈ 1.93), while logistics is considered a design variable — siting, short wet-haul, hub-and-spoke pre-conditioning and campaign operations — rather than an insurmountable obstacle (EWR ≈ 1.92). Consumer acceptance and comparability are mid-range (weighted ≈ 59.87, mean = 60, composite ≈ 7.40, EWR ≈ 1.85): Experts consider acceptance to be achievable with transparent communication about safety and the long history of microbial foods, although proactive communication remains important. Geography ranks lowest (weighted ≈ 39.98; mean ≈ 33.33; composite ≈ 4.94; EWR ≈ 1.85) as fermentation is largely location-agnostic. Siting choices influence logistics and costs, but these issues can usually be resolved.

4.3.2.2 Further barriers identified during Delphi III

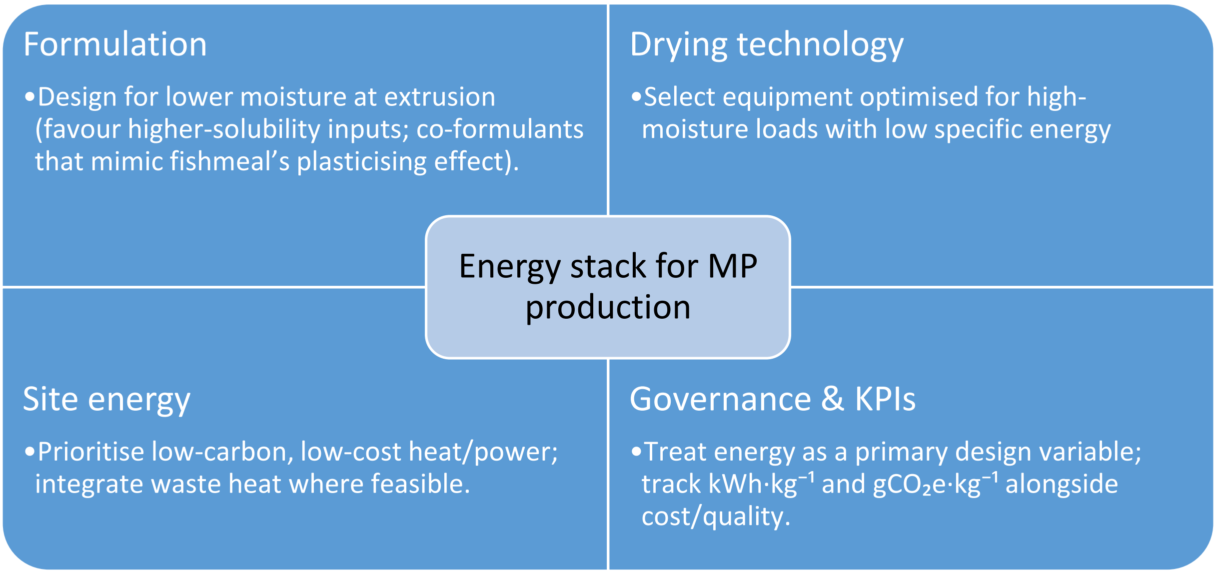
4.3.2.2.1 *Main energy hotspots:*

Experts converge on a single dominant issue: drying, especially post-extrusion pellet drying. The mechanism is consistent: to produce coherent pellets, many formulations require a significant amount of additional moisture during extrusion. Where key ingredients have low water solubility (a recurring issue for several plant proteins), operators must increase the water content to achieve the desired structure. This water must then be removed, which lengthens drying times and increases thermal demand. By contrast, more water-soluble components enable pellet formation at lower moisture levels, reducing evaporation requirements and kWh per kilogram. Respondents repeatedly cite fishmeal as an effective natural plasticiser, as it enables strong pellets with little added water. Common plant-based substitutes lack this effect and increase energy use. In short, the dryer's workload is set by formulation physics upstream; if structure relies on high moisture, the energy bill follows.

Beyond the unit operation, energy is a key driver of both OPEX and LCA. The type and source of energy used, the temperature/heat profile required across steps and opportunities for industrial symbiosis (e.g. waste-heat integration) all influence outcomes. Decisions made here have dual consequences: they alter the environmental profile (gCO_2e per kg of product) and affect cash costs. The effect is compounded by equipment and fuels: dryers differ markedly in their specific energy consumption for wet intermediates, natural gas raises carbon intensity relative to bio-based fuels (all else being equal) and additional thermal loads can arise in downstream polishing (e.g. nucleic acid reduction) and in certain pre-processing steps. Nevertheless, the consensus from interviews is that drying remains the largest single hotspot, with other heat uses important but secondary.

Taken together, the qualitative evidence provides a coherent overview of the system: energy demand is concentrated in the drying process, with the magnitude largely determined by the formulation and moisture requirements earlier in the process. This is then translated into actual kWh and CO_2e at the plant scale through dryer selection and power/heat sourcing. The following actionable implications can be drawn:

***Figure 16**: Energy stack for MP production: sequencing formulation, drying technology, site energy, and KPI governance to*



reduce price per kilo and gCO_2e/kg.

4.3.2.2.2 *Toxicity of raw material*

Experts frame raw-material toxicity primarily as a contaminant management issue rather than an intrinsic showstopper. The recurrent hazards are pesticide residues, possible antibiotic carry-over (flagged as uncertain but monitored), heavy metals accumulated in soils, and assorted environmental pollutants. For inputs that ultimately enter the human food chain, these risks are already bounded by regulation and routine monitoring, yet experts emphasise that compliance must be demonstrated lot-by-lot, and cannot be generally assumed. Risk is highly feedstock-dependent: heterogeneous, household-like wastes are viewed as higher-risk vectors for bacteria, moulds and metals, whereas traceable industrial food side streams (e.g., brewers' spent grains, potato peels, sugar-beet molasses) are considered comparatively safer owing to provenance and process history. The legal/practical boundary between "waste" and "by-product" is decisive here: waste streams cannot enter human food chains, making classification itself a toxicity and compliance gate.

Beyond exogenous contaminants, intrinsic composition matters—particularly nucleic acids in microbial proteins. Several experts note species sensitivities in aquaculture and flag purine load as a potential concern in human nutrition (e.g., gout risk). While outright toxicity is not expected for well-made extracted or microbial proteins, experts call for explicit monitoring and, where needed, reduction of nucleic-acid levels for sensitive uses. Anti-nutritional factors are also acknowledged: extracted proteins vary by botanical source but are generally manageable; for microbial proteins, risks are application-specific and can be mitigated via processing and formulation. A practical nuance raised for some residues is pigment carry-over—acceptable (even desirable) in certain fish (trout/salmon) but undesirable elsewhere—reinforcing the need for provenance control and specification limits on such components.

Downstream, product purity is pivotal. In liquid-medium fermentations, hydrolysed/dissolved nutrients increase the chance of carry-over if separation is suboptimal. Because safety and metabolisability depend on how cleanly biomass is separated from residual substrates, experts expect robust downstream processing (solid–liquid separation, multi-stage washing/polishing, controlled drying) that reliably minimises residuals—mirroring the vigilance now common for other novel inputs (e.g., insects).

Operationally, the message is consistent: treat toxicity as a managed compliance routine. In practice this means prioritising traceable industrial side streams and excluding or strongly pre-treating heterogeneous household-like wastes; qualifying suppliers against tight specification windows with certificates of analysis; running lot-by-lot screens for metals, pesticide residues and, where relevant, antibiotics; integrating HACCP with end-to-end traceability back to fields/inputs; and enforcing clear hold/rework/reject protocols for out-of-spec lots. In parallel, establish nucleic-acid monitoring and reduction targets for aquaculture and other sensitive applications, and keep anti-nutritional factors/pigments within declared bounds through feedstock selection and processing.

Taken together, expert views converge on a pragmatic conclusion: with disciplined feedstock choice, hygiene, and downstream purification, raw-material toxicity is controllable; the residual risks sit in contaminants and compositional load, both addressable through the routines explained above.

4.3.2.2.3 *Upscaling and safety & sustainability risks*

Experts agree that a simple test of credibility on a large scale is whether the process can consistently deliver the same product safely and sustainably, batch after batch, under industrial conditions — not just in a well-controlled pilot scheme. As operations move from pilot to demonstration and commercial production, variability typically increases; accordingly, regulators (including EU Novel Foods for human consumption) and customers evaluate longitudinal evidence rather than single time points. In practice, experts are expected to demonstrate a validated process for moving from the pilot stage to demonstration and then to commercial operation. They must use time-series data to prove that specifications, safety attributes and performance remain within predefined limits across multiple batches.

Scale-up is consistently identified as the stage at which small deviations can become systemic risks. Experts expect health, machine and operator exposure issues (e.g. dust generation) to be eliminated before commercialisation, with documented mitigations such as enclosures, extraction systems and personal protective equipment, and explosion protection where applicable. In order to be sustainable, higher and steadier throughputs must reduce the environmental impact per unit only if the bioreactor/aeration strategy, separation train, dryer choice and (where relevant) solvent stewardship maintain specification stability while keeping energy use and emissions within declared limits.

The operational playbook is therefore evidence-based.

(1) run consecutive validation campaigns that track critical quality attributes (CQAs), safety markers, and environmental KPIs over time;
(2) implement in-/at-line monitoring and statistical process control across fermentation and downstream processing to keep materials and parameters within control limits as capacity increases;
(3) release lots based on documented trend analyses rather than single-batch snapshots.

Following this approach mitigates the main risks associated with scaling up, such as rising variability, operator safety and durability of sustainability claims, by replacing assumptions with repeatable, time-series evidence generated under industrial conditions. This aligns regulatory and customer expectations with scaled manufacturing.

4.3.3 Expectations and limitations for MP – Key findings

Key takeaways:

- Specification-led, as-processed value: MP is purchased based on performance following real unit operations (hydration, shear and heat), rather than bench numbers.
- Near-term traction: Aquafeed first, then premium pet food, which follows once taste, as-processed function and cost-in-use converge.
- The gates that will decide adoption are protein tier, digestibility, IAA profile, palatability and plant fit (dry, free-flowing and low-dust), as well as clean and complete safety dossiers.
- System levers, not silver bullets: price parity comes from feedstock discipline, solvent-lean/energy-efficient downstream processing and drying strategy, while regulation sets the pace.

Entry criteria (non-negotiables):

- Nutrition and bioavailability (feed):
  - CP bands: about 50–60% = entry as a protein ingredient, 60–65% = routine use, and about 65–75% = fishmeal tier.
  - Digestibility: ≥85% for protein and key essential amino acids (EAAs) as processed (conditioning/extrusion).
  - IAA profile: fishmeal-adjacent; lysine is often the first limiting factor and methionine is frequently low (closed at diet level).
- Palatability: intake gate; staged inclusion with hard stop criteria.
- Function and sensory (food): clean flavour and colour, and targeted technological function (gelation/texturisation, stable emulsification, controlled viscosity and water/oil binding) that survives the processing history.
- Safety and compliance: HACCP/GMP; lot-level certificates of analysis for contaminants and microbiology; nucleic acid management where relevant; and traceability from start to finish.

Plant fitness and physical form

- Factory-ready formats: Dry, free-flowing, low-dust powders and granulates with declared moisture content/activity water (aw), particle size distribution, bulk density and flow indices; safety data sheets (SDS) and practical handling guidance.
- Processability (feed): predictable dispersion and hydration, no penalty for pellet durability, and compatibility maps for pH, salts and binders.

Application scope and market position

- Feed (aquafeed lead): MP is competitive in terms of cost when it offers high CP, high digestibility, a complementable amino acid profile and a mill-ready form. Measured FCR/intake gains can justify limited premiums.
- Food: MP excels in function-led applications with as-processed specifications and application toolkits (dosage bands, set points, compatibility maps).
- Scale matters: routine inclusion requires consistent tonnage with precise specifications over time.

Operations and feedstock strategy:

- 'Feedstock strategy = pricing strategy.' Prioritise traceable, spec-stable industrial side streams and avoid heterogeneous 'waste-like' inputs unless they are pre-conditioned.
- To cut 'wet miles', co-locate fermentation and the first stage of downstream processing with wet residues. Use hub-and-spoke aggregation, rapid intake QC and blending to keep C:N, moisture and inhibitors within spec.

Energy drivers and main hotspots:

- Drying dominates OPEX/LCA, especially post-extrusion pellet drying.
- Actionable levers:
  - Formulation: Design for lower moisture processing.

- Equipment: select dryers with low specific energy for high-moisture loads and use heat recovery and moisture sensing.
- Site energy: Secure low-carbon, low-cost heat and power and integrate waste heat where feasible.
- Track KPIs such as kWh/kg and gCO_2e/kg, as well as cost and quality.

Output homogeneity and format engineering:

- Maintain tight specification windows, publish lot-to-lot ranges and use corrective blends/partial concentration where needed.
- Ship dry, stable formats that are engineered for shelf life and flow.

Regulatory pacing and SSbD enablers:

- For feed (residue routes), use a two-step sequence: (1) assess feedstock eligibility (hygiene, traceability, HACCP and contaminants); then (2) compile an ingredient dossier (specifications, safety and functionality; GMO documentation if applicable).
- For food, implement disciplined Novel Foods operations (pre-submission alignment, template-driven dossiers and time-bound studies).
- SSbD-aligned policy: reward verified outcomes (safety, performance and sustainability), harmonise labels and methods to reduce approval friction and increase investor confidence.

Leverage points and limitations:

1. The dominant gates are regulation (which sets the sequence and timing) and scalability (which drives cost convergence and supply reliability).
2. Price reduction is achieved through clean feedstocks, solvent-lean and energy-efficient downstream processing, and logistics that minimise water transport.
3. To contain variability and ensure plant fit, use tight specification windows, corrective blending and flow-engineered formats.
4. Geography and logistics are design variables, not hard blockers, when siting, aggregation and outbound formats are planned coherently.

5 Exploration of the market potential

Chapter 5 synthesises the findings from three Delphi rounds and desk research in order to assess the EU market potential for AgriLoop routes and translate it into investable, SSbD-aligned pathways. Section 5.1 (PHAs) establishes the market baseline, identifies the demand drivers, maps priority applications, and derives process and end-of-life entry rules. As outlined in Section 5.2 (MP), the adoption path (feed → pet → food), price/scale levers, functional guardrails and regulatory routes are considered. Cross-cutting enablers, such as factory-gate pre-conditioning, hub-and-spoke/co-location, and evidence ladders that support price per function procurement, are made explicit to convert technical readiness into bankable offtake.

5.1 Estimates of market potential of PHA

Section 5.1 provides an estimate of the EU market potential for PHAs. It establishes a market baseline and regional context, identifies demand drivers (outcome-based policies, price per function procurement, cost curves driven by scale, and field-linked evidence), maps priority applications and market segments, and derives an entry playbook ('framed process', feedstock/supply design, solvent-lean downstream processing, and modular 5–25 $kt \cdot y^{-1}$ production trains). The section also benchmarks production economics against incumbents and alternatives and summarises the implications for regulation, end-of-life acceptance, infrastructure readiness, risks and go/no-go gates, so that soil-exposed thin gauges and function-led coatings can lead to bankable offtake.

5.1.1 Market baseline and context

Experts at Delphi I–III anticipate robust growth in the bioplastics market, with biodegradable polymers set to dominate. One expert estimated that the market would reach about 2.2 Mt by 2022, rising to about 6.3 Mt by 2027, with over 50% of the capacity being biodegradable. Packaging is expected to remain the largest market, while the automotive and construction sectors are also predicted to grow. Asia is currently the production centre and is expected to increase its market share from about 41% to about 63% by 2027. PHA mulch films are already in use in China. Europe is considered to have significant potential but is currently under-scaled with few major producers. According to one interviewee, land availability is not a physical constraint, with less than 1% of global land currently used for bioplastics and sufficient land available in Europe.

Within this baseline, PHAs are positioned according to soil-relevant biodegradation and biocompatibility, which clearly differentiates them from PLA in soil and from PBS/PBAT where soil-side evidence is required. While several experts credit PHAs with faster and more complete breakdown under realistic conditions, others caution about their brittleness and overly rapid decay for multi-year outdoor use. The most coherent early demand is expected in agriculture and horticulture, where products predictably come into contact with soil during use (e.g. mulch films and plant-through pots), and where operational issues (e.g. retrieval and waste handling) are important; one expert cited very high part counts (approximately 0.8–1.0 million clips per hectare). Despite interest from major companies, the market mood is cooperative: demand exceeds current capacity, but new polymers must enter the market via targeted niches due to the small-scale costs involved and the need for application-specific evidence. In terms of conversion, extrusion is proving to be more popular than injection moulding. While workable film production methods do exist, slow crystallisation and embrittlement during post-processing remain constraints, and producing strong, flexible clips is not routine. Regionally, significant production capacity today is associated with China, South Korea and the US. Overall, the situation indicates an early pull for PHA in soil-exposed, thin-gauge formats, a European scale/maturity gap, and the importance of field-relevant end-of-life evidence in translating interest into procurement.

5.1.2 Determinants of market potential

Market pull is strongest where the end-of-life performance of a product is integral to its function. Experts across Delphi I–III agree that soil-exposed, thin-gauge formats, such as seasonal mulch films and plant-through/plant-with pots, are the most in-demand because fragment-free, in-soil biodegradation eliminates the need for retrieval work, prevents contaminated waste streams and retains organic matter in the soil. Controlled-release fertiliser coatings present a near-term opportunity: the polymer mass per hectare is low; persistence must track nutrient-release profiles; and the disappearance of the coating must not leave any persistent fragments. Credible PHA coatings can therefore meet an emerging compliance need.

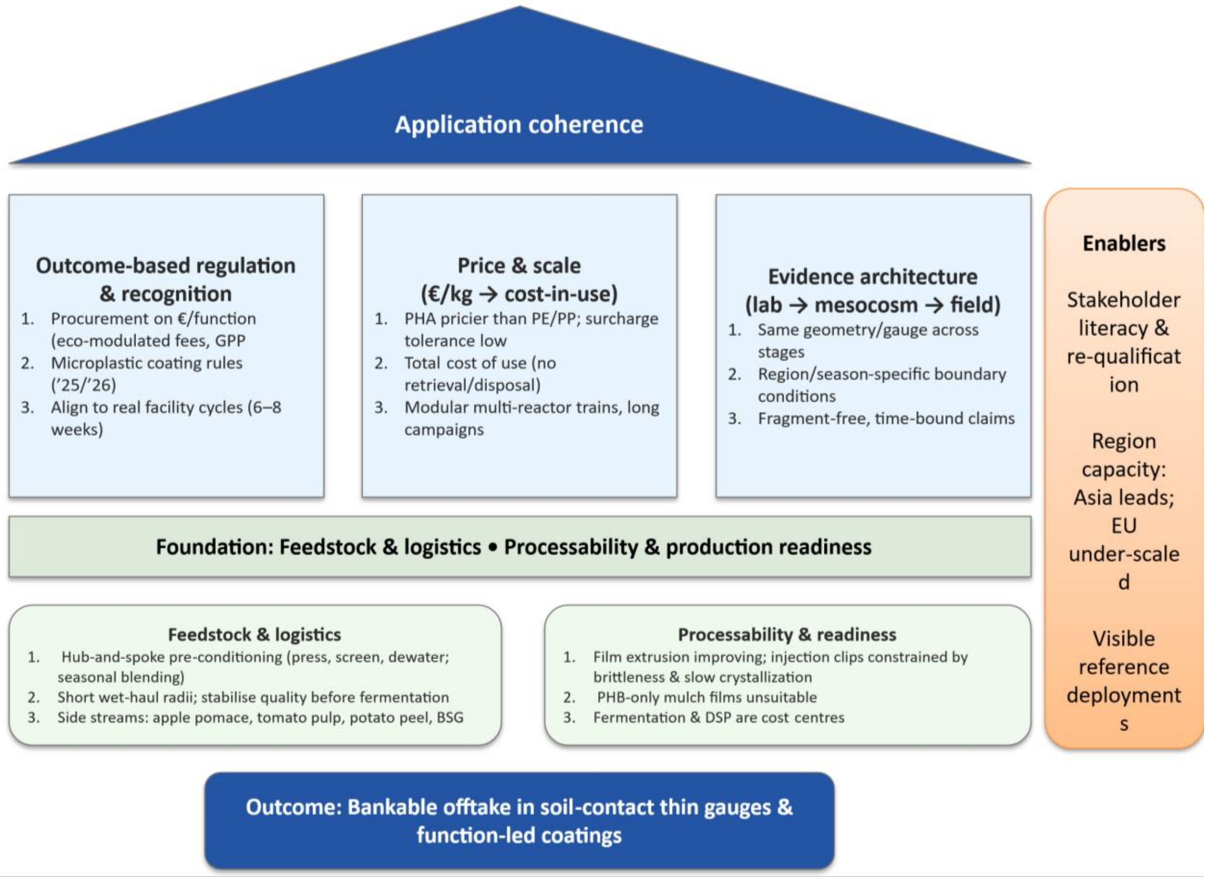


Figure 17: *Application coherence framework for PHA market entry (Own compilation by Ecozept).*

Regulation amplifies demand when it recognises these outcomes. Experts consistently link procurement to environment-matched, time-bound, fragment-free degradation, which is backed by evidence ranging from the laboratory to the mesocosm to the field. This evidence uses true gauging and local boundary conditions (e.g. soil type, climate and season). Where such outcome-based recognition is available, buyers shift from price per kilo to price per function (e.g. via eco-modulated fees or green public procurement), and agriculture becomes a receptive first market. Several experts also note a policy shift towards 'recyclable' , yet emphasise that PHAs' comparative advantage lies in composting and soil end-of-life management, given the challenge of achieving high-quality recycling for mixed materials. They highlight practical alignment issues — many composting facilities run 6–8-week cycles, whereas some certificates assume a period of around six months — thereby reinforcing the value of field-linked data. In parallel, the forthcoming European restrictions on microplastic-generating fertiliser coatings (2025/26) are seen as an opportunity for PHA-based coatings.

Price and scale determine how quickly that demand translates into volume. Experts describe PHA as significantly more expensive than PE/PP (and often PLA), with farmers and converters only tolerating a small surcharge. One stakeholder estimate put acceptance at around €0.10–0.20/kg, and several experts reported that the cost of functional PHA mulch films was up to three times that of conventional films. Nevertheless, the total cost of use can offset these differences where retrieval and disposal are avoided. Experts also highlight the potential benefits of fossil-plastic price volatility and 'full-cost' accounting (including collection, disposal, and logistics), which could enhance PHA's competitive advantage. On the supply side, economies of scale and longer campaigns, particularly in standardised, modular, multi-reactor trains, are considered the operational model that unlocks larger tenders and steadier specifications.

Evidence architecture directly determines adoption. Buyers request dossiers that track the same article geometry and gauge throughout the laboratory, mesocosm and field stages, with explicit boundary conditions. Performance windows are narrow by design: products must retain their properties throughout their service life and then decay quickly without leaving any persistent fragments behind. As degradation rates vary across Europe due to climate differences, region-specific and season-aware claims carry more weight in procurement and permitting.

Feedstock mobilisation and logistics can be transformed from a constraint into a differentiator. Experts stress that the issue is not theoretical biomass, but rather converting seasonal, low-density, perishable and variable streams into specification-grade inputs at cost. Recommended strategies include processing high-moisture by-products close to the source, transporting more concentrated fractions and employing a hub-and-spoke system for pre-conditioning, which involves pressing, screening and partial dewatering, as well as seasonal blending. This system should have short wet-haul radii and be used for campaign operations. Commonly cited side streams include residues from apple processing, tomato pulp, potato peel and brewers' spent grains (BSG). Experts are cautiously optimistic that logistics will adapt as demand grows, provided intake is governed by specifications and quality is stabilised prior to fermentation.

Processability and production readiness influence which applications will be scaled up first. While converters report progress in film extrusion, they also note slow crystallisation and temperature-sensitive behaviour, which makes flexible formats and strong, durable, injection-moulded clips more difficult to produce unless blends or robust processing windows are developed. PHB-only mulch films are widely considered to be unsuitable due to their brittleness. Upstream fermentation and downstream purification remain the economic centre of gravity. Reliance on clean sugars and oils improves control but raises costs. Meanwhile, residue-based routes must manage heterogeneity and inhibitor loads. Looking ahead, experts point to alternative inputs, such as starch-bearing wastewater from potato washing, or synthetic routes via waste-derived fatty acids, as promising, albeit still in the pilot stage.

Finally, the level of stakeholder literacy affects the speed of uptake. Some customers still see plastic and discount the benefits of the circular economy or confuse compostability and recyclability. Experts recommend structured re-qualification with visible reference deployments in soil-exposed applications and clear, field-specific evidence packages that demonstrate technical advantages and inspire purchasing confidence. Regionally, Asia remains the main production centre, while Europe lacks major local producers. Several experts view this as both a present constraint and a future opportunity, should outcome-based policy and credible evidence unlock local investment.

Together, these factors — application coherence, outcome-oriented regulation, cost/scale trajectories, credible biodegradation evidence, stabilised feed quality logistics and converter-facing education — determine where PHAs can achieve initial success and how quickly volumes can grow. The most investable path involves pairing receptive, soil-contact use cases and microplastics-driven niches with modular scale-up and disciplined evidence. This uses early revenues to finance the process learning required for broader market entry.

5.1.3 Application landscape and segmentation

Across Delphi I–III, the clearest market opportunities for residue-based PHAs arise where their defining advantage — verified, fragment-free biodegradation in soil within realistic timeframes — is intrinsic to the product's value. This indicates thin, soil-exposed formats with a low polymer mass per hectare, as well as function-led coatings where disappearance is part of the performance specification. Conversely, multi-year, thick-section articles fall outside the scope of the near term unless their geometry and formulation are re-engineered and dual proof (service life and end-of-life) is available.

<u>Near-term core fits.</u>

(1) Mulch films are the priority for entry. They must retain their integrity for at least one crop cycle (typically around six months in an open field) and then disintegrate and biodegrade in the soil without leaving any persistent fragments behind. The gauge depends on the crop and climate: thinner for short, fast rotations (e.g. lettuce), provided that installation and early-season stresses are withstood; thicker for longer cycles (e.g. peppers). Starch-based PHA blends with minimal stabilisation and pigmentation balance tear resistance, weld strength, and in-field breakdown. Qualification involves stable film blowing (bubble stability, welds and low scrap) coupled with mesocosm and field data under declared boundary conditions. PHB-only films are widely reported as unfeasible due to their brittleness.

(2) Plant-through/plant-with pots convert biodegradability into labour and survival benefits by holding their shape throughout propagation, logistics and planting before breaking down in soil under agronomic conditions. Dossiers must confirm soil safety, including that of additives and contaminants. Long-life pots (5–10 years) are not attractive.

(3) Horticultural twines and ties for tomatoes, cucumbers and beans require six months of UV resistance and load capacity during use, followed by two to four months of disintegration in compost or soil. Stabiliser levels should be kept to a minimum to ensure protection at the end of the product's life. Achieving flexibility remains challenging; single-season, compostable formats are the logical first step.

(4) Controlled-release fertiliser coatings are a function-led adjacent fit, offering low coating mass per hectare and persistence matched to nutrient-release profiles. They also ensure complete, fragment-free biodegradation after use. The regulatory pressure on microplastics from 2025/26 creates a defined demand pool, with the strongest economics in regions where leaching is prevalent and in longer seasons.

<u>Conditional/medium-term options.</u>

(1) Grow/seedling bags have a short service life and are valued for their ability to dissolve in soil. They require a careful balance of early-life strength and rapid post-use decay and are highly price sensitive.

(2) Clips for vines and greenhouses attract interest as biodegradable soil alternatives to PLA/PP. However, strength–flexibility trade-offs and temperature-sensitive processing (bleeding and stickiness at lower temperatures) limit their feasibility for injection moulding in the near term.

(3) Tree guards, shelters and tubes could be used where 2–3 years' durability is required before they disappear safely; more evidence on weathering and impact is needed.

(4) Green waste bags and tea bag films are a credible option where compostability is visible and valued. However, products must align with real facility cycles, which are often 4–12 weeks, and local acceptance.

(5) Fishing nets and selected rigid trays could enter the market if they are lightweight and the end-of-life value is priced in; otherwise, polyolefins dominate.

(6) Micro-irrigation pipes with thin walls are only feasible with re-engineered geometry to reduce wall thickness and fragmentation risk; thick walls slow mineralisation.

<u>Deferred/not suitable at present.</u>

(1) Greenhouse films with a transparency/UV stability of 7–8 years conflict with PHA’s hydrolysable backbone and soil-degradation proposition. Without complex multilayers and dual proof, they remain out of scope.

(2) Thick, long-life outdoor parts face durability and fragment persistence risks in the absence of multilayer architectures and outcome proof.

(3) PHB-only mulch films remain unsuitable due to brittleness.

(4) Long-life horticultural pots and intensive-cycle pots are not attractive options because the durability window and the risk of root obstruction conflict with the soil-degradation brief.

The positioning logic and specifications.

The go-to-market strategy focuses on cost per function rather than cost per kilogram wherever field-relevant biodegradation removes the need for labour-intensive retrieval, avoids contaminated waste streams and keeps organic matter in the soil. Film extrusion demonstrates the greatest processing readiness at present; however, injection parts requiring both strength and flexibility are limited by slow crystallisation and temperature sensitivity, hence the focus on thin gauges and coatings. Each offer should be supplied with a region-specific evidence pack containing information on article geometry/gauge, soil type, moisture/temperature and placement, as well as disintegration, CO_2 evolution and time-resolved particle-size distributions, so that buyers can procure against verified functionality.

Table 15: *Application landscape for residue-based PHAs: market fit, specifications, end-of-life & feasibility (Own compilation by Ecozept).*

Application	Market segment	Target service life	Key specifications (excerpt)	End- of - Life target & evidence	Value / business case	Feasibility
Mulch films	Core (near-term)	≥1 season	Thin gauge; stable bubble/welds; PHA–starch blends; minimal stabilisation/pigmentation; PHB-only unsuitable	Soil disintegration + mineralisation; fragment-free; mesocosm/field data (soil/climate/placement, CO_2, time-resolved particle size)	price per function (no retrieval, less contaminated waste, organics stay on field)	High
Plant-through/plant-with pots	Core (near-term)	Weeks–months	Shape-stable through propagation/logistics/planting; then soil breakdown; check additives/contaminants	Soil degradation: soil safety verified; article-specific geometry	Labour savings, better transplant survival	High
Horticultural twines/ties	Core (near-term)	about 6 months use + 2–4 months decay	UV/load capacity; flexibility remains a challenge; keep stabiliser low	Compost/soil disintegration in 2–4 months; fragment-free	Lower handling/disposal effort	Medium–High
Controlled-release fertiliser coatings	Core (near-term)	Season / release window	Low polymer mass/ha; permeability matched to nutrient release	Complete, fragment-free biodegradation post-use; field/kinetics data	Clear policy pull (microplastics restrictions 2025/26); €/function	High
Grow/seedling bags	Conditional / medium term	Short	Early-life strength + rapid soil decay; price-sensitive	Soil degradation; align with local practice	Labour savings; easy deployment	Medium

Application	Market segment	Target service life	Key specifications (excerpt)	End- of - Life target & evidence	Value / business case	Feasibility
Clips (vine/greenhouse)	Conditional / medium term	1 season	Injection moulding: strength–flex trade-off; stickiness/bleeding at lower temps; robust mechanics needed	Target: soil biodegradation; fragment-free proof	PLA/PP alternative when end-of-life matters	Medium (processing-limited)
Tree guards/shelters	Conditional / medium term	2–3 years	Weathering/impact resistance to be evidenced	Safe disappearance; field data needed	end-of-life benefit after service period	Medium (evidence pending)
Green-waste bags / tea-bag films	Conditional / medium term	Weeks	Visible compostability; facility cycles often 4–12 weeks	Compost acceptance is regional; fragment-free	Acceptance in organics collection	Medium (infrastructure-dependent)
Fishing nets / selected rigid trays	Conditional / niche	Case-dependent	Lightweight design; often conventional end-of-life	end-of-life value must be priced in	Niche wins where function priced	Low–Medium
Micro-irrigation pipes (thin concepts)	Conditional (concept)	Multi-season	Re-engineer to thin walls; address fragment risk	Credible field degradation	Only with design innovation	Low
Transport trays	Second wave	6–60 months	Stiffness, opacity, colour; PHB-leaning blends	No bio-end-of-life claim	Conventional end-of-life; robust logistics	High
Greenhouse films (7–8 years)	Deferred	7–8 years	Long-term UV & transparency vs PHA hydrolysis	Dual proof (service + end-of-life) lacking	Polyolefins superior today	Low
Thick, long-life outdoor parts	Deferred	Multi-year	Thick walls → slow kinetics; fragment risk	Outcome proof lacking	Economically/technically weak	Low
PHB-only mulch films	Not suitable	–	Brittle	–	–	Low
Long-life pots / intensive cycles	Not attractive	5–10 years	Durability window conflicts with soil degradation; root obstruction risk	–	High cost, limited benefit	Low

5.1.4 "Framed process" implications for market entry

Across Delphi II–III, experts agree on a staged approach from residues to marketable PHA, prioritising control and evidence over a direct route to polymer. The first step is to stabilise heterogeneous by-products into specification-grade intermediates (e.g. sugars or lactic acid), provided this reduces inhibitor load and increases tradability. These intermediates must be engineered to have a high titre (to avoid costly evaporation), be highly pure (to protect catalysts/biocatalysts), be sterilisable (for bioprocess compatibility) and have a documented absence of inhibitors or adventitious contaminants. The second step is to route these intermediates to polymer grades whose architecture (co-monomers/MWD and additive package) is tuned to the target article's service window and end-of-life route. The controlling idea is to design backwards from the use case: the end use requirements dictate the process recipe.

Pre-treatment is repeatedly identified as the bottleneck, and feedstock simplicity as the solution. However, once lignocellulosics are introduced, pre-treatments generate furans and phenolics that reduce titres and necessitate detoxification steps, resulting in additional CAPEX and OPEX costs, as well as carbon losses. Consequently, experts report cleaner, more reproducible outcomes with non-lignocellulosic, inhibitor-lean streams (selected oils or compositionally stable food waste) that require little more than filtration. However, variability remains the adversary, so experts advocate hub-and-spoke preconditioning (short wet haul, regional densification and seasonal blending) and real-time characterisation (inline/at-line analytics, soft sensing and SPC) to normalise feed quality before fermentation. Where residues are used directly, the objective is to prevent inhibitor formation rather than remove it afterwards.

Experts indicated that documentation and purification expectations increase with the intended use. For technical/agricultural B2B formats (e.g. mulch films and plant-through pots), leaner polishing and lighter files were considered acceptable where fragment-free biodegradation under declared conditions was evidenced in the field. For food-adjacent applications, respondents pointed to the need for tighter specifications for raw materials, migration limits, control of contaminants and allergens, and HACCP-based traceability. For health-sensitive applications, experts expected requirements approaching GMP practice, such as validated sterilisation and tight limits on residuals, though views varied by use case. Across all categories, experts emphasised that credible end-of-life dossiers (lab → mesocosm → field), tied to article geometry and climate, are essential for market access.

In practice, this 'framed' approach translates into a market entry playbook.

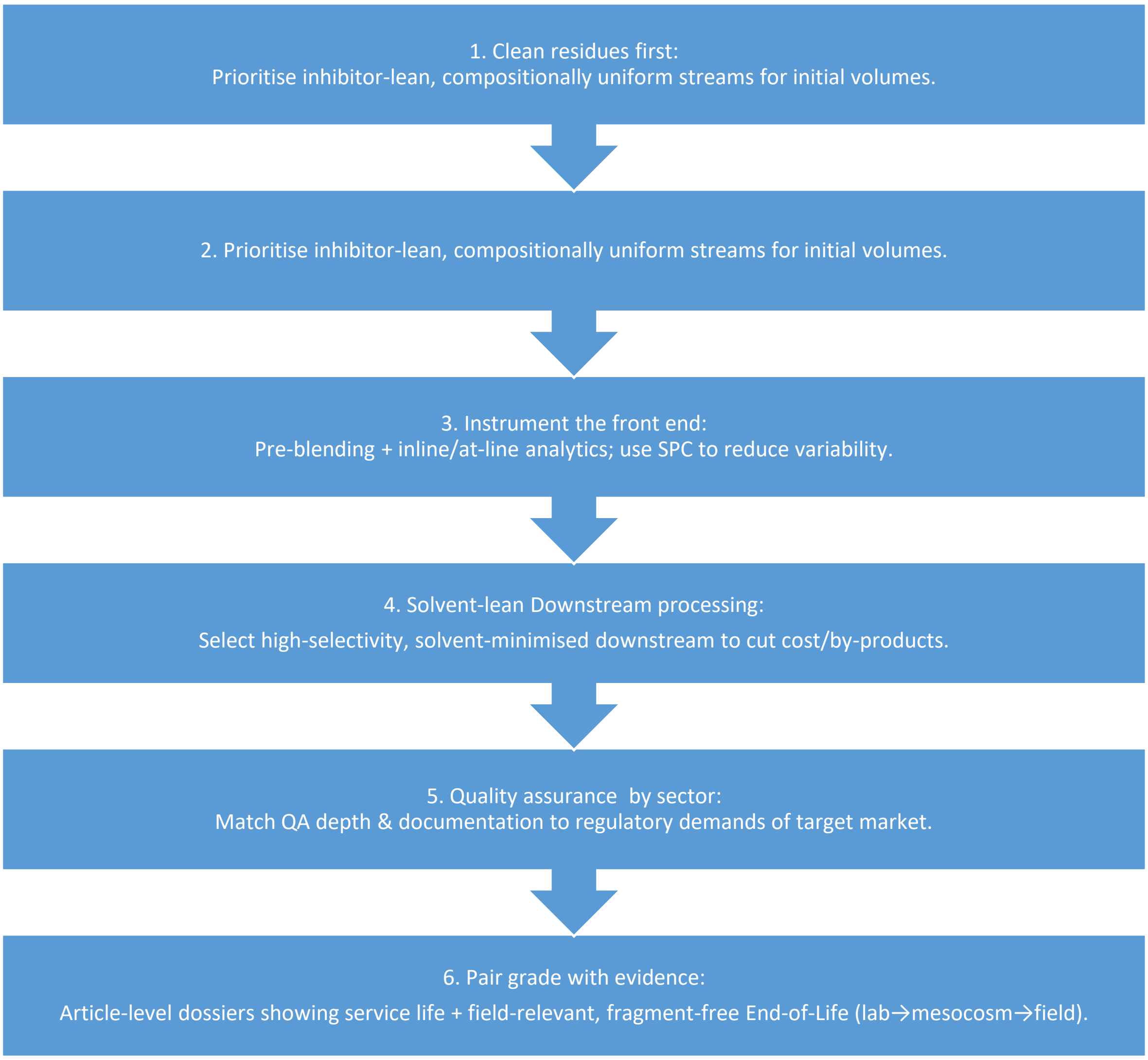


Figure 18: *Framed process' market-entry workflow for residue-based PHAs (Own compilation by Ecozept).*

This sequencing enables entry into technical and agricultural B2B niches where biodegradation is mission-critical, and documentation requirements are manageable. At the same time, it builds the process control and evidence base required for more stringent markets.

5.1.5 Feedstock pathways and supply design

Experts describe three feasible feedstock archetypes, each with clear trade-offs. Primary raw materials (such as refined sugars and vegetable oils) deliver the cleanest chemistry and the tightest process windows. They minimise variability and simplify the downstream process, but they are more expensive and do not make use of residues. At the other extreme is food waste: abundant and attractive to society, yet intrinsically heterogeneous in terms of moisture, fats, nutrients, salts and preservatives. Each truckload changes the composition, necessitating additional expenditure on sorting, buffering and pre-treatment just to restore reproducibility. Agricultural residues appear to offer a pragmatic middle path: they are voluminous and stable in different regions. However, lignocellulosic pre-treatments generate furans and phenolics that reduce yields and necessitate detoxification steps, such as washing, over-liming, adsorption and enzymatic polishing. This erodes the initial cost advantage. Therefore, it is unsurprising that today's large-scale producers still rely on standard sugars and oils, while secondary streams remain a frontier for development. Table 16 summarises the three archetypes with distinct trade-offs:

Table 16: *Feedstock archetypes for residue-to-biopolymer routes (Own compilation by Ecozept).*

Archetype	Strengths	Constraints	Implications / When to use
Primary (sugars/oils)	Clean, repeatable chemistry; simpler downstream processing	Higher cost base; competes with food system	Stabilise first volumes; high-spec markets; when regulatory speed and repeatability matter
Food waste	Abundant, circular narrative	Heterogeneous; needs sorting/buffering/pretreatment; traceability/hygiene risk	Only with tight sourcing & preconditioning; start local, controlled streams
Agricultural residues	Voluminous & regionally stable	Lignocellulosic inhibitors (furfural, HMF, phenolics) → detox costs & yield loss	Select non-lignocellulosic/low-inhibitor streams; prove detox at scale; hub-and-spoke intake

The design implications are consistent: residues must be treated as variable raw materials and stabilised before biology. Pre-treatment is the choke point, and feedstock simplicity is the relief valve. Experts report cleaner, more repeatable outcomes with non-lignocellulosic, inhibitor-lean side streams (e.g., selected oils or compositionally stable food-processing by-products) that often require little more than filtration. Where residues are used directly, the operational priority is to prevent inhibitor formation rather than remove it afterwards; if unavoidable, detoxification should only be applied when reliable at scale and economically defensible. In parallel, strain and operating windows can be adapted to tolerate residual inhibitor loads so that residue economics survive contact with real fermentation.

Supply design focuses on minimising variability and moving as little water as possible. A hub-and-spoke pre-conditioning approach—with short wet-haul radii from farms/processors to regional hubs—densifies and stabilises inputs through sorting, dewatering, pasteurisation/acidification, partial hydrolysis and simple detoxification, then forwards uniform intermediates to fermentation sites. This “freeze the quality” step limits freshness loss and prevents variability from propagating into unstable growth, erratic PHA accumulation and wider scatter in molecular weight and rheology between lots. Seasonal blending and buffer capacity smooth compositional drift.

Commercially, consistency is key, so contracting mirrors the technical approach: multi-year, risk-stratified supply agreements specify moisture, ash and inhibitor indices; batch tagging and segregation maintain traceability; and blending records document how variability is absorbed. Siting follows the residue map—co-locate with high-volume, homogeneous streams where feasible; otherwise rely on regional densification hubs to protect quality and cost. In practice, this favours inhibitor-lean, compositionally uniform streams for initial volumes, while lignocellulosic routes are pursued selectively where detoxification is proven and added steps do not negate the advantage.

5.1.6 Production economics and scalability

Across Delphi I–III, the cost architecture of residue-based PHAs is clear: downstream processing dominates OPEX/CAPEX, while price remains the main factor influencing market scale. Current transaction bands cluster around €5–10/kg (often about €6/kg), with the premium largely rooted in cell disruption, phase separation, purification, and drying and pelletising, especially where significant amounts of solvents and utilities (heat, power, chilled water and compressed air) are required. Although raw-material pricing is important, it is not the sole determining factor because residue heterogeneity and inhibitor formation can negate any 'cheap carbon' advantage through detoxification steps, reduced yields and additional unit operations. Geography complicates this picture: lower factor costs and robust, non-sterile, salt-tolerant processes enable lower prices in China, whereas higher energy, labour and compliance costs, as well as fewer large-scale assets, keep European prices elevated. On the demand side, willingness to pay in B2B seems to be modest: growers and converters typically accept only a premium of about 3–5 % unless biodegradability alleviates real operational issues (e.g. mulch film retrieval) or meets specific regulatory requirements.

Process design therefore begins at the front end. Pretreatment is the choke point and feedstock simplicity is the relief valve. Side streams that are inhibitor-lean and compositionally uniform deliver cleaner, more repeatable outcomes than lignocellulosics that generate furans and phenolics. The recurring operating model aligns campaign production with harvest windows and uses a hub-and-spoke densification system close to sources ('short wet haul'). It also installs spec-driven preconditioning, such as sorting, blending, screening and dewatering, and, where justified, pasteurisation, mild acidification or partial hydrolysis, to stabilise quality before fermentation. Inline/at-line analytics and SPC at intake can normalise feed quality and prevent downstream processing from becoming an expensive place to fix variability. These realities should be reflected in contracting: multi-year volumes with flexibility bands, risk-stratified sourcing and seasonal blending protect both availability and cost, while biogas incentives on the same organics are factored into sourcing choices.

Scale-up expectations are pragmatic: replication is favoured over gigantism for residue routes. Standardised, automated, multi-reactor trains with a capacity of 5–25 $kt \cdot a^{-1}$ are favoured as they offer redundancy, permit maintenance without complete shutdowns, and, crucially, facilitate accelerated learning regarding heat/mass transfer, solvent-loop dynamics, fouling, and stability prior to committing capital. Long-campaign or continuous operation is employed from the outset to maximise overall equipment effectiveness and minimise changeovers. Grade-specific standard operating procedures, together with inline/at-line analytics and SPC, ensure that crystallisation and rheology remain predictable, enabling converters to experience uneventful, drop-in behaviour. A first commercial plant is considered feasible for Europe within the next few years if offtake and permitting align. Given higher factor costs, disciplined operations and simplified downstream processing are prerequisites for regional cost competitiveness.

The cost-down pathway is operationally specific and consistent across interviews. Firstly, increase the titres, productivities and purities so that less broth — and therefore less downstream processing — is required per kilogram of polymer. Secondly, switch to solvent-lean or audited near-closed recovery with explicit KPIs for solvent balance. Where polishing is required, favour counter-current and membrane steps, applying 'purity-to-purpose' to ensure that sensitive markets receive the necessary depth while technical and agricultural ADgrades avoid over-processing. Thirdly, standardise and automate processes to stabilise critical quality attributes and reduce waste. Fourthly, start with inhibitor-lean residues upstream, hub-and-spoke preconditioning, and seasonal blending so that variability does not propagate into biology and downstream processing. Side-stream choices (water recirculation, salinity control, valorisation of cell debris/residues via anaerobic digestion (AD) or soil amendments where permissible, and recovery of process aids) further influence both the environmental footprint and unit economics by diverting tonnes of material from disposal.

Policy interacts directly with affordability and sequencing. Where purchasing frameworks recognise verified, fragment-free biodegradation (e.g. via eco-modulated fees and green public procurement), environmental performance translates into compliance value, widening tolerance for a price delta as costs trend down. In the absence of such outcome-based recognition, PHAs face direct competition with low-cost polyolefins and mid-priced biopolyesters. Most experts therefore stage markets, anchoring early volumes in soil-exposed, thin-gauge formats such as mulch films, plant-through/plant-with pots, and controlled-release fertiliser coatings, where polymer mass per hectare is low and end-of-life is intrinsic to value. They then propose to use the resulting cadence and learning, such as higher titres, solvent-lean downstream processing, standardised trains and inhibitor-lean feeds, to reduce the cost per kilogramme for broader entry. Under these coordinated measures, long-term expectations converge on € 3–4/kg for selected volumes. Without them, prices remain in the upper half of the € 5–10/kg range, and mainstream uptake remains limited.

Cost-down levers and price corridors (PHA)

Translating the production-economics analysis into deployment guidance, six levers co-determine cost compression; together they define realistic price corridors that shape addressable demand.

1. Raise titre/productivity/purity to shorten cycles and reduce downstream processing intensity.
2. Implement solvent-lean or audited near-closed downstream processing with recovery KPIs; where specifications allow, use aqueous/enzymatic or membrane steps.
3. Standardise and automate modular multi-reactor trains; run long campaigns/continuous; use in-/at-line analytics and SPC to cut scatter and scrap.
4. Govern feedstock by specification (intake analytics, inhibitor-avoiding pretreatments, seasonal blending, densification/hub-and-spoke).
5. Sequence markets into use cases where end-of-life value is priced-in (soil-exposed thin gauges; function-led coatings) to finance learning before contesting ultra price-sensitive segments.
6. Align policy with outcomes (eco-modulated fees, green public procurement, recognition of fragment-free biodegradation).

Price corridors (indicative):

- Status-quo operations: upper half of €5–10/kg → limited mainstream B2B uptake.
- Improved operations at credible scale (≈5–25 kt·a^{-1}) with outcome-based procurement: about €4–6/kg.
- Best-case (policy-supported, high utilisation, benign feedstocks, disciplined downstream processing): €3–4/kg for selected volumes.

5.1.7 Competitiveness vs incumbents and alternatives

Across Delphi I–III, experts frame the competitiveness of PHAs as application-specific. In the context of low-cost PE/PP, the agricultural sector is one of the most price-sensitive polymer markets. Therefore, PHAs only compete where end-of-life is a valued feature, rather than an optional extra. In thin, soil-exposed formats (e.g. seasonal mulch films and plant-through/plant-with pots), fragment-free, field-relevant biodegradation can eliminate the need for labour-intensive retrieval, prevent contaminated waste streams and retain organic matter in the soil — benefits that can offset the higher cost of the resin. However, where such benefits are absent (e.g. generic rigid packs), entrenched polyolefin economics and recycling infrastructures dominate, and experts do not expect PHAs to be competitive on price alone.

The picture is different for other biopolymers. PLA is often criticised for its slow rate of soil breakdown, whereas PBS/PBAT can satisfy composting claims at a lower cost, particularly for waste management. PHA emerges as the preferred option where soil-side performance is mandatory and must be demonstrated under realistic conditions, such as for thin in-field films, plantable pots and controlled-release fertiliser coatings. In coatings, the polymer mass per hectare is low, and the function is inseparable from end-of-life processes (the polymer persists in order to modulate release and then disappears without leaving any persistent fragments). Experts also note that impending restrictions on microplastics in conventional coatings create a regulatory environment that favours PHAs. However, flexible film production remains technically challenging due to slow crystallisation and the risk of bleeding at lower temperatures. Consequently, some experts view PHA as more suitable for rigid items unless blends or processing windows are proven.

Blending is treated as a tactical enabler, not a price fixer. Experts use blends (e.g. with PBS/PLA or softer PHAs) to adjust stiffness and toughness, improve runnability, or accelerate degradation in cold regions. However, they caution that blending alone rarely closes the price per kilo gap. The commercial logic is to use blends to unlock processability or deliver the required end-of-life performance in the target environment, and then to justify any premium through avoided operations (no retrieval), compliance value or category-specific mandates.

Two cross-cutting levers recur in the interviews. The first is the full cost of use. When disposal, contamination and labour costs are factored in, PHAs can appear attractive in certain applications, despite several experts emphasising that many farm-gate comparisons currently show biodegradable films to be priced at up to about 3× that of conventional alternatives. Secondly, the policy context: outcome-based recognition (fragment-free, time-bounded and environment-matched degradation) and procurement signals can shift purchasing from price per kilo to price per function. This improves the position of PHAs against both petro-incumbents and lower-cost biopolyesters. However, where recyclability is prioritised over compostability and such recognition is missing, PHAs face headwinds — another reason why experts emphasise the importance of robust laboratory, mesocosm and field evidence packages tied to article geometry and local conditions.

5.1.8 Regulation and end-of-life acceptance

Regulation emerges as one of the strongest drivers of demand for residue-based PHAs: it accelerates adoption wherever rules reward verified end-of-life outcomes in the intended environment but stalls it where broad material classes are policed. The market opportunity is concentrated in use cases where buyers can procure "€/function" once time-bound, fragment-free biodegradation under realistic conditions is evidenced. This favours thin-gauge, soil-exposed formats such as mulch films and plant-through/plant-with pots, as well as controlled-release fertiliser coatings. Disappearance in situ removes the need for retrieval labour, prevents contaminated waste streams and retains organic matter in soils.

Experts therefore advocate outcome-based eligibility, whereby permissions and obligations are tied to demonstrated performance in the target environment (e.g. soil) within specific time frames and with defined geometry and thickness to prevent fragmentation. Certificates remain useful only when anchored in an 'evidence ladder' from laboratory to mesocosm to field, using the actual article and declared boundary conditions (e.g. soil type, moisture/temperature, placement and season). Where such recognition is granted, procurement reliably shifts from price per kilo to €/function, improving the position of PHA versus petro-incumbents and lower-cost biopolyesters.

Policy is already creating tangible demand pools. European restrictions on microplastics in controlled-release fertilisers (2025/26) are often cited as an ideal entry point: the amount of polymer per hectare is low, acceptance depends on matching nutrient-release profiles and complete, fragment-free biodegradation is mandatory. Experts also point to niches that are already governed by biodegradability requirements, such as forestry standards and German rules for biodegradable urns, alongside agriculture-focused measures that are under discussion, such as subsidies, financial incentives, and obligations to declare polypropylene use per hectare, that could expand early markets.

Further reducing friction would require harmonised methods and labels. Environment-specific labels (e.g. soil, home compost, industrial compost) that encode boundary conditions and link methods, thresholds, labels and enforcement would lower audit costs, curb greenwashing and shorten specification cycles for converters, brands and public buyers, turning evidence into faster access. In parallel, technology-neutral market design levers can translate verified outcomes into bankable demand by recognising fragment-free biodegradation in EPR/fee and circularity accounting where functionally required, embedding outcome-based criteria in green public procurement, using time-bound EPR modulation for certified articles (rather than open-ended subsidies) and pairing this with levies on non-conforming incumbents, allowing verified biological degradation to count in defined quota categories and co-funding interoperable, field-linked test capacity so that competition is based on performance and cost.

Feedstock policy coherence also matters. For example, biogas incentives can outbid materials pathways for the same organics, which tightens supply and erodes cost advantages. Therefore, experts call for a hierarchy that prioritises residue-to-materials conversion when technical and safety criteria are met. This should be supported by traceability, with procurement awarding points for verified residue-based content. The positioning against other polymers remains clear in these contexts: PLA's slower soil behaviour contrasts with PHA's field-relevant biodegradation. While PBS/PBAT may be cost-effective for composting, it cannot be used as a substitute where credible soil biodegradation is the acceptance criterion — precisely in the settings where collection is impractical and contamination is high.

5.1.9 Logistics and infrastructure readiness

The success of logistics and infrastructure readiness hinges on ensuring that variable, wet side streams behave like spec-grade inputs before they are transported. Across Delphi I–III, experts have agreed on a practical, deployment-ready approach: keep wet hauls short, co-locate with high-volume, homogeneous sources where possible and use regional hub-and-spoke preconditioning to 'freeze' quality. At the hub, simple unit operations such as pressing/screening, partial dewatering and, where justified, pasteurisation, mild acidification or conversion to partial hydrolysates stabilise composition and microbial load, ensuring that intermediates can be shipped reliably. These steps are established for several concentrated by-product streams (e.g. apple pomace, tomato pulp, potato peel and BSG), although adoption varies by region and operator.

Inside the plant, achieving readiness involves choreography rather than heroics. This includes campaign operations with storage buffers, traceable batch tagging and segregation, as well as in-line and at-line analytics with SPC, all of which help to ensure consistent grades. Multi-year supply agreements ensure product availability and stabilise prices, while hub-level densification mitigates the impact of seasonal fluctuations before they affect the fermentation process. Several experts expect the broader value chain to adapt as demand grows. Logistics for new inputs are considered manageable when specifications are clear and volumes are predictable.

Market access improves on the disposal interface when end-of-life pathways are engineered into logistics from the start. For compostable products, aligning with the practices of local facilities is important because many plants run 6–8-week cycles and some still refuse compostables irrespective of certificates. Article-specific, field-linked data can help to secure acceptance where collection is used. For products intended for soil exposure (e.g. mulch films and plant-through pots), providing evidence of biodegradation specific to the region reduces reliance on waste-system gatekeepers. Controlled-release fertiliser coatings are an ideal solution: they fit into existing agricultural input channels, require low polymer mass per hectare and are already subject to microplastic regulations.

Overall, respondents' preferred infrastructure playbook is clear: prioritise concentrated, inhibitor-lean residues; precondition locally via hubs; run campaigns with rigorous quality assurance ; and integrate end-of-life considerations into distribution and customer onboarding. This shifts the discussion from constraints to executable strategies for converting today's infrastructure into a viable source of residue-based PHAs.

5.1.10 Risks, sensitivities, and mitigations

This section summarises the key sensitivities and their associated mitigations in a quick-reference matrix. Detailed evidence and guidance can be found in the referenced chapters.

Table 17: *Risk–mitigation matrix for residue-based PHA deployment (Own compilation by Ecozept).*

Sensitivity	Importance	Primary mitigation	Reference
Feedstock variability	Drives yield/quality scatter; propagates into downstream processing and product specifications	Spec-driven intake; hub-and-spoke pre-conditioning (press/screen, dewater, blending; where justified pasteurisation/mild acidification/partial hydrolysis); short wet haul	§5.1.9; §4.2.2.1.4

Seasonality	Compresses campaigns; lowers asset utilisation	Campaign operations; cold/covered buffers; multi-year contracts; seasonal blending	§5.1.9; §5.1.6
downstream processing cost / solvents	Largest price per kilo driver	Solvent-lean or audited near-closed downstream processing with recovery KPIs; counter-current/membranes; "purity-to-purpose" finishing depth	§5.1.6; §4.2.2.1.4
Converter runnability	Qualification fails with drift in melt/crystallisation	Grade-specific standard operating procedures (drying, temperature/screw/die); nucleation/formulation; targeted blends; tight CoAs	§4.2.1.2–§4.2.1.7
Price exposure	Low willingness-to-pay in B2B	Cost-in-use framing (incl. amino acids top-ups/palatants); staged markets (thin, soil-exposed); standardised 5–25 $kt \cdot y^{-1}$ trains	§5.1.6; §5.1.8
end-of-life acceptance / regulation	Gatekeeper for access and procurement	Evidence ladder (lab→mesocosm→field) with boundary conditions and article geometry; environment-specific dossiers (soil/home/industrial compost)	§5.1.8; §4.2.1.4
Logistics & moisture	Wet miles, hygiene windows, short storage	Short wet haul; co-location; regional hubs (press/dewater); ship dry, free-flowing SKUs	§5.1.9
Contamination & safety	Hazard carry-over; credibility of claims	HACCP-like CCPs at intake/detox/fermentation/release; additive governance and documentation	§4.2.1.9; §4.2.1.6
Scale-up variability & environment	Variability rises with scale; operator exposure	Consecutive validation campaigns; in/at-line analytics + SPC; enclosure/extraction, personal protective equipment, (where relevant) explosion protection	§5.1.6; §4.2.2.1.4

5.1.11 Estimates of market opportunities for PHA – key messages

Key takeaways:

- Where PHA wins first: thin, soil-exposed formats where fragment-free, field-relevant biodegradation is part of the product's function, such as mulch films, plant-through/plant-with pots, horticultural ties and controlled-release fertiliser coatings.
- How demand is specified: procurement shifts from price per kilo to price per function once lab, mesocosm and field evidence (article geometry, soil, climate and season) is in place.
- What unlocks scale: solvent-lean downstream processing; an energy strategy (drying); modular trains with high uptime; and spec-led feedstock hubs. Near-term price logic is total cost of use, not resin parity.

Entry criteria (non-negotiables):

- Evidence passport: field-linked, fragment-free biodegradation; service life met, then 'let go'; claims tied to real article gauge and boundary conditions.
- Economics: a credible cost-down path (titration/productivity increase, solvent closure, counter-current/membranes, modular assets); a target price band of €3–4/kg for selected volumes over time. Until then, justify via cost-in-use (no retrieval, cleaner waste and soil organics retention).
- Feedstock and logistics: inhibitor-lean and uniform side streams; short wet haul; hub-and-spoke preconditioning (pressing, dewatering, blending and pasteurisation/acidification where justified); multi-year supply with specification windows.
- Processability: stable film blowing (bubble/welds) and managed crystallisation. Injection parts requiring strength and flexibility will be in the second wave, unless blends and windows are proven.
- Compliance/SSbD: traceability and contamination control from residue to resin, with claims anchored in harmonised test methods and environment-specific labels.

Near-term core

- Mulch films: one-season integrity → soil disintegration and mineralisation. PHB is considered brittle, but PHA–starch blends require minimal stabilisation and pigments.
- Plant-through/plant-with pots: shape-stable throughout propagation, logistics and planting, and soil breakdown; soil safety dossier for additives and contaminants.
- Horticultural twines/ties: about 6 months UV/load → 2–4 months compost/soil disintegration; flexibility challenging — single-season formats first.

- Controlled-release fertiliser coatings: low mass per hectare; persistence matched to nutrient release for fragment-free disappearance. Microplastics restrictions (2025/26) will create an immediate demand pool.

Competitive positioning (by alternative).

- vs PE/PP: compete only where end-of-life is intrinsic and priced accordingly.
- vs PLA: PHA is preferred where soil-side performance must be demonstrated.
- vs. PBS/PBAT: Composting-oriented alternatives may be cheaper, but they are not substitutes where soil biodegradation is the acceptance criterion.
- Blends are tactical (stiffness/toughness, runnability, cold-region kinetics) and are not a price equaliser.

Risks and mitigations (execution view):

- Variability (residues): specification-driven intake, hub preconditioning, inline/at-line analytics and SPC; conversion to stable intermediates where justified.
- downstream processing/energy OPEX: avoid over-processing, close solvent loops, prioritise drying efficiency and integrate waste heat.
- Converter runnability: grade standard operating procedures (drying, temperatures, nucleation), targeted blends; prioritise films and coatings first.
- end-of-life acceptance: align evidence with local soil/composting cycles (many plants run for 4-12 weeks) and use article-specific field data.
- Policy cadence: Target segments with outcome-based rules (fertiliser coatings and mandated biodegradable items). Prepare labels and methods alignment.

Table 18: *Application readiness matrix for residue-based PHAs (Own compilation by Ecozept).*

Application	TRL	MRL*	Readiness	Primary gates (SSbD tags)
Mulch films	7–8	6–7	High	Stable film blowing; field-relevant, fragment-free biodegradation dossiers; pigment/stabiliser.
Plant-through/plant-with pots	7	6–7	High	Shape stability to planting → soil degradation; soil safety/migration checks
Controlled-release fertiliser coatings	6–7	6–7	High	Release-profile match + complete post-use biodegradation; microplastics compliance
Horticultural twines/ties	6	5–6	Medium	UV/load about 1 season; flexibility; end-of-life disintegration in compost/soil
Green-waste / tea-bag films	6	5–6	Medium	Facility cycles 4–12 weeks; local acceptance
Injection clips (vine/greenhouse)	5–6	3–4	Low	Toughness vs brittleness; temperature window; article-level end-of-life proof

5.2 Estimates of market potential of MP

Section 5.2 estimates the European market potential for MP by distilling the results of three Delphi rounds and a desk analysis into investable, SSbD-aligned options. We structure the adoption process as follows: feed → pet → food. We then assess the key determinants (price/scale, as-processed functionality and evidence, and regulation) and map segment fit (aquaculture first, premium pet food as a pricing bridge and food contingent on sensory parity and cost-in-use). Geography/logistics, feedstock classification and site energy (with drying as the dominant load) are treated as design variables. The outcome is a decision toolkit comprising claims-ready dossiers, specification tiers and staged inclusion trials that translates technical feasibility into bankable offtakes.

5.2.1 Assessment of market potential of MP

5.2.1.1 MP For food

MP is framed as nutritionally “good enough” for mainstream use—its indispensable amino-acid profile sits in the soy range—but nutrition is not the market gate. Volume adoption is decided first by sensory performance under real processing (clean flavour without off-notes, acceptable colour, meat-relevant texture/mouthfeel), and second by price. Experts repeatedly note that consumers buy taste, not amino-acid tables; “microbial” per se carries little willingness-to-pay unless it delivers validated functional or health advantages. Price parity—or a clear cost-in-use rationale (e.g., shorter ingredient lists, fewer texturisers, lower wastage)—is therefore pivotal. Acceptance also shows regional variation; positioning MP within familiar food-fermentation narratives helps, but taste and price remain the decisive levers across markets.

From a functional perspective, experts treat MP as a toolkit rather than a commodity that can be swapped one-for-one. In development kitchens, predictable techno-functionality under actual unit operations wins: gelation and texturisation for bite and elasticity, stable emulsification, water/oil binding, and tractable hydration and flow through extrusion, cook-hold, pasteurisation/retort and freeze-thaw. Fungal-based MPs are particularly promising for providing "bite" in meat alternatives, while egg proteins remain dominant in systems that require strong binding/gelling, such as certain bakery products and sauces. In practice, high-MP products rarely contain 100% MP; formulators blend MP with complementary plant proteins and a lean binder/structurant stack to improve cohesion, juiciness and shape retention without increasing cost or label complexity. This mirrors UK mycoprotein precedents, where blends plus targeted binders, rather than stand-alone MP, define the winning architecture.

This pragmatism carries over to supplier expectations. Buyers ask for clear application guidance and *as-processed* specifications so that functionality demonstrated in tests is repeatable on real lines; experts specifically mention dosage ranges, processing targets and compatibility maps. Two gating issues recur:

(i) explicit nucleic-acid (purine) management for sensitive uses, and
(ii) a Novel Foods pathway that is rigorous but slower and costlier in practice than its nominal timeline, making early scoping/pre-submission alignment valuable.

Set against cheap, industrialised soy/pea baselines and a still-maturing MP category, the commercial prescription is incremental and evidence-led: drive sensory parity at competitive cost-in-use; use MP where it demonstrably simplifies recipes or enables cleaner labels while holding texture and taste; and scale through blended architectures that showcase MP’s distinctive strengths (especially fungal “bite”) while managing its gaps. In short, nutrition clears the acceptability bar, but repeatable functionality, clean sensory, and a credible price story decide whether MP graduates from pilot buzz to sustained, high-volume adoption.

5.2.1.2 For feed

Across interviews, aquaculture emerges as the clearest early market for microbial protein (MP), but only if three technical gates and a hard price test are met. First, crude protein needs to sit at or above about 60% to enter the conversation and closer to about 65–75% to play credibly in the fishmeal tier. Second, digestibility must be high in practice—not just in vitro—with experts citing ≈≥85% for protein/IAA availability as the working threshold. Third, the indispensable amino-acid (IAA) profile must be "fishmeal-adjacent": lysine is typically first-limiting and methionine can run short, both of which nutritionists can solve at the diet level via blending and, where permitted, crystalline amino acids. Species nuance then refines the bar: MP's arginine strength is attractive for salmonids; histidine sufficiency links directly to cataract management in salmon; and carnivorous fish tolerate little carbohydrate, so formulations must deliver digestible energy through lipids rather than starch. Palatability is the following gate before—yeast-based MPs tend to be well accepted, whereas some bacterial MPs can require palatants or processing to tame off-notes. The adoption process is staged and evidence led. Formulators start with an inclusion rate of around 10–15%, with predefined intake stop criteria. They only expand the rate when performance is consistent across species and life stages.

Market fit, in this telling, is a tiering problem as much as a technology problem. Aquafeed buyers screen MP on three axes:

(a) Is MP in the right protein tier?
(b) Are digestibility and bioavailability proven in real diets, not just bench assays?
(c) Is the composition aligned to species constraints (adequate protein and fat, minimal fibre/sugars for piscivores)?

Several nutritionists also ask for a clean separation of protein-nitrogen from non-protein nitrogen, so the protein label reflects usable amino-nitrogen. Price then decides the pace of uptake: MP must compete against least-cost blends of soy concentrates, fish by-product meals, and corn gluten; demand accelerates either as MP costs fall with scale/learning or when conventional inputs tighten. Importantly, feed regulation is viewed as more tractable than food, particularly if residue-based routes come with hygiene, traceability, and contaminant control—making aquaculture a pragmatic beachhead before moving into pet and, later, human food.

Experts nonetheless see structural reasons MP can win a seat at the aquafeed table even at modest inclusion. Unlike many plant proteins, MP generally lacks classic anti-nutritional factors (phytate, saponins), which improves mineral availability and tolerance. Its fine, homogeneous particle size supports uniform micro-pellet production for early life stages—an operational advantage in hatcheries. Select strains bring bioactives (pigments, antioxidants, enzymes) that can support health or product quality (e.g., natural colorants), creating functional USPs at low inclusion. Because leading formulators already optimize across least cost × nutrition × footprint, a fishmeal-adjacent MP with robust growth/FCR data and a transparent, energy-source-sensitive LCA can gain preference in constrained recipes. Several experts therefore describe aquaculture as a suitable first entry: the nutrition is compatible, the functionality can be proven quickly in controlled trials, and the buying centres are analytic and specification driven.

Beyond aquaculture, starter feeds for poultry and piglets surface as attractive, premium niches where gut-integrity or resilience co-benefits justify low-inclusion, higher-price use while reference sets build. Pet nutrition is flagged as a high-willingness-to-pay adjacency with fewer regulatory hurdles than human food and a stronger premium logic—useful for early commercial traction and brand storytelling.

What buyers want from suppliers is unusually concrete. They expect specification tiers by CP and digestibility (e.g., ≥60% and ≥65–75% CP SKUs) plus full composition sheets (amino acids, fatty acids, vitamins/minerals, moisture/aw, particle-size distributions, flowability) so they can drop MP into least-cost solvers with confidence.

They want trial packages by species and life stage mapping inclusion against intake, FCR, growth, survival, palatability, and health markers—especially around the 0–15% band where most initial purchasing happens. They ask for processability data through conditioning, extrusion, and drying (hydration/dispersion kinetics, pellet durability, fines), including mitigation guidance where enzymatic hydrolysates risk stickiness (binder choice, dryer set-points). And they require feed-oriented regulatory and safety documentation—HACCP/GMP, contaminant screens, residue-route traceability—because "faster in feed than food" still depends on clean, complete dossiers.

Taken together, the opportunity thesis is pragmatic rather than heroic: position MP as a fishmeal-adjacent, high-spec complementary protein used at modest inclusions to improve formulation efficiency and resilience (nutrient density, palatability, potential health co-benefits), then scale share as costs fall and spec consistency is proven at volume. In the near term, aquaculture leads; poultry/piglet starters and premium pet nutrition provide profitable adjacencies that help finance scale-up, deepen the evidence base, and broaden acceptance ahead of more demanding food markets.

5.2.1.3 Pet food

Pet nutrition emerges as a pragmatic bridge market between bulk feed and human food. Regulatory pathways are generally lighter and faster than those for novel foods, yet the willingness to pay is significantly higher than in commodity feed. Premium pet food buyers are not looking for generic protein; they want high-specification, low-inclusion functional ingredients that reliably improve formulation performance. Specifically, this requires hard nutritional evidence such as credible crude-protein tiers with in vivo digestibility and a transparent indispensable amino-acid profile, proven palatability across formats and, where available, validated co-benefits such as gut resilience or skin and coat outcomes. While sustainability narratives (e.g. reduced pressure on marine stocks and residue upcycling) can add consumer appeal, experts caution that they must be backed by audited LCAs, traceable sourcing and clean safety dossiers. On their own, they seldom justify a B2B price premium. Therefore, the commercial logic favours a 'claims-ready' dossier approach: suppliers who can provide digestibility and palatability data, contaminant and allergen screening, and simple health-marker readouts alongside reliable, consistent supply will win faster briefings and brand trials.

From a strategic perspective, several experts view pet as an attractive sequencing step. Margins and reference wins from premium SKUs can finance scale learning, mitigate manufacturing consistency risks, and professionalise evidence packages. These capabilities translate well into adjacent markets, such as aquafeed for volume at modest inclusion and, later, human food once taste, cost-in-use, and authorisation gates are cleared. This approach is consistent with the broader adoption of MP: competing on function per euro, making claims auditable, and treating sustainability as an evidence-based amplifier rather than the product itself.

5.2.1.4 Sequenced go-to-market (feed → pet → food)

A staged entry — feed → premium pet food → human food — emerges as the lowest-risk route, as the evidence burden, pricing power and regulatory friction increase in that order. The first step is aquafeed, where adoption is governed by cost-in-use and specification fit. Suppliers should strictly conduct inclusion trials within approved contexts and deliver an MP that meets the already defined protein/digestibility and amino acid guardrails (see 5.2.1.2), managing palatability via staged inclusion or process adjustments where necessary. The objective is to provide longitudinal proof of digestibility, intake/FCR and survival, and to ensure lot-to-lot stability in order to secure bankable offtakes.

Premium pet food then acts as a bridge in terms of both price and dossier requirements: the requirements are lighter than those for human food, yet more stringent than for bulk feed, and the willingness to pay is higher. Winning offers come with a package of validated digestibility, an indispensable amino acid profile, palatability and simple health and welfare readouts, as well as reliable supply. The resulting references and QC data can be recycled back into aquafeed scale-up.

Human food production follows once three criteria are met: sensory neutrality, techno-functional equivalence for the target unit operations and cost-in-use parity. Authorisation runs in parallel via disciplined Novel Foods operations (see section 4.3.2.2), with application toolkits prepared for priority formats (dosage bands, process set points and compatibility maps). Nucleic acid management is addressed where relevant.

Operationally, early offtakes load larger/continuous trains and reduce the cost per kilogramme (see 5.2.2), while the geography can be sequenced — faster jurisdictions first — until EU filings mature. The approach is straightforward: start where the evidence bar is achievable and the cost-in-use is justifiable; use these successes to finance capacity; enter the food market when the price, sensory profile and dossier are aligned.

5.2.1.5 Further suitable applications

Beyond the primary food and aquafeed routes (and the dedicated pet-food bridge in 5.2.1.3), experts point to a set of niches but attractive applications where MP's attributes or co-products can unlock value at modest volumes and higher prices.

Starter diets for poultry and piglets top the list: buyers will pay for low-inclusion ingredients that combine high crude protein and digestibility with functional co-benefits (gut integrity, resilience, immunity). Yeast MPs are often intrinsically palatable; bacterial MPs can work with palatant support. Adoption remains evidence-led and life-stage specific, with staged trials to define inclusion ceilings. A second pocket is pigments and bioactives: strains like *Phaffia* (astaxanthin) or microbially derived antioxidants add value in aquaculture and premium pet SKUs as low-dose, high-price add-ins, provided efficacy is documented (colour scores, stress markers). Several experts also flagged dual-nutrient propositions—MP routes that co-produce beneficial lipids (EPA/DHA)—to target salmonids and other omega-3-dependent species with function-led SKUs rather than commodity protein.

On the food side, MP can enter as a techno-functional booster rather than a bulk protein: clean emulsifiers, water/oil binders, and gelling fractions (including metabolite-rich outputs from solid-state or tailored fermentations) that simplify binder stacks at low inclusion, contingent on "as-processed" specifications that reflect real hydration, shear, and thermal histories. At the other end of the value spectrum, by-product outlets (e.g., broth derivatives into plant fertilisers) are not strategic markets but serve as safety valves for off-spec lots, improving site economics and reducing waste. Strategically, several experts situate MP within a broader microbial platform—alongside fermenter-made fishmeal/fish oil and targeted bioactives—so suppliers can bundle protein, lipids, and pigments for aquafeed/pet buyers seeking integrated solutions.

Commercially, these "other" applications are claims- and data-driven: buyers expect palatability and digestibility evidence, full amino acids (and where relevant FA) profiles, and— for bioactives—validated health or product-quality outcomes. While absolute volumes are modest, willingness to pay is higher than in commodity feed, making these niches useful margin bridges that fund learning curves and capacity ramps until bulk aquafeed—and later food—volumes can carry the cost base.

5.2.1.6 Inappropriate applications

Experts reject blanket "no-go" claims for MP in feed or food. Suitability is consistently framed as context-dependent—a function of species, life stage, target inclusion, and specification—and best established through stepwise trials and formulation modelling rather than assumptions. Within that evidence-first stance, several recurrent risk cases and boundary conditions shape how and where MP should be used.

The clearest red flag is broiler nutrition, where experts repeatedly cite nucleic-acid (purine) load as a constraint. Broilers have limited purine catabolism; high nucleic acids can elevate serum uric acid, depress intake, and erode performance. The consensus is restricted, managed use only: cap inclusion rates, prioritise low-nucleic acids MPs or validated nucleic acids -reduction processes, and monitor intake, FCR, and uric-acid markers as part of predefined stop criteria. A second cross-cutting gate is palatability. While many yeast MPs are well accepted, some microbial sources carry off-notes that trigger feed avoidance and rapid weight loss if deployed at scale without mitigation. Here, experts prescribe a test-and-tune protocol: staged inclusions (often starting about 10–15%), sensory screening, palatant support or processing adjustments where warranted, and hard stop rules when intake drops or FCR deteriorates.

In aquaculture, limits are defined by specifications rather than by blanket exclusions. Products with a crude protein content below about 50–55% or poor digestibility are not suitable as primary protein ingredients and should only be used as functional components if at all, rather than as fishmeal-adjacent proteins. Designing diets for carnivores introduces another boundary: digestible energy must be lipid-led. MP formats that introduce excess structural carbohydrate are inappropriate at higher inclusion rates without compensatory formulation. Conversely, high-specification SKUs (≥60–65% crude protein, ≥85% digestibility and complementable essential amino acid profiles) remain within scope when palatability and performance are demonstrated.

For human food, the gate is as much regulatory and sensory as it is nutritional. Experts emphasise that the use of MP is inappropriate where use-specific safety and adequacy have not been demonstrated (e.g. unmanaged nucleic acids for sensitive populations or dossiers that fall short of the expectations for novel foods) or where the format cannot tolerate colour or flavour carry-over and off-notes cannot be demonstrably controlled. Additionally, legal classification is important: materials classified as 'waste' rather than 'by-product' cannot be used for food until their eligibility and traceability are established, which renders any such applications out of scope regardless of their technical potential.

The operational takeaway is anchored in evidence. Treat “inappropriate” as a data-driven, revisable conclusion:

(iii) run species- and life-stage-specific pilots with predefined stop criteria;
(iv) cap inclusion where biology dictates (broilers, carnivorous fish) and deploy nucleic acids - reduction/palatability fixes where they work;
(v) reposition MPs that fail primary-protein thresholds as functional additives or redirect them to better-fitting species/segments.

In this framing, risk is managed not by blanket exclusions but by disciplined specification, staged validation, and willingness to move the ingredient to the context where it demonstrably fits.

5.2.2 Determinants of market potential

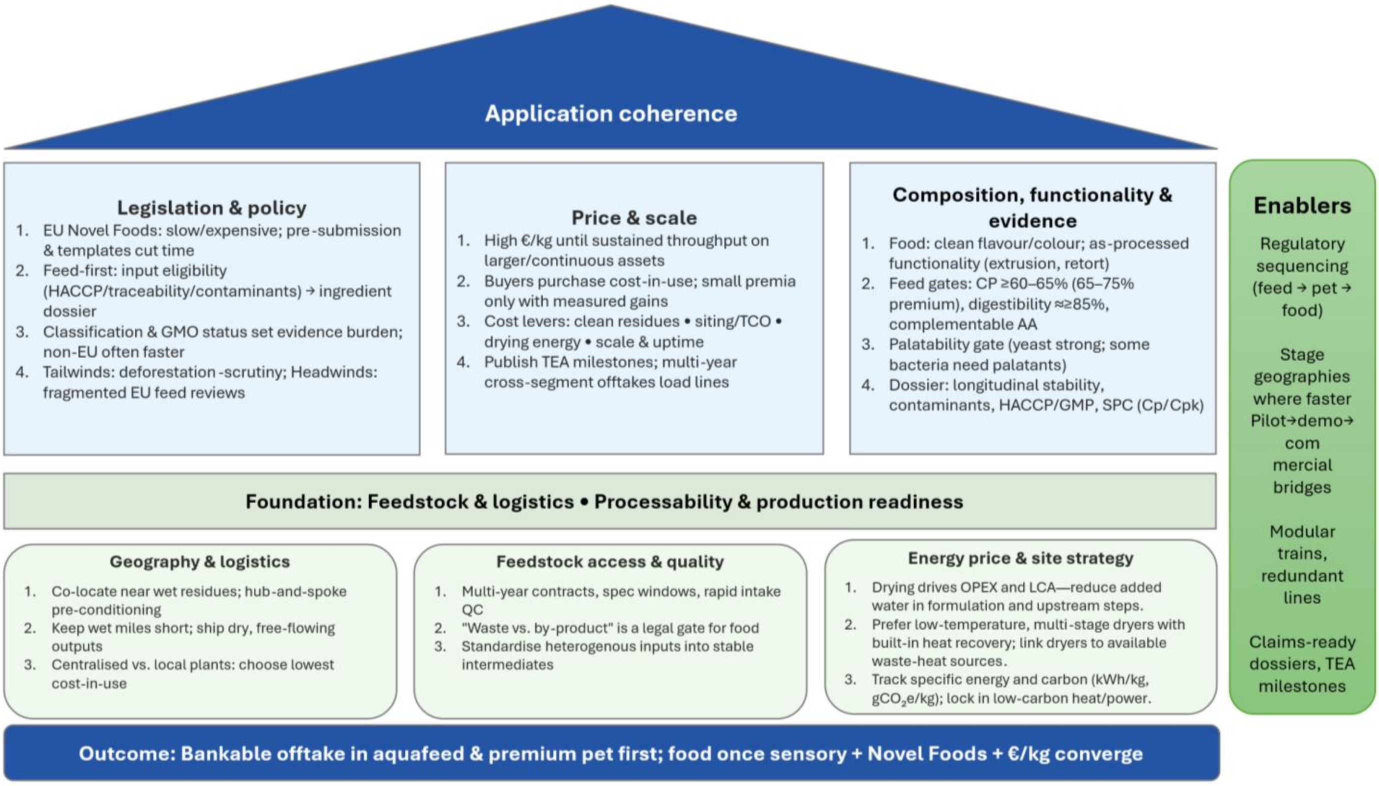


Figure 19: *Application-coherence map for microbial protein (MP) (Own compilation by Ecozept, based on Delphi interviews).*

5.2.2.1 Legislative and policy context

Regulation is the dominant clock and compass for market entry—more decisive than technology readiness or even raw unit cost. For human food, experts credit the EU Novel Foods regime with building trust through rigor, but describe a process that is slow, costly, and opaque in practice: the nominal about 2-year review frequently overruns (toxicology, allergenicity where relevant, contaminants, manufacturing controls, and "as-processed" specifications). What practitioners want is not looser rules but clearer ones: early scoping and templates, structured pre-submission dialogues, and predictable review choreography that shortens elapsed time without diluting standards. Many experts now plan for elongated timelines by staging their dossiers (safety first, functionality later), and by sequencing geographies where non-EU jurisdictions can move faster, using those launches to build references and longitudinal safety data ahead of an EU filing. Several experts—especially in aquaculture and premium pet—also flag the GMO status of the production organism as a practical constraint for claims and market access; where non-GMO positioning is required, organism and processing choices (and documentation) should be planned accordingly.

Feed is widely seen as the nearer-term entry point, especially for residue-based routes, but it has its own two-stage process: first, the eligibility of the intended residual inputs must be secured (e.g. hygiene, HACCP, traceability and contaminant panels); only then can the ingredient dossier advance. Several respondents described EU feed approvals as complex and protracted. Fragmented expert interpretations (e.g. whether immune-modulatory effects are a risk or an intended function) can reset evidence expectations and add years to the process. Classification choices significantly alter the burden of proof, so reaching an early agreement on the category is a strategic decision, not a clerical one. In contrast, multiple non-EU systems were described as faster and more straightforward, which is influencing site selection and the order of the first commercial deployments.

Policy headwinds and tailwinds compound these procedural realities. On the upside, incoming deforestation-linked import restrictions could tighten scrutiny on conventional proteins and improve the relative case for microbial protein—if suppliers can substantiate clean sourcing, robust traceability, and credible LCAs. On the downside, experts argued that the EU's feed evaluation architecture would benefit from system-level reform—risk-tiered assessments, time-bound reviews, and integrated expert panels—to reduce administrative drag without compromising safety, and to align regulatory throughput with strategic goals such as European/Norwegian protein self-sufficiency.

Taken together, the entry playbook is regulatory-first and sequencing-aware: map classification and claims early; pre-consult authorities on data expectations; treat feedstock eligibility (for residue routes) as a formal milestone; and keep pilots within currently approved contexts while broader approvals mature. Where timing is critical, stage geographies (launch first where reviews are faster) and ladder categories (feed → pet → food) to accumulate revenue, references, and longitudinal safety/quality evidence that de-risk subsequent filings. In this framing, regulation is not a background constraint but an active design variable: getting it right determines when volume appears, where it appears first, and at what cost of capital.

5.2.2.2 Price and scale

According to experts, price and scale are inextricably linked: early-stage production carries a high cost per kilogramme, and only sustained throughput on larger or continuous assets can reduce costs. This creates a self-reinforcing loop: without sufficient volume, costs remain high and buyers hesitate; without a credible reduction in costs, offtakes remain provisional and plants remain underloaded. Practitioners attribute this dynamic to buyer economics: in the feed industry, reference price points are a few hundred euros per tonne, with around 85% of the cost being raw materials. Therefore, achieving cost-in-use parity or near-parity is essential for entry into the market.
In the food industry, the 'microbial' label alone does not command a premium; adoption hinges on sensory parity during real processing and, where applicable, substantiated health or functional benefits. Sustainability narratives help with brand positioning, but they are not strong price drivers. That said, several buyers valued reliable, stable-priced supply as a hedge against soy/pea price volatility, which is a useful form of differentiation even without a consumer premium. Yet most urged producers to publish transparent Techno-economic analysis (TEA) milestones tied to specific scale steps in order to make the cost trajectory bankable.

Feed formulators evaluate microbial protein against fishmeal and soy using a least-cost approach, explicitly counting the cost of crystalline amino acids and palatants. Only small premiums are tolerated when low-inclusion additions deliver measurable gains, such as better intake/FCR or survival, or when they reduce supply risk. Benchmarks are incumbent-anchored — fishmeal/soy parity, not novelty pricing — and multiple experts stressed that meaningful annual tonnage at tight specifications is what simultaneously unlocks adoption and the next stage of reducing costs.

The total cost of ownership across the chain is what actually moves the €/kg, not a single 'silver bullet'. Four recurring levers emerge.

(1) Feedstock economics and cleanliness: cheaper, specification-stable residues reduce the need for conditioning and purification; variable or 'dirty' inputs increase costs at both ends of the chain.
(2) Processing intensity and location: keep upstream purification lean, co-locate near wet residues to avoid transporting water, and decide where to dewater or finish the product (ship intermediates short and dry/pelletised output long) based on total cost of ownership rather than unit operations in isolation.
(3) Energy: drying dominates OPEX and footprint; formulations that behave like fishmeal (plasticising and water-soluble fractions) reduce dryer time. A site's energy strategy (Power purchase agreements (PPAs)/low-

carbon power, waste-heat integration, dryer selection and heat recovery) can significantly impact both price per kilo and LCA.

(4) Scale and uptime: decisive factors include equipment sizing, overhead dilution, procurement/logistics efficiency and steady utilisation.

Sub-pilot assets struggle to demonstrate credible curves. Producers make cost reductions visible to off takers and financiers by moving to ≥about 50,000 Liters reactors and then taking 10k → 30–50k t/y steps.

Two second-order points should be considered in the discussion. Firstly, using microbial broth as a small, functional 'booster' is typically an insignificant cost and can facilitate entry, whereas full replacement remains costly. Secondly, capital follows credible load plans, such as multi-year, cross-segment offtakes (feed → pet → food), which keep production lines busy while economies of scale and learning reduce the cost per kilogramme.

The practical takeaway is that market potential expands in lockstep with a documented, milestone-based cost-down pathway. This involves locking in affordable, clean residues, co-locating and dewatering smartly, designing for low-energy drying, aggregating demand to run bigger/continuous processes, and publishing stepwise price per kilo targets tied to throughput milestones. Food adoption depends on sensory and cost factors, while feed adoption depends on cost-in-use factors. Both depend on achieving scale, which in turn depends on convincing stakeholders of the demand and total cost of ownership story upfront.

5.2.2.3 Composition, functionality and evidence

Across interviews, “marketable” meant far more than a clean certificates of analysis: buyers in both food and feed insisted on as-processed performance that survives real unit operations and holds steady as plants scale. Practitioners want functionality measured after the relevant hydration, shear and thermal histories, then trended over time so they can see drift—or the lack of it—at increasing throughput. In this frame, static specifications are hygiene factors; what earns adoption is longitudinal proof that the same inputs, run through the buyer’s actual process, deliver the same outcome month after month.

In food, acceptance is won on three fronts: clean flavour (off-note control), credible colour management, and a functional profile that persists through the intended process. Experts expect quantified, as-processed functional specifications (standardised rheology/emulsion/water-binding/flow read-outs under process-relevant boundary conditions) (see 4.3.1.1). Suppliers that land deals show up with application toolkits—dosage bands, process set-points, and compatibility maps for salts, pH, hydrocolloids and co-proteins—and they report those specifications as processed, not just as-received. Nutrition/safety must be evidenced in parallel: indispensable amino-acid profiles, allergenicity assessments, control of anti-nutritional factors, and—where applicable—nucleic-acid (purine) limits with the reduction method. Shelf-life and handling claims are tied to moisture/Aw targets and clear storage standard operating procedures.

The gates are equally explicit in feed and even more price disciplined. The cited baselines were ≥60–65% crude protein with high digestibility and a complementable amino acid profile. Species-specific nuances matter for example, arginine strength is useful in salmonids, while histidine sufficiency is linked to cataract control. Carnivores tolerate little carbohydrate, so digestible energy must rely on lipids. Palatability acts as the intake gate: yeast MPs are often readily accepted, whereas some bacterial MPs may require palatants or processing to mask unpleasant flavours. Inclusion is staged and evidence-based (many start at around 10–15% with predefined stop criteria, such as a drop in intake of more than 10–15% or sustained FCR deterioration). Mills also consider form and handling when buying: dry, free-flowing, low-dust powders or granules (often pelleted or lightly fat-coated) with defined particle size bands, bulk density and flow indices. The moisture content/Aw should typically range around less than 0.7 and they must be proven to run cleanly at typical plant humidity and temperature, while preserving pellet durability with low fines.

What the dossier must show—across sectors—is stability under scale. Regulators and customers asked for lot-to-lot trend charts from pilot → demo → commercial runs, covering specification stability, safety and performance. Complete packages include macro-composition, IAA profiles and species/life-stage-relevant digestibility coefficients (for feed); contaminant panels (metals, pesticides/POPs, and mycotoxins where relevant), microbiology, nucleic-acid content and reduction method where applicable; plus, HACCP/GMP evidence, traceability, and hold/rework/reject protocols. On manufacturing control, experts looked for SPC on critical process/material parameters and demonstrated process capability (Cp/Cpk) across campaigns—not just single-batch snapshots. The synthesis is straightforward: repeatable specifications + as-processed functionality + longitudinal proof are the decisive ingredients of marketability; anything less reads as R&D, not supply.

Species- and life-stage specificity (including limits)

Suitability is context dependent. For aquaculture, carnivorous species tolerate little carbohydrate, so digestible energy is lipid-led; amino-acid nuances matter (e.g., lysine first-limiting; histidine/arginine relevance in salmonids). A clear risk case exists for broilers due to nucleic-acid (purine) load—requiring inclusion caps and/or nucleic acids reduction. Early-life aquafeeds benefit from fine, homogeneous powders that aid micro-pellet uniformity. These biological specifics shape ceiling levels, price realisation and the order of market entry.

5.2.2.4 Geography and logistics as market enablers

Geography functions as a design variable rather than a hard constraint. Wet, variable residues should be converted close to the source, while dry, stable outputs should be transported over greater distances. In practice, this involves co-locating fermentation and the first stage of downstream processing with residue hubs or upstream processors. Hub-and-spoke collection is used to buffer seasonality and minimise 'water miles' through early sorting, dewatering and light pretreatment. The logistics barrier chapter and the PHA supply-design section set out detailed rationales and intake rules (see 4.2.2.1.3 and 5.1.5).

Two siting archetypes recur and are typically compared in techno-economic analysis:

(i) centralised hubs that exploit scale and utility integration across a wider catchment, but which manage more complex inbound flows, and

(ii) local/decentralised plants with short, reliable inbound routes for wet streams, but which potentially incur higher unit costs.

Experts benchmark the options based on the following criteria: inbound mass and water moved; lead times; buffer/preservation needs; cost per tonne-kilometre; and delivery service level agreements to mills or factories. They then select the configuration with the lowest cost-in-use at the required reliability. A frequent compromise involves converting heterogeneous residues into stable intermediates (concentrates or partially processed fractions) near the point of origin before shipping, which stabilises both quality and economics.

Execution differs by region. Within the EU, the model is workable when paired with buffer stocks or vendor-managed inventory, thanks to contracted, time-definite lanes and mature third-party logistic networks. Outside the EU, however, route quality and lead times vary more widely, so stress-testing, contingency lanes and higher on-site buffers are necessary. For outbound shipments, especially feed, buyers expect dry, free-flowing formats (such as pellets or granules) that can be processed cleanly in plants. They also require clear storage and handling standard operating procedures, as well as nutrition and safety documentation. The detailed physical specifications and 'as-processed' performance requirements are addressed in section 5.2.2.3.

When integrated in this way — co-location where it saves water miles, dry outbound where distance is unavoidable and contracted lanes supported by buffers — logistics becomes an enabler of market access and cost predictability rather than a barrier.

5.2.2.5 Feedstock access, quality and classification

Market potential begins at the intake gate. The strongest predictors of feasibility and price are access to affordable, specification-stable side streams: clean, well-characterised inputs reduce purification effort and shorten regulatory paths, whereas seasonal drift, inhibitor load and hauling water increase cost and risk. The decisive legal factor is classification: waste versus by-product determines eligibility, notably for food routes. Therefore, teams stage work as follows: input eligibility (hygiene, HACCP, traceability and contaminant panels) → ingredient dossier.

Quality control begins at the weighbridge. Typical specification parameters include the C:N ratio, dry solids content, fermentable sugars, inhibitor markers (furans and phenolic compounds) and contaminants (metals, pesticide residues and antibiotics/microbiology where relevant). Industrial food side streams (e.g. brewers' spent grains, potato peels and sugar beet molasses) are repeatedly found to be safer and more traceable than household-type organics. As upstream noise is reflected in product macros (notably fat level/profile), producers treat output as a recipe control problem, monitoring lot-by-lot composition and applying predefined corrective blends to maintain specifications.

The process and location are designed together to minimise wet handling and variability. Where feasible, fermentation (or the first stage of downstream processing) is located alongside residue hubs. Otherwise, a hub-and-spoke model incorporating pre-conditioning (sorting, dewatering/concentration and inhibitor-lean pretreatments) 'freezes' quality prior to transport. If day-to-day drift persists, some operators standardise the process upstream to produce fermentable intermediates (e.g. mixed sugars, glycerol and alcohols) in order to decouple uptime from residue variability. Products are transported outbound as free-flowing powders or granulates with defined physical specifications (moisture content, a_w value of less than 0.7, particle size distribution, bulk density and flow indices) to ensure clean dosing and compatibility with the plant.

Commercially, contracts mirror the technical approach, comprising multi-year, risk-stratified agreements with defined specification windows and on-arrival quality control (QC), backed by buffer storage and seasonal blending. In practice, TEAs co-optimise residue cost per tonne and processing intensity. They choose residue-dense locations with year-round supply, keep wet inbound transport short, and ship dry, tightly specified SKUs farther. This turns feedstock access, quality, and classification from constraints into enablers for early feed volumes and, subsequently, expansion into pet food.

5.2.2.6 Energy price, source and site energy strategy

Energy acts as both a cost regulator and a driver of the environmental footprint, with post-extrusion pellet drying being described repeatedly as the dominant source of heat (see Section 4.3.2.2.3, 'Main energy hotspots'). The size of this load is determined by the formulation physics upstream: if a recipe requires a high moisture content for binding and shaping, the drying process is more costly; however, if the ingredients are more water-soluble or have inherent plasticising properties, coherent pellets can be formed at a lower moisture content, reducing the evaporative load. Practitioners use fishmeal as the practical benchmark — a 'natural plasticiser' that allows strong pellets to be formed with comparatively little added water — whereas several plant proteins (notably soy) lack this property and increase drying energy (see Section 5.2.2.3 on as-processed functionality and pellet behaviour). Additional thermal steps, such as nucleic acid reduction, can add meaningful heat duty. Upstream pre-processing also consumes energy, but both remain secondary to the dryer's load.

As there is no single lever, companies engineer three layers as a stack. Firstly, in terms of formulation, reduce added water via ingredient selection and process aids, pursue upstream dewatering/concentration so that less water enters the line, and target higher cell densities or continuous/long-campaign fermentation to dilute fixed energy overheads per kilogram (see links to intake and processing choices in sections 5.2.2.5 and 4.2.2.1.4). Secondly, in terms of equipment and heat recovery, choose dryers and recovery architectures that are tuned to the actual moisture profile, such as low-ΔT, multi-stage configurations with counter-current air, condensate/air recirculation, and in-line moisture sensing. This ensures that heat is applied only where it adds value (see Section 4.2.2.1.4, 'Production—Operations & Flowsheet'). Thirdly, the site's energy strategy should involve securing clean, low-cost heat and power (e.g. via PPAs or on-site renewables), harvesting waste heat from neighbours or on-site utilities, and scheduling energy-intensive steps to coincide with off-peak tariffs where possible. Co-location and hub-and-spoke strategies that minimise 'water miles' will reinforce these gains (see Section 5.2.2.4, 'Geography and logistics as market enablers'). Fuel choices are explicit: natural gas increases carbon intensity, whereas bio-based fuels decrease it (see 4.3.2.2.3 for more information).

Execution is KPI-driven. Teams track kWh/kg and gCO_2e/kg in TEA/LCA, benchmarking dryer configurations and energy sources while co-optimising energy savings against product quality and throughput (see section 4.3.2.2.3). The most credible plans are read from left to right: first, minimise the amount of added water in the mix; then, fit the dryer and heat recovery to the moisture curve; and finally, lock in low-carbon heat and power with industrial symbiosis where available (see section 4.2.2.1.5 on solvent and utility closure for complementary environmental health and safety and OPEX impacts). When these layers are co-designed rather than treated individually, energy shifts from being a structural penalty to becoming a managed variable, with clear pathways for reducing both price per kilo and CO_2e/kg.

5.2.3 Arguments for higher price of MP

In **food**, Pricing power is conditional and earned through performance rather than provenance. Buyers report little intrinsic willingness to pay for a 'microbial' label. Any uplift requires sensory parity (clean flavour, acceptable colour and texture that survives the intended unit operations) and substantiated, communicable benefits. Where premiums are observed, they are typically small and conditional, amounting to a low single digit percentage (sometimes about 5–10%), and are tied to cost-in-use advantages (e.g. leaner binder stacks, lower quality risk). Otherwise, parity is the realistic target for achieving volume adoption. However, MP can still differentiate B2B by stabilising specifications and availability compared to volatile soy and pea inputs.

In **feed**, MP is used as a low-inclusion, functionality-led ingredient rather than a bulk commodity. A defensible price is based on the evidence outlined in Section 5.2.1.2: high crude protein content, high digestibility, an indispensable amino acid profile that can be supplemented, and no negative effects on intake, growth, FCR or health. Formulators purchase based on cost-in-use versus fishmeal/soy, explicitly accounting for amino acid top-ups and palatants. Premiums are only awarded when MP measurably improves FCR/survival, reduces supply/price volatility or mitigates risk through spec stability/traceability. Palatability is the intake gate (yeasts are often strong and some bacterial MPs require palatants), with staged inclusion (frequent pilots at about 10–15%). Narratives around sustainability (e.g. residue upcycling and reduced pressure on wild stocks) are monetised downstream in branding and retail, but feed buyers rarely pay extra for a smaller environmental footprint alone.

5.2.4 Advantages compared to current alternatives

In food, MP have a role to play when they deliver the right processed techno-functional profile for the target product, providing clean flavour and acceptable colour, as well as predictable behaviours such as stable emulsification, water/oil binding, gelation/texturisation and controllable viscosity, which survive hydration, shear and thermal processes. As cost and label constraints dominate most categories, formulators rarely use 100% MP; instead, they use a blend-first approach (MP + complementary plant proteins with a lean, purpose-built binder stack) to achieve the desired texture while simplifying recipes. Suppliers that succeed in this area provide application toolkits (dosage bands, process set points and compatibility maps) and report processed specifications (see 5.2.2.3). Where these elements are in place and the taste is comparable, MP can reduce the complexity of binders and hydrocolloids and improve cost-effectiveness compared to plant-only systems.

In feed, MP's advantages over many plant proteins are more evident. As single-cell proteins, they typically avoid common anti-nutritional factors and behave more like fishmeal in terms of formulation. The fine, homogeneous particle size also supports the production of uniform micro-pellets in early life stages. Palatability remains strain-dependent (yeasts often perform well) and must be demonstrated, but when intake is maintained, MP can be incorporated into least-cost optimisation as a complementary protein. The indispensable amino acid profile is similar to that of fishmeal. Selected strains offer additional value through bioactives (e.g. pigments/antioxidants) or beneficial lipids, enabling the development of targeted SKUs for salmonids or starter diets. Adoption is evidence-led and staged, with inclusion increased against predefined performance benchmarks rather than on novelty alone (see sections 5.2.1.2 and 5.2.2.3).

The system-level advantages are real, but conditional. Experts value MP for its supply reliability and price stability (decoupling from soy and fishmeal volatility), as well as for its credible sustainability benefits, such as lower land and freshwater use, residue upcycling and reduced pressure on marine stocks. However, both OPEX and LCA hinge on energy — drying, especially post-extrusion pellet drying, is the dominant heat hotspot. The fastest improvements in outcomes are achieved when three layers are co-designed: a formulation that enables lower added moisture; dryer/heat-recovery architectures that are tuned to the moisture profile; and site energy strategies that secure clean, low-cost heat and power, as well as waste-heat links (see 5.2.2.6). Geography and logistics are design variables rather than fixed constraints; keeping wet, variable residues close to the conversion process while reserving distance for dry, stable outputs makes quality and delivery schedules more robust (see 5.2.2.4).

Overall, compared with plant-only or volatile marine inputs, MP can offer performance-led functionality at blend levels in food and fishmeal-adjacent formulation behaviour in feed, as well as tighter specifications and supply control — provided suppliers can provide evidence of processing, staged inclusion/performance data and energy-efficient processing that protects both cost per kilogramme and environmental impact.

5.2.5 Future developments

The outlook for microbial protein (MP) is positive but based on scenarios rather than forecasts. Teams are planning against four reinforcing arcs, each with named milestones and contingencies: scaling down and reducing costs, regulatory operations, energy strategy and expanding the platform beyond protein. Regarding scale and cost reduction, the centre of gravity is shifting from pilot schemes to larger or continuous processes with high uptime, located near stable residues and designed to avoid over-processing. Stepwise capacity increases (pilot → about 10 $kt \cdot y^{-1}$ → about 30–50 $kt \cdot y^{-1}$) are tied to transparent price per kilo milestones and backed by multi-year supply agreements — aquafeed first, premium pet food next and food later. Buyers confirm that they will increase their use of MP once time-definite deliveries and lot-to-lot stability have been proven, which will reduce costs; dissenters accept the mechanism, but request TEA updates at each stage. (See also Sections 5.2.1.3 and 5.2.2.1/ 5.2.2.2 for adoption gates and price drivers.)

Regulatory operations are treated as an execution discipline, not a black box. For food, the EU Novel Foods route is reliable, but slow to implement. Most interviewees expect clearer guidance, structured pre-submission and better panel coordination to deliver faster results than legal reform. For feed, especially with residue inputs, front-end eligibility of streams (hygiene, HACCP, traceability and contaminants) is the first gate. Pilots run on inputs that are already eligible while broader permissions catch up. Policy tailwinds (e.g. tighter rules on imports linked to deforestation) are viewed as amplifiers rather than primary demand drivers. Therefore, plans assume longer-than-nominal timelines and present evidence accordingly. (See Section 5.2.2.1 for regulatory details.)

Energy is a key factor in both OPEX and LCA. Drying, especially post-extrusion pellet drying, dominates the heat bill. Formulation physics upstream determine the evaporative duty, while dryer/heat choices and site energy sourcing translate this into kWh/kg and gCO_2e/kg. Future-ready sites combine lower-moisture formulations with low ΔT multi-stage drying and waste heat integration with clean, low-cost power and heat (e.g. PPAs). Several operators already track kWh/kg and gCO_2e/kg as board-level KPIs, and assess locations for tariff resilience in order to mitigate volatility. (See 5.2.2.6 for the energy stack.)

The platform expansion thesis widens the scope of MP from 'protein only' to include co-products and targeted fractions, such as lipids (EPA/DHA) and bioactives (pigments, enzymes and antioxidants), alongside process advances, including multi-culture, high-cell-density/continuous fermentation and nucleic-acid reduction for sensitive applications and targeted fractionation for application-ready SKUs. Commercial hygiene is shifting towards standardised as-processed test batteries and claims-ready data packs (e.g. digestibility, palatability, health markers and life cycle assessment (LCA)) that can be used across categories. (see 5.2.1.2, 5.2.2.3.)

Experts plan within bands rather than using linear forecasts. In a base case, approvals progress steadily and costs decline incrementally as capacity increases; the use of modified proteins (MP) in aquafeed and pet food grows modestly, and food production expands where Novel Foods dossiers mature. Under a policy tailwind, clearer guidance, time-bound reviews and tighter import scrutiny accelerate EU-centric demand. With an energy tailwind, access to cheap, clean heat or power, or industrial symbiosis (waste heat), materially lowers the cost per kilogramme (€/kg) and the grams of CO_2 equivalent per kilogramme (gCO_2e/kg). In a commodity shock scenario, price spikes or supply instability in fishmeal or fish oil open-up opportunities where MP is ready to be specified and delivered.

The execution agenda that follows is as follows: anchor plans in scenario bands rather than fixed 10-year numbers; publish cost and carbon milestones tied to named capacity steps; maintain a visible regulatory operations plan (pre-submission alignment, dossier templates and panel coordination); finalise the energy strategy early in the process (PPAs and waste heat); and develop evidence that is ready for claims (digestibility, palatability, simple health read-outs and LCAs) to reduce the risk of purchasing across feed, pet and food. This combination of factors transforms current momentum — industry interest, public funding and active R&D — into bankable offtakes and scalable supply, without making overly precise promises about timing.

5.2.6 Practical go-to-market implications

5.2.6.1 Food function under real conditions

A pragmatic route to market for food products begins with sensory neutrality and as-processed functionality rather than making claims. Off-notes are controlled at both the upstream (strain and substrate choice) and downstream (washing, deodorisation and fractionation) stages. The function is then demonstrated after the relevant unit operations, such as hydration, shear, and thermal histories (e.g. extrusion, cook-hold, retort/pasteurisation, or freeze-thaw), using standardised readouts (e.g. gel rheology G′/G″, emulsion stability/creaming indices, water/oil holding capacity, and flow curves). Suppliers provide application toolkits containing dosage bands, process set points and compatibility maps for pH/ionic strength, salts/calcium, hydrocolloids and co-proteins, and report specifications as processed, not just as received. Lot-to-lot stability, dry/low-dust formats, and clear storage standard operating procedures are baseline expectations. Nucleic acid management (purine limit plus reduction method) is explicit where relevant. At taste parity, MP earns a place when it clearly simplifies recipes or mitigates quality risks at a competitive cost (see 5.2.2.3).

5.2.6.2 Feed and premium pet: staged adoption

In terms of feed for aquaculture, this can be achieved if three conditions are met: a protein tier of 60–65% CP (or 65–75% for a fishmeal-tier proposition), high digestibility of 85% for protein/IAAs in real diets, and a fishmeal-adjacent amino acid profile (with lysine as the first limiting amino acid and methionine often low, closed at diet level). Intake is the operational gate: yeast MPs are often well accepted, whereas some bacterial MPs may require palatants or processing adjustments. Adoption is staged and evidence-led, typically starting at around 10–15% with predefined stop criteria for intake and FCR. The form and handling of products matter when it comes to purchasing: dry, free-flowing, low-dust powders or granules (often pelleted or lightly fat-coated) with defined particle size bands, bulk density, flow indices and a_w targets that keep performance stable at plant humidity and temperature (see 5.2.2.3).

Premium pet food acts as a pricing bridge, offering faster pathways and a higher willingness to pay than human food. Brands buy dossiers, not narratives, so look for validated digestibility, a clear indispensable amino acid profile, palatability data, and where available, simple, credible health and welfare data. Early successes in this area create references, margin and longitudinal quality data that reduce the risk of scaling up in aquafeed and, later, entering the food market.

5.2.6.3 Cross-cutting industrial choices: geography, feedstocks and energy

Geography is treated as a design variable: wet, variable residues are kept close to conversion, while dry, stable outputs are reserved for longer distances. The standard approach is to co-locate fermentation and the first stage of downstream processing near residue hubs to minimise inbound 'water miles', and where distance is unavoidable, to ship dry, stable formats with full physical specifications. Inflow is stabilised via hub-and-spoke pre-conditioning (e.g. sorting, dewatering/concentration and inhibitor-lean pretreatments), rapid intake QC and multi-year contracts with specification windows. Early resolution of 'waste vs. by-product' classification and traceability reduces regulatory friction (see sections 5.2.2.4 and 5.2.2.5).

Energy is a board-level KPI because it affects both OPEX and LCA. Drying, especially post-extrusion pellet drying, dominates the heat load. The fastest improvements come from a stacked approach:

(1) formulation to minimise added water (ingredient selection/process aids);
(2) dryers and heat-recovery architectures matched to the moisture profile; and
(3) a site energy strategy incorporating PPAs, on-site renewables and industrial symbiosis/waste heat. This is tracked using kWh/kg and gCO_2e/kg (see 5.2.2.6).

5.2.6.4 Evidence and cadence: what makes a supply chain credible?

Credibility is earned through longitudinal datasets across pilot, demo and commercial stages. Buyers and regulators look for trend charts showing specification stability, digestibility/palatability, and performance at scale, as well as full contaminant panels, microbiology, SPC on critical process/material parameters, and Cp/Cpk across campaigns. They also look for lot release based on trend analytics rather than single-batch snapshots. For feed routes, the eligibility of residual inputs (in terms of hygiene, HACCP, traceability and contaminants) precedes the ingredient dossier. For food, teams implement a transparent regulatory operations plan involving pre-submission alignment, template-driven dossiers and coordinated endpoints to compress timelines (see sections 5.2.2.3 and 5.2.2.5).

Commercial rhythm is laddered — feed → premium pet → food — tied to capacity ramps and transparent price per kilo milestones. There are also claims-ready packages (performance + LCA) that plug into buyers' least-cost × nutrition × footprint models. The sales focus is on areas where the MP's functional advantage can be monetised (early life stages, premium pet food and specific food formats), while operations drive cost reduction and specification stability to unlock the next volume tier.

5.2.7 Estimates of market opportunities for MP– key messages

Key takeaways:

- MP will first gain traction in the aquafeed market, followed by premium pet food as a pricing bridge, and then starter feeds (for poultry and piglets) as profitable niches. Human food will follow once taste, processing functionality and cost-in-use converge. MP wins as a complementary, specification-led protein source, rather than as a 1:1 commodity swap.

Demand logic: price per kilo → €/function/cost-in-use.

- Feed: buyers optimise cost-in-use versus fishmeal/soya, taking into account amino acid top-ups and palatants. Small premiums are only achieved with measured performance (intake, feed conversion ratio, survival) or lower risk (stable specifications/supply).
- In the food sector, 'microbial' has no intrinsic premium; adoption hinges on clean flavour/colour and as-processed technological functionality that simplifies recipes/enables cleaner labels at a competitive cost.

Entry criteria (non-negotiables):

- Nutrition & biology: CP ≥ about 60–65% (≈65–75% for the fishmeal tier), digestibility ≥85% (protein/IAAs), and a complementable amino acid profile (lysine is often the first limiting amino acid, and methionine is often low).
- Palatability: intake is the deciding factor (some yeast MPs are often strong, while some bacterial MPs require palatants/processing).
- Plant fit: dry, free-flowing and low-dust (particle size bands, bulk density and aw <0.7), and pellet durability/low fines.
- Safety & Dossiers: HACCP/GMP; lot-level certificates of analysis for contaminants and microbiology; nucleic acid management where relevant. For food, as-processed specifications are required (post-hydration, shear and thermal).

Economics and scaling

- Market potential increases when moving from the pilot stage to a production capacity of about 10 $kt \cdot y^{-1}$ to 30–50 $kt \cdot y^{-1}$ with high uptime.
- The price varies according to the cleanliness of the feedstocks, the solvent-lean downstream processing and the energy strategy — drying (especially post-extrusion pellet drying) dominates the heat duty.
- Sites that combine lower-moisture formulations, low-SEC dryers and low-carbon heat and power (including waste-heat integration) will reach parity faster and unlock volume.

Regulatory sequencing (order of events):

- Feed residue routes: feedstock eligibility (hygiene, HACCP, traceability and contaminant panels) must be established before the ingredient dossier can be prepared.
- For food, there are disciplined novel foods operations (pre-submission alignment, template dossiers and time-bound studies).
- Many experts stage launches in faster jurisdictions while EU filings mature in order to build longitudinal evidence and offtakes.

Feedstock and siting (design variables, not fate).

- The strongest predictor of feasibility and price is access to affordable, specification-stable side streams.
- Fermentation and first-stage downstream processing should be co-located near residue hubs, with hub-and-spoke pre-conditioning used to minimise wet miles.
- The legal classification (by-product vs waste) for food routes must be settled up front.

Competitive positioning by segment:

- For aquafeed, the position is fishmeal-adjacent at modest inclusion once the three gates (CP, digestibility and amino acids profile) are met.

- Premium pet food: higher WtP for claims-ready dossiers (e.g. digestibility, palatability and simple health markers).
- Food: MP enters as a functional toolkit (gelation/texture, clean emulsification and controlled viscosity) with as-processed data for the target unit operations.

Evidence package (speed lever):

- Buyers and authorities want longitudinal proof of the pilot, demo and commercial stages: lot-to-lot spec stability, species/life-stage digestibility and palatability/performance, full contaminant panels and plant-fit data (flowability, moisture/aw and particle size).
- Application toolkits (dosage bands, set points and compatibility maps) reduce trial cycles and accelerate offtakes.

Scenario levers (not substitutes for scale, but upside)

- Policy tailwinds (clearer feed/food guidance and deforestation-linked import scrutiny), energy advantages (cheap and clean heat and power, and industrial symbiosis) and commodity shocks (fishmeal and soy volatility) can accelerate market share where MP is ready to meet specifications and can be delivered.

Bottom line:

- The near-term potential lies in areas where spec-led functionality and cost-in-use are competitive: aquafeed first, premium pet food next and food later. The key is coherent execution across regulatory sequencing, feedstock and siting, and energy-centred process design, backed by evidence that can be used to support claims.

Table 19: *Market readiness matrix for microbial-protein applications (Own compilation by Ecozept).*

Application / Offer	TRL	MRL*	Readiness	Primary gates (SSbD tags)
Aquafeed protein concentrates (≥60–65 % CP)	7–8	6–7	[illegible]	Digestibility ≥≈85 %, fishmeal-adjacent amino acids, palatability, low-dust plant fit *(S, Circ, Sust)*
Premium pet nutrition (low-incl. functional)	6–7	6–7	[illegible]	Digestibility & palatability data; simple health markers; traceability *(S, SocEcon, Sust)*
Starter feeds (poultry/piglets)	6–7	5–6	[illegible]	Inclusion caps (nucleic acids where relevant); gut-integrity markers; species-specific data *(S)*
Hatchery micro-pellets / microdiets	7–8	6–7	[illegible]	Fine, homogeneous particle size distribution; pellet durability/low fines; intake stability *(S, Circ)*
Human food (function toolkit)	5–6	3–4	[illegible]	**As-processed** functionality; clean flavour/colour; Novel Foods dossier *(S, SocEcon)*
Bioactives/pigments co-products (add-ins)	6–7	5–6	[illegible]	Efficacy evidence (colour/health markers); safety & specifications *(S, Sust)*

6 Results of market assessment in China

The market assessment of scalable side streams in China was described in detail in D1.2, chapter 6. Therefore, this report only contains a summary of the key results. More detailed information can be found in D1.2.

6.1 Qualitative Assessment of Scalable Side-Stream Opportunities in China's Agri-Food System

China's agri-food economy combines geographically dispersed primary production with highly clustered processing hubs, and it is within these hubs that practical, scalable side-stream opportunities materialize. When the unit of analysis shifts from where crops are grown to where they are processed, the spatial logic of residues becomes legible: breweries in major urban and peri-urban centres generate daily flows of brewer's spent grains (BSG); baijiu distilleries concentrated in Sichuan, Jiangsu and Anhui discharge protein- and fiber-rich wet grains; apple processors in Shaanxi and Shanxi and citrus processors in Guangdong, Fujian and Guangxi produce pomace and peels suitable for pectin, polyphenols and essential oils; potato processors along the north-west corridor release peels and starch fines; and the North China Plain together with the Northeast remain dense sources of straw and cobs. This processing-first map aligns with how logistics, contracts and quality control operate on the ground, clarifying not only where residues arise but also which of them can be aggregated at sufficient scale and cadence to support investment.

6.2 Method and Framing

This study takes a qualitative yet systematic approach. The analysis focuses on industrial side streams rather than primary field residues because the former are more concentrated, homogeneous and contractable. Rather than crop acreage, it maps processing capacity and location, recognising that fresh-market flows and interprovincial trade often decouple cultivation from processing. Where direct residue data is incomplete, volumes are inferred from processed-product outputs and verified through industry interviews and independent totals. This emphasis on processing nodes — plants, cooperatives, and large distilleries — yields a picture of actionable feedstock 'hotspots' that aligns with logistics constraints, plant hygiene regimes, and the specification mindset of prospective business-to-business buyers.

6.3 Residue Hotspots and Their Value Logic

Breweries form the first and most dependable cluster. BSG is the largest, most regular solid flow in the system, produced on an almost daily cadence close to major consumption centers. Compositionally, BSG offers proteins and arabinoxylan-rich hemicellulose with residual starch, supporting ingredient and biomaterial routes after modest pretreatment, and providing a viable fermentation substrate once recalcitrance is addressed. The constraints are overwhelmingly logistical—short wet-haul radius, rapid spoilage, and plant-specific variability in moisture and particle size—so solutions that co-locate pressing and low-temperature drying, or that move wet material very short distances into feed or fermentation, dominate early feasibility.

Baijiu distilleries constitute a second, distinct hotspot. Wet distillers' grains are nutrient-rich but heterogeneous and even wetter than BSG. They fit naturally with anaerobic digestion and fertilizer integration, which many facilities already operate or can accommodate. Where hygiene and mycotoxin control can be demonstrated, selective drying and fractionation unlock feed ingredients with defined specifications. The practical model here is to anchor value in energy and fertilizer while carving out consistent fractions for higher-value outlets, thereby keeping cash flow stable while the higher-margin layers are qualified.

Fruit processors offer campaign-based opportunities with rich chemistry. Apple pomace supports pectin and polyphenol extraction before solids are routed to energy or animal nutrition; citrus peels combine essential oils, flavonoids and pectin and require swift stabilization. Because processors often bear removal costs during campaigns, on-site extractive modules aligned to plant hygiene protocols and shift patterns are attractive. The business case depends on cascading designs that take premium fractions first—under mild conditions that preserve food or cosmetic grade—and then monetize remaining sugars, fibers and process water via fermentation or digestion.

Potato processors in the north-west corridor generate peels and starch-rich fines that blend extractives with energy routes. Phenolics and starch recovery can be implemented on the front end, with biogas or combined heat and power providing the back-end anchor. Many facilities already offtake to biogas or sell wet peels locally; adding compact extractive steps that do not disrupt line cadence upgrades margins with minimal logistics risk. Where drying is required, waste-heat integration and hygienic belt or fluidized-bed dryers are decisive for both cost and specification.

Finally, straw and cobs remain massive in volume across the North China Plain and the Northeast but are diffuse and seasonal. The near-term logic favours quality field return to improve soil organic matter and yield stability, complemented by hub-and-spoke anaerobic digestion where collection economics clear. Material and energy routes are feasible where densification hubs exist, yet they are capital- and logistics-intensive and must compete with agronomic priorities.

6.4 Determinants of Feasibility

Four themes recur across provinces and sectors. First, scale with cadence is critical. Streams that flow daily or weekly—such as BSG and, in some cases, distillers' grains—accelerate bankability because they support continuous operations and lean inventories. Campaign streams can be sizable, but they require campaign-ready equipment, storage and labor plans, and return on capital depends on tightly run production windows.

Second, composition underwrites value. BSG's arabinoxylans and proteins support food and materials plays and can feed fermentation after pretreatment. Citrus and apple residues naturally prioritize essential oils, pectin and other polyphenols before energy or feed. Potato peels and fines couple phenolic extracts with starch and then energy. Baijiu grains can enter feed markets where mycotoxin controls and microbiology are proven, while anaerobic digestion remains a dependable base case.

Third, costs are local and dominated by logistics. Short-haul collection, handling at the plant gate, and simple unit operations—pressing, drying, ensiling—determine viability more than nameplate yields. Climate and urban conditions matter: monsoon humidity challenges drying economics; urban traffic and loading windows constrain truck cycles; and water, steam and power availability shape whether extraction or drying is cost-effective.

Fourth, policy is a material tailwind, albeit uneven in execution. National and provincial agendas prioritize straw utilization, manure resource use, rural pollution control and circular economy pilots. These programs translate, in some localities, into advantageous land-use permissions, tariff structures for on-site energy, or grants for modular equipment. However, implementation varies by prefecture, making early engagement with environmental and agricultural bureaus, along with pragmatic compliance—HACCP/GMP where feed-oriented, contaminant screens, and traceability—a determinant of time-to-revenue.

6.5 Prioritization and Sequencing

At the intersection of volume, regularity, composition and centralization, a practical sequence emerges. Breweries are the first move: BSG offers the largest and most regular pan-urban opportunity with multiple demand outlets and short learning cycles from pilot to offtake. Fruit processing follows : apple and citrus residues are compositionally rich and well suited to co-located extraction with energy or feedback-ends during campaigns. Baijiu grains are attractive where anaerobic digestion already exists or can be installed, with selective drying or fractionation unlocking feed customers once quality assurance is demonstrated. Potato peels and fines add a complementary corridor play, leveraging waste heat and hygienic drying to produce specification-grade ingredients while keeping biogas as the fallback. Straw and cobs function best as regional soil and energy programs, driven by agronomic and municipal objectives and pursued where collection densities and densification hubs justify the investment.

Two caveats frame this prioritization. Many streams have incumbent uses—feed, biogas, compost—which cap near-term margins but stabilize offtake and de-risk early cash flows. And while some provincial residue estimates rely on proxies due to data gaps, triangulation with independent totals and operator interviews suggests the sizing is directionally robust; nevertheless, local confirmation is necessary before committing capital.

6.6 From Hotspots to Projects

Translating hotspots into investable projects rests on co-location, cascading design and specification-led sales. For wet streams, co-locating compact modules for pressing, decanting and low-temperature drying reduces spoilage and haul costs while aligning operations with plant hygiene and utilities. For fruit campaigns, compact extraction skids for essential oils and pectin that run in sync with juice presses allow high-value fractions to be captured without disrupting host operations, with exhausted solids routed to energy or animal nutrition. In all cases, buyers in feed, ingredients and materials markets purchase on specification, not on narrative. Clear specification tiers—moisture, protein, ash, particle size, oil content—plus processability evidence through conditioning, extrusion and drying, microbiology, and contaminant panels shorten qualification cycles. Trial packages that link inclusion rates to functional outcomes (intake, FCR, growth, palatability, health markers) turn samples into adoption.

A staged rollout reduces execution risk. Discovery work secures gate access, samples and term sheets with breweries and fruit processors in each target region. Co-located pilots then run through full shifts and weekend campaigns to capture variability and generate specification-conformant samples for customers. First commercial "cells" scale those modules at one brewery and one fruit plant, with offtake contracts incorporating price adjustment mechanisms for moisture and inclusion rates. Replication extends standardized cells to additional hubs, adding anaerobic digestion or waste-heat recovery where justified by load factors and utility tariffs. Across this sequence, key indicators include capture rate at gate, time to stabilization, specification conformance, yields of target extractives, module effectiveness, logistics cost per wet tonne handled, buyer acceptance rates and avoided disposal or displaced energy costs.

6.7 Risk and Mitigation

Supply variability is mitigated by multi-plant portfolios and contracts that specify minimum hours or weekly tonnage, rather than annual volumes. Microbiological and contaminant risk is managed through HACCP-style controls, hold-and-release protocols, validated kill-steps and the maintenance of alternate outlets—anaerobic digestion or compost—for off-spec material. Community and permitting risks are addressed by aligning projects with rural pollution control and circular economy programs, quantifying odor and noise mitigations, and engaging bureaus early to secure predictable timelines. Market adoption risk is reduced by selling on specification with credible trials and by using feed and energy offtakes to absorb initial volumes while higher-value customers complete qualification.

6.8 Summary

The analysis implies a pragmatic commercialization pathway for side-stream valorisation in China. By prioritizing processing hubs, co-locating equipment, and stacking value in cascading designs, projects can start with reliable, policy-aligned outlets—feed and energy—and rapidly layer extractives or materials where chemistry supports a premium. Breweries and fruit processors provide near-term wins with short learning cycles and visible environmental benefits; baijiu and potato processors extend the portfolio with digestion-anchored stacks and specification-grade ingredients; straw and cobs remain regional soil and energy programs that deliver agronomic and climate value where collection economics are favorable. Throughout, the discipline of processing-not-production mapping and a specification-first posture with buyers convert environmental intent into commercially credible execution.

In sum, China’s clustered processing hubs generate large, reliable and compositionally attractive side streams whose centralization aligns with biorefinery and fermentation value chains. Success is most likely where cascading designs, short logistics and specification-driven B2B sales meet early policy engagement and practical compliance. This combination balances environmental benefits with bankable operations and provides a clear, sequenced route from hotspot identification to portfolio-level impact.

7 Bibliography

Beiderbeck, D., Frevel, N., von der Gracht, H.A., Schmidt, S.L., Schweitzer, V.M., 2021. Preparing, conducting, and analyzing Delphi surveys: Cross-disciplinary practices, new directions, and advancements. MethodsX 8, 101401. https://doi.org/10.1016/j.mex.2021.101401

Belton, V., Stewart, T.J., 2002. Multiple Criteria Decision Analysis. Springer US, Boston, MA. https://doi.org/10.1007/978-1-4615-1495-4

Bisquert, P., Hecham, A., Buche, P., Koptelov, M., 2025. Justified Preference Aggregation in Agri-Food Systems: An Approach, Argumentation Methods, and Tools. Int. J. Agric. Environ. Inf. Syst. IJAEIS 16, 1–26. https://doi.org/10.4018/IJAEIS.393045

Brady, S.R., 2015. Utilizing and Adapting the Delphi Method for Use in Qualitative Research. Int. J. Qual. Methods 14, 1609406915621381. https://doi.org/10.1177/1609406915621381

Bui, T.-D., Tsai, F.M., Tseng, M.-L., Tan, R.R., Yu, K.D.S., Lim, M.K., 2021. Sustainable supply chain management towards disruption and organizational ambidexterity: A data driven analysis. Sustain. Prod. Consum. 26, 373–410. https://doi.org/10.1016/j.spc.2020.09.017

Cohen, J., 1960. A coefficient of agreement for nominal scales. Educ. Psychol. Meas. 20, 37–46. https://doi.org/10.1177/001316446002000104

Conchin, S., Carey, S., 2018. The expert's guide to mealtime interventions - A Delphi method survey. Clin. Nutr. Edinb. Scotl. 37, 1992–2000. https://doi.org/10.1016/j.clnu.2017.09.005

Denzin, N.K., 2017. The Research Act: A Theoretical Introduction to Sociological Methods. Routledge, New York. https://doi.org/10.4324/9781315134543

Fitch, K., Bernstein, S.J., Aguilar, M.D., Burnand, B., LaCalle, J.R., Lazaro, P., van het Loo, M., McDonnell, J., Vader, J., Kahan, J.P., 2001. The RAND/UCLA Appropriateness Method User's Manual.

Frewer, L.J., Bergmann, K., Brennan, M., Lion, R., Meertens, R., Rowe, G., Siegrist, M., Vereijken, C., 2011. Consumer response to novel agri-food technologies: Implications for predicting consumer acceptance of emerging food technologies. Trends Food Sci. Technol. 22, 442–456. https://doi.org/10.1016/j.tifs.2011.05.005

Haber, C., Schärli, A., 2021. Defining Spotting in Dance: A Delphi Method Study Evaluating Expert Opinions. Front. Psychol. 12. https://doi.org/10.3389/fpsyg.2021.540396

Habibi, A., Sarafrazi, A., Izadyar, S., 2014. Delphi Technique Theoretical Framework in Qualitative. Int J Eng Sci 3, 8–13.

Hsu, C.-C., Sandford, B.A., n.d. The Delphi Technique: Making Sense of Consensus. https://doi.org/10.7275/PDZ9-TH90

Huguet Cabot, P.-L., Navigli, R., 2021. REBEL: Relation Extraction By End-to-end Language generation, in: Moens, M.-F., Huang, X., Specia, L., Yih, S.W. (Eds.), Findings of the Association for Computational Linguistics: EMNLP 2021. Presented at the Findings 2021, Association for Computational Linguistics, Punta Cana, Dominican Republic, pp. 2370–2381. https://doi.org/10.18653/v1/2021.findings-emnlp.204

Jaiswal, S., 2021. Natural Language Processing - Dependency Parsing. Data Sci. URL https://towardsdatascience.com/natural-language-processing-dependency-parsing-cf094bbbe3f7/ (accessed 10.22.25).

Keeney, R.L., Raiffa, H., 1993. Decisions with Multiple Objectives: Preferences and Value Trade-Offs. Cambridge University Press, Cambridge. https://doi.org/10.1017/CBO9781139174084

Koptelov, M., Linck, J., Bisquert, P., Buche, P., Roche, M., 2025. AgriCode: Automated coding for qualitative research and its application to the valorization of agricultural residues. SoftwareX 31, 102258.

Lewin, S., Booth, A., Glenton, C., Munthe-Kaas, H., Rashidian, A., Wainwright, M., Bohren, M.A., Tunçalp, Ö., Colvin, C.J., Garside, R., Carlsen, B., Langlois, E.V., Noyes, J., 2018. Applying GRADE-CERQual to qualitative evidence synthesis findings: introduction to the series. Implement. Sci. 13, 2. https://doi.org/10.1186/s13012-017-0688-3

Lilja, K.K., Laakso, K., Palomäki, J., 2011. Using the Delphi Method.

Linstone, H.A., Turoff, M. (Eds.), 1975. The Delphi method: techniques and applications. Reading, Mass. : Addison-Wesley Pub. Co., Advanced Book Program.

Miles, M.B., Huberman, A.M., Saldana, J., 2014. Qualitative data analysis: a methods sourcebook, Third edition. ed. SAGE Publications, Inc., Thousand Oaks, Califorinia.

Okoli, C., Pawlowski, S.D., 2004. The Delphi method as a research tool: an example, design considerations and applications. Inf. Manage. 42, 15–29. https://doi.org/10.1016/j.im.2003.11.002

Padel, S., Midmore, P., 2005. The development of the European market for organic products: insights from a Delphi study. Br. Food J. 107, 626–646. https://doi.org/10.1108/00070700510611011

Sablatzky, T., 2022. The Delphi Method. Hypothesis Res. J. Health Inf. Prof. 34. https://doi.org/10.18060/26224

Young, H.P., 1974. An axiomatization of Borda's rule. J. Econ. Theory 9, 43–52. https://doi.org/10.1016/0022-0531(74)90073-8

8 Data Management Plan follow-up

N°	Dataset name	Open Data	Closed Data	Means of dissemination	Maximum delay before access	Data set access
1	WP1.1_ECOZEPT_BS	Results of interviews conducted with different types of stakeholders (data of experts' assessment will be collected) in Workpackage 1 Task 1.1	NA pseudonymized data set containing sensitive personal data (GDPR)	Scientific and popularized publications, conferences, various dissemination and capacity-building events	Once published and at the latest 2 years after the end of the project	Ecozept intern data
2	WP1.1_INRAE_PB	Collection of interviews containing expert knowledge on agricultural waste valorization, annotated using the Delphi I method and associated with pseudonymized stakeholders	NA pseudonymized data set containing sensitive personal data (GDPR)	Scientific and popularized publications, conferences, various dissemination and capacity-building events	Once published and at the latest 2 years after the end of the project	https://doi.org/10.57745/91BXIY
3	WP1.1_INRAE_PB2	Collection of annotated expert interview excerpts on agricultural residue valorization, containing named entities representing key criteria to support qualitative analysis	NA pseudonymized data set containing sensitive personal data (GDPR)	Scientific and popularized publications, conferences, various dissemination and capacity-building events	Once published and at the latest 2 years after the end of the project	https://doi.org/10.57745/E6ZAG1

***TABLE 20:** Summary of the main information regarding the data produced for this deliverable.*

This table above sums up the main information regarding the data produced for this deliverable, where is it stored and are the specific rules to respect concerning access, publication and FAIR principles.

N°	Dataset name	Owner	Name of the current contact	IPR issues	Use of third-party	Restrictions on data sharing (Y/N)
1	WP1.1_ECOZEPT_BS	Ecozept	Jan Linck	Require data transfer contract with chinese partners for closed data	no	Yes, compliance with GDPR (see closed data)
2	WP1.1_INRAE_PB	INRAE	Pierre Bisquert	Require co-responsible contract for personal data treatment to be signed between INRAE and ECOZEPT	no	Yes, compliance with GDPR (see closed data)
3	WP1.1_INRAE_PB2	INRAE	Pierre Bisquert	Require co-responsible contract for personal data treatment to be signed between INRAE and ECOZEPT	no	Yes, compliance with GDPR (see closed data)

TABLE 21: Summary of main information regarding potential Intellectual property protection or GDPR issues.

This table above sums up the main information regarding potential Intellectual property protection or GDPR issues.

Annex I. Guidelines for the first round of AgriLoop stakeholder interviews according to the Delphi method

Research questions:

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

Table 1: Examined feedstock (in line with examined residue streams of DSS+):

Apple
Tomato
Grape
Potatoes
brewer's spent grains

Table 2: 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 3: 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
Potential users of PHA applications	Arable farmers/ horticulture businesses; applied practical research (national research centers, e.g. Landesanstalten in Germany)	PHA applications (Table 2)

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

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.

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)

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
    - 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)

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)
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)

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
    - 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)

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)

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)

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

Annex II. Guidelines for the second round of AgriLoop stakeholder interviews according to the Delphi method

Research questions:

4. What are the general market opportunities for xyz?
5. What are stakeholders' expectations regarding the valorisation/the function of xyz?
6. What are the actual and potential limits/barriers for xyz?

Table 1: Examined feedstock (in line with examined residue streams of DSS+):

Apple
Tomato
Grape
Potatoes
Brewer's grains

Table 2: Examined end-products

Raw material	**Sub-category**
PHA	mulch films
	pots
	twines (=Bindegarne)
	growth protectors (=Wuchshüllen)
	greenhouses
	nets
	grow/seedling bags
Microbial proteins (for animal feed)	
Extracted proteins (for animal feed)	
Bioproteins for food	

Table3: 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 1)
	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 2)
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
Potential users of microbial and extracted proteins for food	Food industry, producers of protein food	Microbial and/ or extracted proteins
Potential users of PHA applications	Arable farmers/ horticulture businesses; applied practical research (national research centers, e.g. Landesanstalten in Germany)	PHA applications (Table 2)

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

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)
In our Horizon 2020 project "AgriLoop" (https://www.agriloop-project.eu/) powerful partners such as NOVA Institute, Wageningen Research and University of Gent work on developing processes to convert agri-residues into extracted and microbial proteins as well as bio-based and biodegradable materials. We are now identifying market opportunities including limitations and try to identify expectations of stakeholders within the value chain.

Thank you very much for 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/FCAC 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.
Inform: Some of the data you provide will be published anonymously

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

Block "Introduction and ice breaker":

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

Block "current structures"

1. How do you currently valorise your agricultural by-products/residues of apple-/tomato-/grape-/potato processing/brewer's grains (see Table 1)? (Q6) (additional question)

2. What is the financial compensation you receive for providing your agricultural by-products for valorisation? Additionally, who handles and finances the transportation of these by-products? (***important**: **ask exactly for which unit the price applies, e.g., per ton wet material, per ton dry material, per cubic meter**, etc.)*? (Q29)

3. How integral are agricultural by-products to your current value chains? What would be the impact if these by-products were redirected to alternative valorisation pathways (economically, environmentally, eg.)?

4. A. In the previous round of expert interviews, we were told that satisfaction with the current valorisation of agricultural residues is largely low due to low profitability. Do you agree with this?

   B. Would the valorisation of your agricultural by-product apple-/tomato-/grape-/potato processing/brewer's grains in alternative pathways like PHA production to to mulch films or horticultural pots or extracted / microbial protein be a preferable alternative for you and lead to more satisfaction? If yes, under what conditions?

5. Which other (new, alternative) pathways have you heard of? (Q8) (not only the residues we focus on)

Block "strengths and challenges"

1. In the previous round of interviews, the experts often spoke of positive effects through valorisation. (environmental benefits, cost savings associated from reduced by-product management)
   Do you confirm this and in which domains?

   Would the valorisation of residues to PHA or protein for feed and food bring more benefits than the current standards?

2. In the previous round of interviews, the experts identified the following as the main challenges for the valorisation of agricultural by products:
   1. Transportation & Logistics
   2. Processing difficulties
   3. Limited seasonal availability of feedstock
   4. Legislation

   Do you agree with that?
   Could you elaborate on each one based on your experience?

3. How could challenges in transportation & logistics, processing, seasonal availability of feedstock and legislation be overcome? (Q36) Please address one challenge at a time.

Block "expectations"

1. What would an ideal valorisation solution for **your** by-products of apple-/tomato-/grape-/potato processing /brewer's grains look like (see Table 1)? Could you explain, why? (Q8.2)
   *(**Internal remark: give examples like conversion in plant proteins, produce mulch-films for application on own farm, etc.**)*

   Would you consider the valorisation of residues to PHA as an ideal valorisation process?

2. Experts stated that financial support, an adapted framework, and a functioning network are crucial for an ideal valorization process of by-products (apple-/tomato-/grape-/potato processing /brewer's grains see Table 1)? (Q8.5) E.g.

   Do you agree with this?

   Can you specify which financial support (level of supply chain, activity) you find most useful?

3. What are your expectations regarding the valorisation of by-products from apple-/tomato-/grape-/potato processing /brewer's grains in terms of effort and Output (Benefits from result)? (Q8.6)

   Do you agree that the valorisation to PHA or proteins gains more output compared to the current valorisation?

4. When thinking about residue-based PHA-applications for agriculture. Which products would meet for your practical needs the best? (mulch films, twines, clips, pots) (Q16.1) (do not ask to food processors)

5. Under which circumstances would you be willing to pay a higher price for PHA from agricultural residues than for conventional materials? (Q31) (do not ask to food processors)

Block „Outlook and perspectives"

6. Do you observe any new solutions in the area of valorisation of by-products from apple-/tomato-/grape-/potato processing /brewer's grains in your professional environment? (Q8.6)

7. In your opinion, where is the development going regarding the use of the by-products from apple-/tomato-/grape-/potato processing /brewer's grains? (Q8.7)
   For example outlet the most developed, production e.g.

•

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

Block "Introduction and ice breaker":

Before starting with the first question I want to clarify one thing: When talking about PHA end-products we are speaking about mulch films, horticultural pots, twines, growth protectors, greenhouses, nets, grow/seedling. I will not mention all of them below. However, if you have specific information on any of these products for the relevant questions, please feel free to provide it.

16. To begin with, please briefly describe your company and your position within the company.
17. 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

18. In previous interviews, experts assessed significant market potential for PHA end-products like mulch films, horticultural pots, twines, growth protectors, greenhouses, nets, grow/seedling compared to conventional materials?
    Do you agree with their assessment? (Q9) Why or why not?

19. Regarding the market potential of mulch films, horticultural pots, twines, growth protectors, greenhouses, nets, grow/seedling bags of PHA, experts identified biodegradability, price, legislation and logistics as determining factors. Do you agree with all of those factors? (Q10), e.g.:

    If yes, what is the most determining factor? And **why**?

20. Experts stated that mulch films are the best application of PHA in agriculture, followed by PHA clips, blends, twines, and seedling bags. Do you agree with this? Why or why not? (Q13)

21. How do you perceive the competitiveness of PHA derived from agricultural by-products in the market compared to conventional products (applications from petrochemicals)? (Q11)

    6.1. Do you know any examples of specific agricultural applications where PHA products outperform conventional alternatives? (Q4)6

22. Which other applications of PHA are attractive in terms of functionality? (Q14)

23. For which agricultural applications is PHA not suitable? And **Why**? Which properties are missing? (Q15)

Block 2: Stakeholders' expectations

24. What functional requirements must PHA meet to be effectively used in various agricultural applications (e.g., mulch films, horticultural pots, twines, growth protectors, greenhouses, nets, grow/seedling bags)? Please consider: (Q27)
    a. Material Properties: What specific characteristics (e.g., strength, flexibility, thickness) are necessary across these applications?
    b. Service Life: What is the expected lifespan for these products in practical use?
    c. Usage: How should these products perform based on typical consumer use?

25. What specific features must PHA possess for practical usability in agricultural applications like mulch films, horticultural pots, twines, growth protectors, greenhouses, nets, grow/seedling bags (Table 2)? (Q27)
    a. Key features appreciated by consumers:
    b. Key features appreciated by industries:
    c. Ability to print on the material; example: Printability is key.

26. In how far is contamination of the material/end-application an issue? (Q31)
    a. Mycotoxins
    b. Microplastic
    c. Pesticides

27. In producing composite products, experts in the previous round suggested that PHA should be partially supplemented by other materials like cellulose to compost faster. Do you agree with this? Why or why not? (Q28)

28. 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? (Q30)

Block 3: Limits and barriers

29. Do you agree that scalability, price, production, durability, seasonal availability of feedstock, and regional distribution are the primary challenges for the market potential of PHA? (Q36.1)

30. How could these challenges be overcome? (Q38)

31. How do you assess the scalability of PHA production? And how would you scale up? (Q39)

32. 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? (Q40)

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":

Just one comment before we start with the first question: According to our literature review, apple, tomato, grape, potato or brewer's grains residues have a high potential in terms of volume and practical possibilities. We are therefore particularly interested in them and mention them in our questions.

17. To begin with, please briefly describe your company and your position within the company.

    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

18. To what extent 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? (Q1)

19. What additional practical advantages do you see in using bio-based and biodegradable from agri-residues mulch films, horticultural pots, twines, growth protectors, greenhouses, nets, grow/seedling bags? (We are talking about the practical use) (Q2)

20. What practical disadvantages have you encountered with bio-based and biodegradable applications? (Q3)

21. Which other bio-based and bio-degradable applications from agri-residues are attractive to you in terms of practical functionality (like, e.g., mulch films, horticultural pots, twines, growth protectors, greenhouses, nets, grow/seedling bags; see Table 2)? (Q13)

22. For which agricultural applications are bio-based and biodegradable material from agri-residues not suitable for you? And why? Which functions could not be fulfilled compared to conventional materials? (Q14)

Block 2: Stakeholders' expectations

23. What functional properties must bio-based and biodegradable mulch films, horticultural pots, twines, growth protectors, greenhouses, nets, grow/seedling bags meet for practical use in your operations? (Q23 ff) (Consider aspects such as durability, environmental resistance, additional functionality, practical considerations, user experience, and technical requirements related to appearance)
    Which one determines the usage the most? And **why**?

24. How important is the issue of contamination generated by the material? (Q30)

25. 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)

    If yes, how much (%)

Block 3: Limits and barriers

26. Do you agree that price, legislation, availability of by-products and development are the biggest barriers for the market potential of PHA-applications from agri-residues? (Q34) Why and why not?
27. How could these barriers be overcome? (Q36)

Block 4: Outlook and perspectives

28. Do you agree that new bio-based and biodegradable solutions derived form agri-residues (e.g., mulch films, plant pots, seed bands) should be low-cost and easy to use? In detail, experts mentioned mulch films, plant pots and seed bands as most suitable solutions. Can you agree with them? (Q8.6)
29. 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? (Q8.7)

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

Block "Introduction and ice breaker":

23. To begin with, please briefly describe your company and your position within the company.
24. 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

1. How do you assess the market potential for extracted/microbial proteins for feed / food? (Q26) In the first round of interviews, experts rated the market potential for extracted/microbial protein as very high. Anlimal feed has more potential than human food. Do you agree with these results? And why?

2. In which markets can these proteins be applied? (Q21)

3. To what specific functionalities or characteristics do you prioritize when evaluating extracted/microbial proteins as alternatives to conventional products? (feed and food) (Q18)

4. Which functions could extracted/ microbial proteins not fulfil compared to conventional proteins for feed / food? (Q19)

5. What functionalities or properties do you consider essential when incorporating extracted/microbial proteins into feed/food products? (Q20)

6. What do you consider to be the best practical use of extracted/ microbial proteins in terms of feed / food regarding their functionality (e.g., feed for aquaculture)? (Q22)

7. Which other applications (besides feedstuff and food) of these proteins are attractive to you in terms of practical functionality (e.g., improved growth rates, feed efficiency)? (Q23)
8. Which applications are inappropriate for the use of extracted/ microbial proteins? (Q20)

Block 2: Stakeholders' expectations

9. What quality and functional requirements must these proteins meet for practical use in your operations (e.g., amino acid profile, digestibility, palatability, contamination levels minimum quantities of certain ingredients, sensory)? (Q33)
10. How do you assess the qualities of extracted/microbial proteins compared to conventional proteins for feed / food? (Q33)
11. Which expectations regarding the qualities of agri-residues as feedstock for processing of extracted/ microbial proteins do you have? (Q342.1)

Block 3: Limits and barriers

12. How does the geographical distribution of agricultural residues (Table 1) influence the production of extracted/microbial proteins? (Q41)
13. How could this logistical challenge be overcome? (Q42)
14. In the first round of interviews, the experts identified:
    1. Price
    2. Legislation
    3. Scalability
    4. Geography & logistics
    5. Consumer acceptance and comparability

    as the main barriers for the market potential of extracted/microbial proteins. Do you argee with that? (Q47)
15. How do you assess the costs of conventional proteins compared to extracted/ microbial proteins? (Q43)
16. When looking at the factors on which the price of extracted/ microbial proteins depends on, experts in the previous round named price of the coproducts, the costs of processing, e.g. purification, the price of microbial broth and the production volume. Can you prioritise the factors? (Q43)
17. Would you be willing to pay a higher price for extracted/ microbial proteins from agricultural residues? (Q45)
18. How do you assess the future development of prices for extracted/ microbial proteins? (Q45)
19. How do you assess the legislation regarding approval of extracted/ microbial proteins as feed or food (e.g., preferential treatment of extracted/ microbial as feed, impediment of extracted/ microbial as feed, etc.)? (Q46)
20. How do you assess the scalability of extracted/ microbial proteins from agricultural residues? (Q48)
21. What does the scalability depend on? (Q49)
22. How does scalability limit today's market success of extracted/ microbial proteins? (Q50)

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

Block "Introduction and ice breaker":

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

Block 1: Market opportunities

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

Block 2: Stakeholders' expectations

27. Which expectation to extracted/ microbial proteins do you have regarding quality, e.g.:
    If not mentioned provide some examples:
    - regarding microbial risks
    - contamination
    - toxicity
    - anti-nutritional factors
    - nutritional qualities
    - amino acid profile
    - digestibility
    - feed conversion ratio
    - minimum quantities of certain ingredients, etc. (Q31)

And why?

28. How do you assess these qualities compared to conventional proteins? (Q32)
29. 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

30. 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)
31. How do you assess the costs of conventional proteins compared to extracted/ microbial proteins? (Q41)

32. When looking at the factors on which the price of extracted/ microbial proteins depends on, experts in the previous round named price of the coproducts, the costs of processing, e.g. purification, the price of microbial broth and the production volume. Can you prioritise the factors? (Q43)

33. How do you assess the future development of prices for extracted/ microbial proteins? (Q43)

34. 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)

Block 4: „Outlook and perspectives"

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

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.

37. 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?

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

39. 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

Annex III: Guidelines for the third round of AgriLoop stakeholder interviews according to the Delphi method

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

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+/FCAC 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.

Questionnaire 1 for traders and manufacturers of the end-product PHA

Block "Introduction and ice breaker":

1. To begin with, please briefly describe your organisation and your position within the company.
2. 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 can we have a framed process to produce PHA from by-product? What specifications does the starting product has to be?

4. We identified mulch films and horticultural pots as key markets for PHA applications? Do you agree and why?

Yes – no - why?

Block 2: Stakeholders' expectations

5. How can we ensure that PHA meets the required standards for reliability and thermomechanical properties for use in mulch films and other agricultural and horticultural applications?

Which plastics/additives need to be formulated with it? This relates to product requirements and specifications.

6. What are the key characteristic for leaving PHA in soil?

7. In producing composite products, experts in the previous round suggested that PHA should be partially supplemented by other materials. What do you think of the mixture idea? Depending on YOUR key application, what additional material and rate could be interesting to mix with PHA?

8. How can we ensure that there is a proper biodegradation? With no harmful components issue of the degradation? (Especially in case of mixtures)

9. In how far is contamination of the material/end-application an issue? (Q31)
   a. Mycotoxins
   b. Microplastic
   c. Pesticides

Block 3: Limits and barriers

10. Below are the issues that are considered to be the biggest barriers to the market potential of PHA and PHA end-products.

Please rank them according to your assessment. (Only numbers can be entered, you can rank as many relevant for your case, but please select at least one). Please also give a justification for your ranking (share the screen with the table).

N	Criterium	Rank (1-6) 1 = very important barrier 6 =least important barrier	Justification
1	Scalability of PHA		
2	Price		
3	Production		
4	Durability		
5	Availability of feedstock and regional distribution		
6	Transportation and logistics		

11. The challenges just mentioned above are some of the main challenges for the market potential of PHA. How would you overcome them? (In a market with barrier as high price and rapid degradation, especially for multi-year crops?)

12. Looking at the PHA production process: What is the different waste and by products created in the process? *In how extent it can expose environment or workers to hazard? Is there a way to reuse it? To change for a safer and sustainable one?*

13. Within the previous round of interviews, experts had different opinions on the production of PHA as a limitation to the market potential.
Some experts believe that production isn't a problem because the technology already exists—it just hasn't been used in Europe yet. Others argue the technology is still too new, so the product made with it might not be consistent.
Do you to agree or disagree? In either case, please explain why. For example, if you disagree, please provide a counterargument.

14. Within the previous round of interviews, experts had different opinions on the legislation as a limitation to the market potential of PHA.
Some experts say that legislation is the biggest barrier—other than price—because they can either stimulate or hinder the market uptake. Others think that legislation is not that important right now since the market is still developing and needs time to grow.
Do you to agree or disagree? In either case, please explain why. For example, if you disagree, please provide a counterargument.

15. How to improve regulation on biobased products? How can we frame legal improvement and subsidies for bioplastics? Depending on application? Should Legislation take into account, that PHA is not a conventional plastic?

16. How can we make PHA price competitive? Economies of scale or subsidies? Or both?

17. How can a consistent supply of raw material/feedstock be ensured while competing with other uses such as biogas production?

18. Does the lack of understanding the actual functionalities and qualities of PHA of by end-users is a key barrier to market? How can it be overcome ?

Questionnaire 2 for feed traders and processors of the end-product extracted and microbial proteins & food producers

Block "Introduction and ice breaker":

1. To begin with, please briefly describe your company and your position within the company.
2. What type of feed/food does your company work on?

Block 1: Market opportunities

3. Given the qualities and profile of the AgriLoop microbe proteins, do you think they could be of interest for aquaculture and/or poultry feed?
4. In your opinion, are there other applications for AgriLoop microbe proteins that could be of interest?
5. Microbial proteins are more expensive compared to current alternatives, what arguments do you see to justify the higher price?
6. What advantages do you see of using microbial proteins as an alternative to current protein sources? (nutritional value, environmental effects, economics)?
7. Does microbial protein need to be combined with additional material to be efficient and acceptable in your value chain (feed and food)? Which additives would you combine with AgriLoop microbe proteins in order to render the more efficient and better acceptable?
8. Which applications are inappropriate for the use of extracted/ microbial proteins? (Q20)

Block 2: Stakeholders' expectations

9. What functionalities or properties do you consider as essential when incorporating extracted/microbial proteins into aquaculture and/or poultry feed? (Q20) Please rank them regarding the importance (share the screen with the table).

Criterium	**Rank (1-6)** **1 = very important functionality** **6 =least important functionality**	**Justification**
Amino acid profile		
nutritional value		
palatability		
digestibility		
other		

10. The microbial produced in AgriLoop contains Histidine, Isoleucine, Leucine, Phenylalanine, Threonine, Valine, Glutamine, Glycine, Proline, Cysteine and Tyrosine. It is high in Leucine, Cysteine and Glutamine.

Which amino acids are needed to be introduced in aquaculture / poultry feed.

11. What are the critical quality and functional requirements (e.g. amino acid profile, digestibility, sensory properties) for the safe and sustainable use of microbial proteins for aquaculture / poultry feed How do you achieve a balance between palatability, nutritional value and digestibility?

12. How do you assess the qualities of extracted/microbial proteins compared to conventional proteins for aquaculture / poultry feed? (Q33)

Where do they have similar, superior or inferior qualities?

13.What processes are interesting for obtaining homogeneous microbial proteins from agricultural residues?

14. How do you ensure a stable raw material?

And a safe and stable product based on it? How does the process stabilise it? How can we adapt it?

Block 3: Limits and barriers

15. In the second round of interviews, the experts identified: Price, Legislation, Scalability, Geography & logistics, Consumer acceptance and comparability as the main barriers for the market potential of extracted/microbial proteins. (share the screen with the table).

N	**Criterium**	**Rank (1-6)** **1 = very important barrier** **6 =least important barrier**	**Justification**
1	Price		
2	Legislation		
3	Scalability		
4	Geography		
5	Logistics		
6	Consumer acceptance and comparability		

Please rank them according to your assessment. (Only numbers can be entered, you can rank as many relevant for your case, but please select at least one). Please also give a justification for your ranking.

16. How are microbial proteins considered in legislation today?

17. How do you assess the current legislation and approval process for extracted/ microbial proteins as feed (e.g., preferential treatment of extracted/ microbial as feed, impediment of extracted/ microbial as feed, etc.)? (Q46)

18. What are the limits of the current legislation for developing MP?

Why is the deforestation legislation is a potential opportunity for MP? What does legislation on deforestation bill imply?

19. When looking at the factors on which the prices of extracted/ microbial proteins depend, experts in the previous round named: price of the coproducts, the costs of processing, e.g. purification, the price of microbial broth and the production volume. (share the screen with the table). Is one of these factors more important than the others and if so, why?. (Q43)

20. Ask just for producer of MP:

What are the main hotspots for energy consumption in the process? How can energy consumption be reduced, and by which processes?

21. *Ask just for producer of MP*

What are the costs of the process compared to other processes?

22. *Ask just for producer of MP*

What does the current transport/ logistics (cost, effort, conditions) for the MP production look like.?

How can transport between agricultural residue production areas and bioreactors be improved?

23. What health risks are associated with producing MP using agricultural residues? Can the raw material (agricultural by-product) used to produce MP be harmful or toxic in any way? To the health of workers or the environment?
24. In how far can scaling up MP production lead to increased risks in safety and sustainability for the whole value chain?

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

Annex IV: ValoNER dataset properties

Table A3. Properties of the dataset used for fine-tuning and evaluation of the ValoNER tool

Data	Number of					
	documents	segments	sentences	words	concepts	entities
Example 1	1	11	12	234	4	18
Example 2	1	29	47	920	5	59
Example 3	1	27	76	991	5	54
Total	**3**	**67**	**135**	**2145**	**14**	**131**
Synthetic	67	995	54626	26668	167	1540
Total	**67**	**995**	**54626**	**26668**	**167**	**1540**
Example 4	1	25	76	935	6	53
Example 5	1	51	106	1979	9	141
Example 6	1	24	51	793	8	42
Example 7	1	25	69	1188	6	53
Total	**4**	**125**	**302**	**4895**	**29**	**289**
TOTAL (w/o synthetic)	**7**	**192**	**437**	**7040**	**43**	**420**
TOTAL (with synthetic)	**74**	**1187**	**55063**	**33708**	**210**	**1960**

Annex V: ValoNER evaluation results

Table A4-1. Evaluation of the ValoNER tool on the examples used to generate synthetic data, which were subsequently used for fine-tuning the models.

Model			***Example 1***		***Example 2***		***Example 3***		**F1**	**Acc**
name	**type**	**threshold**	F1	Acc	F1	Acc	F1	Acc	(mean)	(mean)
UniNER-7B-all	UniversalNER (optimized)	-	0,38	0,87	0,23	0,91	0,04	0,91	0,22	**0,90**
		-	0,33	0,84	0,34	0,91	0,22	0,91	**0,30**	0,89
UniNER-7B-definition	UniversalNER (optimized)	-	0,36	0,86	0,44	0,93	0,02	0,91	0,27	**0,90**
		-	0,36	0,86	0,47	0,93	0,21	0,91	**0,35**	0,90
medium_v2	Gliner (orig)	0,8	0,30	0,93	0,43	0,96	0,23	0,94	0,32	**0,94**
		0,5	0,44	0,92	0,50	0,95	0,26	0,93	**0,40**	0,94
gliner_large-v2.1	Gliner (orig)	0,6	0,33	0,94	0,49	0,96	0,14	0,94	0,32	**0,95**
		0,2	0,39	0,92	0,51	0,95	0,32	0,94	**0,40**	0,93
NuNerZero_span	NuNER (orig)	0,6	0,19	0,93	0,27	0,95	0,15	0,95	0,20	**0,94**
		0,4	0,44	0,93	0,47	0,94	0,30	0,94	**0,40**	0,94
large_v2	Gliner (orig)	0,7	0,50	0,95	0,44	0,96	0,21	0,95	0,38	**0,95**
		0,2	0,54	0,95	0,48	0,94	0,36	0,94	**0,46**	0,95
valoner_medium_v2	Gliner (fine-tuned)	0,6	0,61	0,95	0,49	0,96	0,63	0,96	0,57	**0,96**
		0,5	0,67	0,95	0,61	0,96	0,62	0,96	**0,63**	0,95
valoner_large-v2.1	Gliner (fine-tuned)	0,6	0,60	0,96	0,61	0,96	0,80	0,98	0,67	**0,97**
		0,5	0,70	0,95	0,68	0,96	0,81	0,98	**0,73**	0,96
valoner_large_v2	Gliner (fine-tuned)	0,6	0,71	0,97	0,74	0,97	0,84	0,98	0,76	**0,97**
		0,5	0,75	0,97	0,76	0,97	0,82	0,98	**0,78**	0,97
valoner_nuner_span	NuNER (fine-tuned)	0,4	0,80	0,97	0,78	0,97	0,83	0,98	**0,80**	0,98

Table A4-2. Evaluation of the ValoNER tool on new, unseen examples (which were not used in generating synthetic data or fine-tuning the models).

model	threshold	*Example 4*		*Example 5*		*Example 6*		*Example 7*		F1 (mean)	Acc (mean)
		F1	Acc	F1	Acc	F1	Acc	F1	Acc		
medium_v2	0,5	0,39	0,93	0,44	0,92	0,67	0,97	0,46	0,95	**0,49**	0,94
large_v2	0,2	0,41	0,93	0,45	0,93	0,68	0,97	0,46	0,94	**0,50**	0,94
gliner_large-v2.1	0,5	0,37	0,94	0,55	0,95	0,68	0,98	0,46	0,96	**0,51**	0,96
NuNerZero_span	0,5	0,38	0,95	0,45	0,94	0,68	0,98	0,35	0,96	**0,46**	0,96
valoner_medium_v2	0,5	0,51	0,94	0,57	0,94	0,64	0,96	0,53	0,96	**0,56**	0,95
valoner_large_v2	0,5	0,47	0,94	0,68	0,96	0,74	0,97	0,54	0,96	**0,61**	0,96
valoner_large-v2.1	0,5	0,41	0,94	0,60	0,96	0,77	0,98	0,55	0,97	**0,58**	0,96
valoner_nuner_span	0,4	0,51	0,96	0,68	0,96	0,83	0,98	0,61	0,97	**0,66**	0,97

Annex VI: Ontology to represent justifications

- **hasPositiveEffect(X,Y,Z), hasNegativeEffect(X,Y,Z)** – X has positive/negative effect on Y in the context of Z, for example:
  - *hasNegativeEffect(scalability_of_PHA,production,industrial_scale)* – scalability of PHA has negative effect on production in the industrial scale context.

  If the context is not provided, it can be specified as general, e.g.:
  - "The durability of PHA offers market opportunities" -> *hasPositiveEffect(durability_of_PHA,market_opportunities,general).*

  Possible to transform (using transformation rules):
  hasPositiveEffect(X,Y,Z) -> hasEffect(X,Y,positive,Z), e.g.:
  - *hasPositiveEffect(durability_of_PHA,market_opportunities,general)* -> *hasEffect(durability_of_PHA,market_opportunities,positive,general)* – durability of PHA has effect, which is positive, on market opportunities in general.

  hasNegativeEffect(X,Y,Z) -> hasEffect(X,Y,negative,Z), e.g.:
  - *hasNegativeEffect(scalability_of_PHA,production,industrial_scale)* -> *hasEffect(scalability_of_PHA,production,negative,industrial_scale)* – scalability of PHA has effect, which is negative, on production in the industrial scale context.

- **dependsOn(X,Y,Z)** – X depends on Y in the context of Z, e.g.:
  - *dependsOn(consistent_distribution,availability_of_feedstock, PHA_production)* – consistent distribution depends on availability of feedstock in the context of PHA production.

  Possible to transform (using transformation rules):
  dependsOn(X,Y,Z) -> hasEffect(Y,X,neutral,Z), e.g.:
  - *dependsOn(consistent_distribution,availability_of_feedstock, PHA_production)* -> *hasEffect(availability_of_feedstock, consistent_distribution,neutral,PHA_production)* – availability of feedstock has effect of consistent distribution in the context of PHA production.

- **isMore(X,Y,Z)** – X is more Z than that of Y, e.g.:
  - *isMore(price_of_PHA,fossil_alternatives,higher)* – price of PHA is higher than that of fossil alternatives.
  - *isMore(logistics_in_PHA,fossil_alternatives,complex)* – logistics in PHA is more complex than that in fossil alternatives.

- **isNot(X,Y,Z)**– X is not Y in the context of Z, e.g.:
  - *isNot(production_of_PHA,developed,in_Europe)* – production of PHA is not developed in Europe.

- **is(X,Y,Z,W)** – X is Y in the context of Z and W, e.g.:
  - *is(stable_feedstock,difficult_to_obtain,general,general)* – stable feedstock is difficult to obtain in general.
  - *is(durability_of_PHA,synthetic_materials,similar,general)* – durability of PHA is similar to synthetic materials.

- **canBe(X,Y,Z)** – X can be Y in the context of Z, e.g.:
  - *canBe(price_of_PHA,very_high,specific_grade)* – price of PHA can be very high at specific grade.

  Possible to transform (using transformation rules):
  canBe(X,Y,Z) -> is(X,Y,Z,possible), e.g.:
  - *canBe(price_of_PHA,very_high,specific _rade) -> is(price_of_PHA,very_high, specific_grade, possible)* – price of PHA is possible to be very high at specific grade.

- **mustBe(X,Y,Z)** – X must be Y in the context of Z (or in general), e.g.:
  - *mustBe(logistics_in_PHA,minimal_cost,PHA_*production*)* – logistics must be at minimal cost in the context of PHA production.
  - *mustBe(availability_of_feedstock,stable,general)* – availability of feedstock must be stable in general.

Possible to transform (using transformation rules):
mustBe(X,Y,Z) -> is(X,Y,Z,mandatory), e.g.:
  - *mustBe(logistics_in_PHA,minimal_cost,PHA_*production*)* -> *is(logistics,minimal_cost,PHA_production,mandatory)* – logistics must be at minimal cost in the context of PHA production.
  - *mustBe(availability_of_feedstock,stable,general)* -> *is(availability_of_feedstock,stable,general,mandatory)* – availability of feedstock must be stable in general.