high-value products from agricultural residues through sustainable chains

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Third estimates of biomass residue volumes, composition, bio-based yields and environmental performances

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Executive Summary

The primary goal of this work is to generate early estimates of production yields from agri-residues to protein and biopolymer products, as well as environmental impacts of such destinations. For making objective decisions also yield and environmental impact effects of common destinations (like animal feed and anaerobic digestion) are described.

This approach supports decision taking in WP4 and underpins the benefit of utilizing agri-residues. The ultimate objective is to promote sustainable practices, reduce waste, and contribute to the development of a circular (bio-)economy in Europe and China by maximizing the use of agricultural residues.

In this deliverable, updates are presented for estimates of yields to PHA and microbial proteins. Because integral assessments of complete processing chains are still in development (in Agriloop WP2-4), these updates were derived from recent scientific publications.

Furthermore, the methodology for environmental impact assessment (greenhouse gas emissions effects) – which was further completed in the reporting period – is described in more detail, including updates and more elaborate results. Based on these results some generic conclusions presented in D1.5 are confirmed:

- Environmental performance of residue destinations (including novel pathways explored in AgriLoop) is linked with the chemical composition of the residues. For some specific residue streams novel pathways deliver environmental benefits compared to common destinations, whereas others are more beneficially used in common destinations.
- Although the utilisation of a residue stream is considered sustainable, energy use in intensive processing can have relatively large negative impact on the environmental sustainability of a processing route/application. When making choices regarding the processing route, the impact of the (process) chain must also be taken into account.

In addition, from the quantitative results presented in this report, it is concluded that residue streams with high content of simple carbohydrates seem most favourable for novel destinations (considered in this report: PHA and microbial proteins). Further development of these pathways, e.g. with improved or more dedicated microbial strains, may make them even more environmental beneficial in terms of environmental performance.

From the results the following preliminary generic conclusions were drawn:

- An adequate combination of material – processing pathway – product application is crucial for effective circular and environmental beneficial valorisation of a residue stream.

- Residue streams with high content of simple carbohydrates seem most favourable for novel destinations (considered in this report: PHA and microbial proteins). Further development of these pathways, e.g. with improved or more dedicated microbial strains, may make them even more beneficial in terms of environmental performance.

- Although the use of a residue stream is commonly considered environmentally beneficial, energy use in intensive processing can have relatively large negative impact on the environmental sustainability of the processing route/application. When making choices regarding the processing route, the impact of the (process) chain must also be taken into account.

- The environmental impact of a valorisation option can be significantly influenced by the possibilities and limitations for applications of process residues. These potential applications should be included in the sustainability evaluation of alternative valorisation options.

For the products specifically in scope of Agriloop it is concluded that

- PHA production can be considered an extra cascade step prior to anaerobic digestion. The extra cascade step is beneficial (environmental performance) if the substrate is functional for PHA production, which is amongst others the case for residue streams with high content of simple carbohydrates, like grey starch and molasses.
  (functional = with significant yield, substantial 'nutritional' value for the processes)

- MP production can be considered 'upcycling'. Upcycling is beneficial (environmental performance) if the substrate has limited value in current destination and is functional protein production.

- PHA production from manure + corn residues has higher environmental performance than anaerobic digestion

- Producing mushrooms on lignocellulose residue streams is beneficial compared to leaving the material in the field or composting

1 Introduction

Agricultural and food production practices are associated with considerable environmental burdens through the consumption of resources such as land, water, energy, etc., through emissions and through the generation of large and diverse residue streams. Primary agricultural residues, generated close to the fields, are often dispersed, or left on the field, overlooking their potential contribution to a circular (bio-)economy. Often, leaving the residues on the field is considered essential for maintaining soil health/fertility. Secondary residues are available in large quantity on plant processing sites, where they are often destined to low-value applications or managed as waste.

The residue streams provide a large pool of largely underutilized resources (see e.g. Scarlat et al., 2019). Additional value (in terms of proteins, biopolymers, or other valuable product) can be generated from them. In many situations the residue of extracting valuable components from a primary residue stream may remain available for the purpose that the residues are used for (like soil application). Substantial fraction of persistent fibre components and minerals will end in the residues, which is still functional for agricultural productivity and soil health when applied in the field.

This deliverable aims at estimating production volume potentials of biopolymers (PHA) and (microbial) proteins from major agricultural residue streams in Europe and China and estimates of associated environmental impact (GHG emissions) reduction compared to common destinations.

Production volume potentials are derived from estimations of volumes of residues and predicted yields of conversion/extraction pathways to the products. For that, estimates of actual volume of generated residue streams are derived from agricultural crop production data and volumes of processed products from which the residue streams are obtained. Yields of conversion/extraction pathways to the products are estimated from a residue's chemical composition (in terms of macro-nutrients), with pathway-specific typical extraction/conversion factor per macro-nutrient.

Two indicators for environmental performance of a valorisation pathway are employed in this deliverable: (1) 'degree of circularity', an indicator for resource use efficiency; this describes (with some underpinned weighting factors) yields to final products of a valorisation pathway; (2) greenhouse gas (GHG) emission effects, which addresses the GHG emissions associated with substituted common products in an application, GHG emissions from used energy and other inputs, and emissions of other GHG (methane and nitrous oxide) in the valorisation pathway.

The results are a further iteration of the dataset and heuristics provided in Agriloop deliverable 1.5. Specifically, the following extensions are incorporated:

- Updates are presented for estimates of yields to PHA and microbial proteins, based on updated yield factors derived from recent scientific publications.
- The methodology for environmental impact assessment (with indicators oriented on resource-use-efficiency and greenhouse gas emissions effects) – which was

further completed in the reporting period – is described in more detail, including updates and more elaborate results.

The methodology for environmental impact assessment provides more nuanced insight in preferent destinations of agricultural residues compared to rigid frameworks such as the 'Food waste hierarchy' (European Parliament Council, 2008; Papargyropoulou et al., 2014; Teigiserova et al., 2020) or the 'Waste food scale[1]'. Through early estimating yields to products and environmental impacts per valorisation pathway based on the materials' characteristics, product-specific ranking can be identified. The methodology and quantitative findings can be used as underpinning of decisions on selection of adequate destination pathways per residue stream and of selecting a residue stream(s) per destination.

Comments:

- This deliverable describes yields and impacts of complete processing chains (from residue stream to products). Technical research in Agriloop work packages 2 and 3 is oriented on part of the processing chains for amongst others biopolymers and proteins. Extending the findings of those research findings to complete processing schemes is part of work package 4, which is beyond the scope of this deliverable. Here available heuristics derived from scientific literature are used for describing common destinations and specific pathways in the scope of Agriloop.
- Early estimates are based on a large number of parameters. These parameters are derived from a large number of references. They are considered indicative; practical results may deviate substantially from the early estimates, for example if texture or specific components hinder or inhibit conversion or extraction processes.
- Various factors presented in this report are adjusted compared to earlier documentation (including Agriloop deliverable D1.5), based on amongst others insights from recent references and through more extensive descriptions of processes. In forthcoming work factors may be further updated in the methodologies based on progressive insights (including results from technological research in Agriloop) in order to best support research in Agriloop WP4.

This deliverable D1.6 was delivered as part of **Work Package 1** of the EU-UK-CN project **AgriLoop**, which focuses on early estimates of yields of valorisation pathways from agricultural residues to biopolymers and protein products and environmental performance of the pathways. The report presents the results obtained in **Task 1.2**.

[1] https://www.epa.gov/sustainable-management-food/wasted-food-scale (accessed 2025-10-31)

2 Methodology for estimating yields to biopolymers, proteins and other biobased products

Production potential of biopolymers, proteins and other products in Europe and China can be estimated through combining:

- **Yields of extraction and conversion pathways** from agricultural residues to biopolymers and protein products. Yields (kg product per kg residue stream) are estimated through mass balance models that describe the yield per macro-nutrient. For that, yield factors are presented in sections 2.1 to 2.3. For the conversion processes addressed in this deliverable, rules derived from literature study were used. Compared to the values provided in Deliverable D1.5, yield factors for PHA were updated based on a recent reference (section 2.1) and yield factors for microbial protein production were added (section 2.3).
- **Chemical composition and yields to products.** Based on the yield factors and chemical compositions of selected agri-residues streams early estimates of yields to products are presented in.
- **Volumes of residual streams.** Most likely a factory would exploit (part of) the residue volume from a processing factory or regional available volume. Mapping availability is beyond the level of detail of this study; instead estimations of production volumes per country are presented in section 2.7.

In order to facilitate comparisons of the environmental performance of valorisation pathways with other (more common) pathways - presented in sections 3 and 4 of this deliverable – in this section also yield factors for a number of 'common' pathways are presented.

2.1 Typical yield factors for production of biofuels, chemicals and plastics

Through fermentation and other conversion processes, macronutrients can be converted to various biobased materials. Yield factors in general vary amongst processing pathways. Typical yield factors for a set of common pathways/products are summarized in Table 1 and Table 2.

TABLE 1. MACRONUTRIENT YIELD FACTORS TO ENERGY CARRIERS, KG PRODUCT PER KG FEEDSTOCK (T: THEORETICAL, POTENTIAL YIELD DERIVED FROM AMONGST OTHERS STOCHIOMETRICS; P: PRACTICAL/TYPICAL VALUES, OR RANGE OF VALUES, DERIVED FROM REFERENCES[2]).[3]

Product Macro-nutrient	Biomethane	Bio-ethanol (2nd gen. fermentation)	Bio-ethanol (BTL) (pyrolysis or Fisher Trops)	Biodiesel (FAME)	Biodiesel (HVO)
Protein	0.34 (T)[a] 0.33 (P)[a]				

[2] References: [a] Nova (2015); [b] Li et al. (2018); [c] Golkowska et al (2013); [d] eubia (2022); [e] Sadhukhan et al. (2019); [f] Lovett et al. (2016); [g] IfBB (2025); [h] Burniol-Figols et al. (2018) ; [i] Sohail et al. (2020), [j] Saavedra del Oso et al. (2024).

[3] These conversion factors are for 'first generation-technologies' for non-lignocellulose feedstocks. Higher conversion factors can be obtained from especially lignocellulose feedstocks with second generation processes.

Product Macro-nutrient	Biomethane	Bio-ethanol (2nd gen. fermentation)	Bio-ethanol (BTL) (pyrolysis or Fisher Trops)	Biodiesel (FAME)	Biodiesel (HVO)
Lipids	0.72 (T)[a] 0.56 (P)[a]			1.0 (T)[a] 0.96 (P)[a]	0.75 (P)[a]
Sugar	0.27 (T)[a] 0.26 (P)[a]	0.51 (T) [a,d] 0.47 (P) [a]	0.27(P)		
Starch	0.27 (T)[a] 0.26 (P)[a]	0.57 (T) [d] 0.42 (P) [a]	0.27 (P)		
Cellulose	0.30-0.35 (T)[a,b] 0.18-0.25 (P)[a,b,c]	0.51-0.57 (T) [a,e] 0.35-0.38 (P) [a]	0.12 (P)		
Hemicellulose	0.29 (T)[b] 0.13-0.16 (P)[b]	±0.4 (T)			
*Lignin**					

** Generally, lignin is considered not digestible in biological conversion processes*

TABLE 2. MACRONUTRIENT YIELD FACTORS TO BIOPOLYMERS, KG PRODUCT PER KG FEEDSTOCK (T: THEORETICAL, POTENTIAL YIELD DERIVED FROM AMONGST OTHERS STOCHIOMETRICS; P: PRACTICAL/TYPICAL VALUES, OR RANGE OF VALUES, DERIVED/ESTIMATED FROM REFERENCES[2]).

Product Macro-nutrient	Bio-PE	Bio-PET (30%)	PLA	PEF	PHA
Protein					
Lipids					0.7-0.8[h,l]
Sugar	0.25-0.29 (P)[a,f,g]	0.20[g]	0.68 - 0.80 (T)[a,g] 0.67- 0.77 (P)[a,g]	0.56 (T)[a] 0.51-0.55 (P)[a]	0.34 - 0.48 (T) [a,g,j] 0.40 (P) [g]
Starch	0.20 (P) [g]		0.60 (P)[g]		0.31 – 0.37 (T) [g,j]
Cellulose					
Hemicellulose					
Lignin					

Notes:

- 2nd generation technologies – i.e. with hydrolysis of cellulose components – for biopolymer production are not considered here; therefore for cellulose, hemicellulose and lignin conversion factors are assumed 0.
- The yield factor from lipids to PHA was estimated from a limited number of data points and may depend strongly on specific feedstock and downstream processing. The provided yield factor should be considered indicative.

Remark: with second generation technologies large part of cellulose and hemicellulose may be converted to sugar and consequentially contribute substantially to yields from ligno-cellulose rich streams. Corresponding factors are included for bioethanol (Table 1) but not for biopolymers (Table 2), considering that second generation technologies are not yet common in biopolymer production.

Compared to the factors presented in Deliverable D1.5 the factors for PHA are updated based on a recent reference:

Estimating yield factors for PHA
We have estimated typical yield factors for conversion of material to PHA from Saavedra del Oso et al. (2023), Figure 1.

In the indicated set of processing steps, the yield of anaerobic fermentation to VFAs strongly depends on the processing conditions (like temperature, pH and retention time in fermentation steps) and feedstock characteristics. Considering the feedstock composition, the higher yield factor (0.75) is anticipated for readily digestible components like lipids and simple carbohydrates, whereas we assume that ligno-cellulose compounds are not degraded in the fermentation and that the lower value (0.35) provided is assumed to apply to the 'other carbohydrates' fraction.

For the further processing steps, we assume:

- In VFA separation 90% of VFA ends in the VFA-rich stream.
- In the PHA accumulation step the yield to PHA is on average 65%.
- In the downstream processing on average 75% of the generated PHA is extracted.

The combined yield for lipids and simple carbohydrates is estimated at

$0.75 \times 0.90 \times 0.65 \times 0.75 = 0.329$ g COD_{PHA} / g $COD_{material}$

and for the 'other carbohydrates' fraction at

$0.35 \times 0.90 \times 0.65 \times 0.75 = 0.153$ g COD_{PHA} / g $COD_{material}$

For proteins the yield (including the estimated degree of hydrolysis) is estimated at 0.6 g COD_{vfa} / g $COD_{proteins}$. (typical value derived from Duong et al., 2021). Like for carbohydrates the yield to PHA from proteins is estimated as:

$0.60 \times 0.90 \times 0.65 \times 0.75 = 0.263$ g COD_{PHA} / g $COD_{proteins}$

From above COD yield factors, the mass yield factors in Table 3 were derived (based on estimated COD values 2.8, 1.3, 1.2, 1.1, 1.3 and 1.2 g COD per gram material for lipids, proteins, starch, sugar, 'other carbohydrates' and PHA respectively.

> Remark: The yield factors derived above are on the high side compared values derived from other references. The actual yield will strongly depend on specific material properties and processing conditions (including e.g. duration of the fermentation step). In order to present the <u>potential</u> yield (from optimised processing), here the high yield factors are used.

The residue is anaerobically digested.

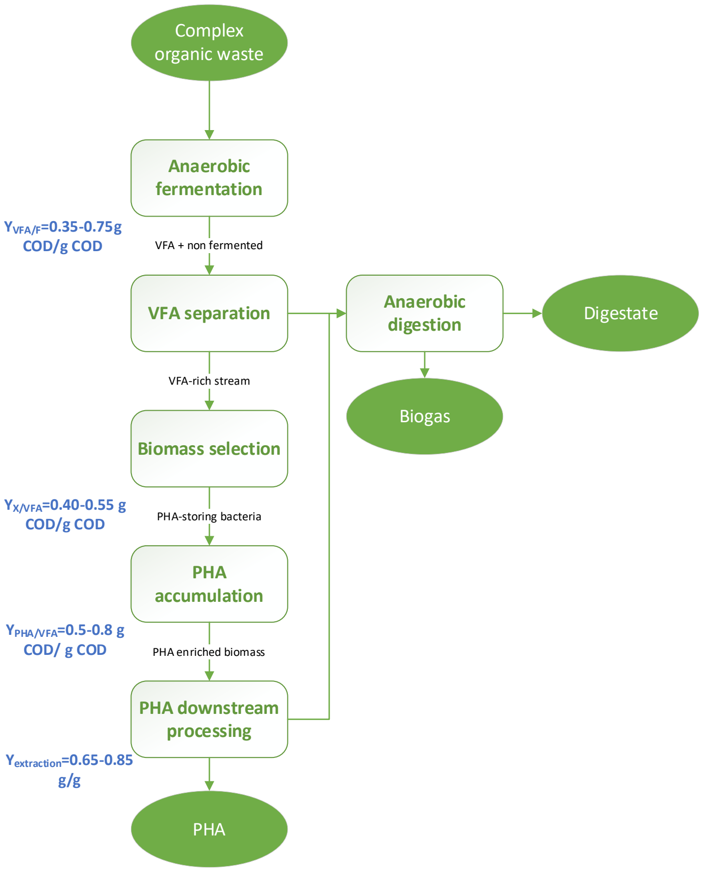

Figure 1. Processing steps and yield factors for PHA production from a residue stream (derived from Saavedra del Oso et al., 2023)

Based on above, combined with estimates from Bos & Sanders (2013), typical/average conversion yields are presented in below table.

Table 3. Assumed average macronutrient conversion factors, kg product per kg component in the feedstock.

Product Macro-nutrient	Biomethane	Bio-ethanol (2nd generation, fermentation)	Bio-ethanol (BTL) (pyrolysis or Fisher Trops)	Biodiesel	PLA	PHA
Protein	0.33					0.29
Lipids	0.56			0.9	0.75	0.77
Sugar	0.26	0.5	0.27		0.6	0.30
Starch	0.26	0.5	0.27			0.33
Cellulose	0.20	0.4	0.12			
Hemicellulose	0.15	0.3				
Lignin						
*Other carbohydrates**	0.22	0.43	0.22			0.17

*Diverse other categories of carbohydrates, generally more persistent than sugar and starch, but less than (hemi-)cellulose. Assumed conversion factors between values for simple and complex carbohydrates.

Estimates of yields (kg DM product per kg DM residue) to the products for the selected residue streams (based on residue compositional information, see section 2.5) are provided in section 2.6.

2.2 Typical yield factors for protein extraction methods

A broad variety of extraction pathways for proteins from organic materials exist, ranging from low-yield processes (mostly resulting in relatively pure, dedicated protein products) to high-yielding processes (resulting in bulk proteins), as reviewed in Voudouris et al. (2017).

Typically, through alkaline or enzymatic hydrolysis, approximately up to 70% of the contained proteins can be extracted (estimated from Estimated from Da Fonseca et al (2023), Uddin et al. (2018) and Voogt et al. (2021). Recent advances include also combinations of physical and chemical processes yielding about 70-90% of proteins depending on the substrate and extraction method (Shawky et al. 2025). Yields closer to 90% are typically associated with more sophisticated, multi-step or hybrid extraction techniques detailed in the 2025 review. These methods might carry possible, scaling, economic or technological limitations that are being addressed in research (Shawky et al. 2025).

Cosun (2019) provides some insights in realistic yields of the high-value protein Rubisco from beet leaves: approximately 30% of the proteins from the sugar beet leaves can be obtained in the Rubisco extract.

2.3 Typical yield factors for microbial protein production

Very diverse pathways for microbial protein (MP) production exist, based on different micro-organisms and technologies. Because the vast majority of studies on MP production are based on agricultural residue streams, and MP micro-organisms require combinations of (macro-)nutrients, straightforward yield factors cannot be given here. As a work-around, here for early estimating (typical) potential yields, we have mass balances from Spiller et al. (2020) as presented for the aerobic heterotrophic bacteria system, with the following estimated yield characteristics:

- 75% of the feedstock's proteins end in the MP product,
- 0.30 g protein is produced per gram simple carbohydrates in the feedstock, of which 75% ends in the MP product.

The total effect is described through the following formula:

$$Y_{protein,MP} = 0.75 \times \left(M_{protein} + 0.3 \times M_{starch} + 0.3 \times M_{sugar}\right)$$

where $Y_{protein,MP}$ is the protein yield in the MP product and $M_{protein}$, M_{starch} and M_{sugar} are the amount of proteins, starch and sugar respectively in the feedstock.

> Remark: Because of limited information on used feedstock's characteristics, above yield factors may be inaccurate. Furthermore. for lipids no yield factors were found. Consequently, the actual yield to protein may be underestimated through above factors.

2.4 Typical yield factors for mushroom production

Lignocellulose agricultural crop residues (e.g. straw) are utilized for food (protein) production through mushrooms. Considering the relatively high ample availability of these agricultural residues, this pathway may be further exploited, so that other resources are made free for new application.

A large variety of mushroom varieties exists, with different (growth) characteristics (Kumla et al., 2020). Here, yield factors are derived from Grimm et al. (2024) for Oyster mushrooms (Pleurotus ostreatus) cultivation (assuming that N is limiting for yield):

- From the results presented by Grimm et al. (2024) it is derived that approximately 25% to 45% of N from the substrate ends in the mushroom (average: 35%) Considering that in mushrooms approximately ⅔ of N is bound in protein (Fujihara et al., 1995), the actual potential yield from N into protein-N in the mushroom is estimated at ⅔ x 35% = 24%.
- Next to proteins, the mushrooms also accumulate 200% to 300% carbohydrates (relative to protein accumulation).
- Approximately 2/3 of C and N of the substrate end in the "spent mushroom substrate", which can be applied as fertilizer.

Remarks:

- For feedstocks with relatively high protein content a high yield factor can only be achieved through combination with lignocellulose rich material.
- In modern button mushroom production other N sources are added (such as poultry and horse manure). This further promotes the yield factor from straw. This practice is not considered here.

2.5 Chemical composition of selected agri-residues streams and associated estimated yield to products

As explained, chemical composition of a material is essential for estimating yields to products through the yield factors.

In Agriloop deliverable D1.5 a complete overview of (estimated) chemical composition was provided. This overview is also provided in Annex 1 of this deliverable.

2.6 Early estimates of yields from agricultural residues to products

Based on the combination of the chemical compositions and yield factors as introduced in sections 2.1 to 2.4, early estimates of yields (kg DM/kg DM) are calculated.

Example: yield from grey starch (with assumed content of 104 g proteins, 13 g lipids, 27 g sugar, 590 g starch and 222 g other carbohydrates per kg DM, see Annex 1) to a few products in the scope of Agriloop:

- PHA:

$$
\begin{aligned}
Y_{PHA} &= 0.29 \times M_{protein} + 0.77 \times M_{lipids} + 0.30 \times M_{sugar} + 0.33 \times M_{starch} \\
&\quad + 0.17 \times M_{other\ carbs} \\
&= 0.29 \times 0.104 + 0.77 \times 0.013 + 0.30 \times 0.027 + 0.33 \times 0.590 + 0.17 \times 0.222 \\
&= 0.29 \text{ kg PHA per kg DM}
\end{aligned}
$$

- Microbial proteins:

$$Y_{protein,MP} = 0.75 \times (M_{protein} + 0.3 \times M_{starch} + 0.3 \times M_{sugar})$$
$$= 0.75 \times (0.104 + 0.3 \times 0.590 + 0.3 \times 0.027) = 0.21 \text{ kg proteins per kg DM}$$

A more complete set of early estimated yield factors for all agri residue streams in scope to biopolymers and proteins based on heuristics presented in above sections is presented in Annex 2.

> Remark: yields are estimated based on assumption that the components from the material are fully (bio)available; reduced yield because of components or textures that hinder conversion and extraction processes are neglected. Consequently, the actual yield may be lower than presented.

2.7 Estimations of volumes of agri-residual streams per country

In order to estimate theoretical potentials to final product, the volumes of selected agri-residual streams per country are quantified. This chapter presents updated results of those presented in Agriloop deliverable D1.4.

To estimate the volumes of the residual streams at country level, different approaches for the agricultural residues (primary residues) and processing residues (secondary residues) were used. For the primary residues, we estimated the volume of residues from crop production areas and volumes per country to estimate the yield of residues per country. For the secondary residues, to estimate the volume of residual streams per country, either direct data on residue generation were used or the residue volumes were estimated from residue factors gathered for each type of residue in combination with production volumes.

Total estimated volumes per residue stream per country are presented in Annex 3.

2.7.1 Estimations of agri-residues volumes from primary production

The amount of residues generated in the field is directly related to crop production area, and may depend on various factors; here it is assumed that the only relevant factor is the actual crop yield.

The foundation for estimating the volumes of above-ground crop residues is the widely accepted studies of Fischer and co-workers (Fischer et al. 2007, Fischer et al. 2009 and Fischer et al. 2010) and Scarlat et al. (2010).

Because of high variance/poor correlations in the expressions we have reviewed publications citing their work to understand, extend and include the involvement of other complementary parameters and dependencies such as factors influencing the yield.

Other more recent studies have used, verified and extended this work (e.g. García-Condado et al. 2019, García-Galindo et al. 2019).

Large variations were found for actual estimates between the heuristics by the different references. Based on comparisons with different practically reported residue yields, a heuristic that provides reasonable values was chosen.

For many crops, for technical reasons, only a limited fraction of the total crop residues can be harvested, e.g. crop residues for cereals consist of roots, stubble and straw; in the current practice only the straw fraction is harvested. Estimates for the fraction of crop residues that actually can be harvested are mentioned by amongst others:

- Scarlat et al. (2010):
  Sustainable removal rates: 40% for wheat, barley, rye and oats, 50% for maize, rice, rapeseed and sunflower,
- Scarlat et al. (2019):
  Technical potential: 58% for wheat, barley rye, oats, and rice, 64% for maize, 50% for rapeseed, 52% for sunflower
- Sustainable removal rate: average for EU estimated at 42% (variable, based on local considerations)
- Selin Noren et al. (2022):
  Technical removal rates around 70% for wheat and 60% for barley.

Here, the technical potential removal rates proposed by Scarlat et al. (2019) are used; for other crop residues the technical potential is assumed 100%.

Table 4 presents the selected heuristics for estimates of technical potential of crop residue volumes.

TABLE 4. CORRELATIONS DERIVED FROM LITERATURE FOR THE VOLUME OF PRIMARY RESIDUES (TECHNICAL POTENTIAL TON DRY MATTER PER HA) RELATED TO CROP YIELD (Y: TON, AS-IS, PER HA).

Crop	Crop residue	Estimate of residue volume per ha	Specific reference
Wheat	*Wheat straw*	$0.58 \times 0.85 \times 2.125 \times Y^{0.6}$	Scarlat et al. 2010
Maize	*Maize (or corn) stover*	$0.64 \times 0.70 \times Y \times (1.337 - 0.1807 * LN(0.863 \times Y))$	Scarlat et al. 2010
Barley	*Barley straw*	$0.58 \times 0.85 \times Y \times (1.38 - 0.2751 \times LN(Y))$	Scarlat et al. 2010
Rye	*Rye straw*	$0.58 \times 0.85 \times Y \times (1.5142 - 0.3007 \times LN(0.866 \times Y))$	Scarlat et al. 2010
Oat	*Oat straw*	$0.58 \times 0.85 \times Y \times (1.3002 - 0.1874 \times LN(0.879 \times Y))$	Scarlat et al. 2010
Triticale	*Triticale straw*	$0.58 \times 0.85 \times 2.125 \times Y^{0.6}$	(estimate for wheat)
Tomatoes	*Tomato crop residues (leaves and stems/tomato plant)*	3.5	Zotarelli et al. 2009
Grapes	*Branches and leaves*	2.9	Molina-Alcaide et al. 2008
Rape or colza seed	*Rapeseed straw*	$0.50 \times 0.60 \times Y \times (2.0475 - 0.452 * LN(0.923 \times Y))$	García-Condado et al. 2019
Sunflower	*Sunflower stalks (straw)*	$0.52 \times 0.60 \times Y \times (3.2189 - 1.1097 * LN(0.928 \times Y))$	Scarlat et al. 2010
Olives	*Olive tree pruning biomass*	$0.574 \times Y$	Padilla- Rascón et al. 2020
	Olive leaves	$0.063 \times Y$	Padilla- Rascón et al. 2020
	Olive pomace	$0.226 \times Y$	Padilla- Rascón et al. 2020
	Olive stones	$0.115 \times Y$	Padilla- Rascón et al. 2020
Potatoes	*Potato crop residues*	$1.6831 + 0.1067 \times Y$	García-Condado et al. 2019
Rice	*Rice straw*	$1.7171 \times Y^{0.7933}$	García-Condado et al. 2019

Crop	Crop residue	Estimate of residue volume per ha	Specific reference
Sugar beet	*Sugar beet leaves* *Sugar beet tops*	0.115 × 0.3266 × Y 0.279 × 0.1516 × Y	Zwart et al. 2004, Locker 2021, greenproteinproject.eu

Actual volumes of crop residues per country are determined through the formulas presented in Table 4, where crop areas and average yield are derived from Eurostat/FAOSTAT (values for 2021).

2.7.2 Estimations of volumes of secondary residues

Secondary residues are generated in processing. Their volumes cannot be directly estimated from crop production volumes in a country, because (a) most crops are used in diverse applications, and (b) crops may be traded between countries prior to processing. A more logical path is estimating the generated volumes of secondary residues from the main product volume. This approach requires estimates of volumes of the main products that resulted in the residue generation and heuristics for residue-to-volume ratios.

Table 5 summarizes estimations for residue-to-product factors (completed and updated compared to the heuristics presented in Agriloop deliverable D1.4).

TABLE 5. USED RESIDUE-TO-PRODUCT RATIOS: ASSUMED VOLUME OF RESIDUE (DRY MATTER WEIGHT) RELATIVE TO VOLUME OF PRODUCT (AS-IS WEIGHT).

Main product	Residue name	Residue-to-product ratio	Reference
Apple juice	*Apple pomace*	0.4 × 0.25	Estimated from Shalini et al. (2010), Turk et al. (2012), Vukušić et al. (2021)
Beer	*Brewer's spent grain*	0.23 × 0.17	Mathias et al. 2015, Olajire (2020)
	Brewer's yeast	0.10 × 0.025	Fillaudeau et al. (2006)
Olive oil	*Olive pits (or stones)*	0.115 × 0.875 / 0.659	Padilla- Rascón et al. 2020
	Extractive Olive Pomace	0.226 × 0.875 / 0.659	Padilla- Rascón et al. 2020
Peanut oil	*Peanut meal*	1.88	Niftem[4]
Peanuts	*Peanut skins*	0.04	Arya et al. (2016)
	Peanut hulls	0.26	Arya et al. (2016)
Potato starch	*Potato pulp*	0.1	Elbersen (2011)
Preprocessed potato[a]	*Potato peels*	0.123 × 0.09 / (1 – 0.09)	Arapoglou et al. 2010
Preprocessed potato[a]	*Grey starch (assumed DM content 12.5%)*	0.125*0.0165 / 0.65	Locker (2021)
Rapeseed oil	*Rapeseed hulls*	0.893 × 0.198 / 0.412	Carré et al. 2015
	Rapeseed meal	0.89 × 0.376 / 0.412	Carré et al. 2015
Rice bran oil	*Rice bran, defatted*	8	Estimated from lipids content of rice bran and defatted rice bran in Table 12.
Milled rice	*Rice husk* *Rice bran*	0.28 0.10	http://www.knowledgebank.irri.org/step-by-step-production/postharvest/rice-by-products
Sugar	*Sugar beet pulp*	50 / 140	Estimated from Harmsen et al. (2014)

[4] https://uphorticulture.in/DPR/Fat%20and%20oil/Ground%20Nut%20Oil%20New.pdf, https://www.niftem.ac.in/site/pmfme/dprnew/peanutoildpr.pdf

	Sugar beet molasses	0.6 × 40 / 140	Estimated from Harmsen et al. (2014)
Sunflower oil	*Sunflower meal*	1.15	Estimated from Le Clef et al. (2015)
Preserved tomatoes	*Tomato skins*	0.003	Estimated from Del Valle et al. (2006) and Casa et al. (2021)
Tomato juice	*Tomato pomace*	0.008	Estimated from Del Valle et al. (2006) and Casa et al. (2021)
Unconcentrated tomato paste and puree	*Tomato pomace*	0.008	Estimated from Del Valle et al. (2006) and Casa et al. (2021)
Concentrated tomato paste and puree	*Tomato pomace*	0.024[b]	Estimated from Del Valle et al. (2006) and Casa et al. (2021)
Wine	*Grape pomace*	0.0214	Ladakis et al. (2020)
	Grape seeds	0.0064	Ladakis et al. (2020)
	Grape stalks	0.0071	Ladakis et al. (2020)

[a] *prepared potatoes, fries and other potato-derived snacks*
[b] *for concentrated tomato product an average concentration factor 3 is assumed*

Volumes of the main products produced per country (from which the residue volumes can be estimated based on the formulas presented in Table 5) were derived from diverse information sources (when available, average for the latest 3 years are used):

- Apple juice: Eurostat (for Europe) (may be inaccurate because these figures may include production of apple juice from imported concentrates).
- Beer: Eurostat (for European countries; average from most recent years for which data are provided) and www.china-briefing.com/news/chinas-beer-market-outlook-and-opportunities (for China).
- Olive oil: Eurostat (only for Europe).
- Peanut oil: production volume according to FAOSTAT (for Europe); www.indexmuni.com (for China; the higher value is considered more accurate than from FAOSTAT).
- Peanut skins: estimated from peanut food supply per country (FAOSTAT) (this may induce significant inaccuracies, but no better information source was found).
- Potato starch: Eurostat (for Europe), estimated from https://www.fnbnews.com/Top-News/global-potato-starch-market-trends-77501 (for China).
- Pre-processed potato: Eurostat (for Europe), https://potatoes.news/potato-processing-in-china-key-products/ (for China).
- Rapeseed oil: Estimated from volume of processed rape and mustard seed (assuming that the volume of mustard seeds can be neglected compared to the volume of rapeseeds) per country (FAOSTAT), with estimated oil yield of 412 kg oil per ton seeds (Carré et al., 2015).
- Rice bran oil: guessed at 20% of the global market, which is 1.8 million tonnes per year (https://www.imarcgroup.com/rice-bran-oil-processing-plant). This is substantially higher than FAOSTAT data (which we consider less reliable).
- Milled rice: estimated from national production of paddy rice, assuming that milling is done in the country of rice production. A milling yield of 72% is assumed (derived from http://www.knowledgebank.irri.org/step-by-step-production/postharvest/rice-by-products).
- Sugar: Estimated from volume of processed sugar beets per country (FAOSTAT), with estimated yield of 140kg sugar per ton beets (Harmsen et al., 2014).

- Sunflower oil: Eurostat (for Europe), www.indexmundi.com (for China)
- Preserved tomatoes, tomato juice, unconcentrated tomato paste and puree and concentrated tomato paste and puree: Eurostat (for Europe).
  For China: no details of production volumes were found. As a work-around, the total volume of processed tomatoes was derived from www.indexmundi.com; next it was assumed that the subdivision over the product categories is equal as for Europe.
- Wine: https://agridata.ec.europa.eu (for Europe), https://www.oiv.int/sites/default/files/2024-04/oiv_state_of_the_world_vine_and_wine_sector_in_2023.pdf (for China).

2.8 Estimations of yields per residue stream to selected products per country

Through combining the volumes of residue streams with chemical composition data and yield factors to selected products, the product's production potential volume per country can be estimated.

$$V_{product\ j} = V_{residue} \times \sum_{components\ i} (y_{i,j} \times m_i)$$

where

- $V_{product\ j}$ is the estimated production potential to product j (tonnes).
- $V_{residue}$ is the estimated volume of the residue (tonnes).
- $y_{i,j}$ stands for the yield factor of macro-nutrient i to product j (kg/kg).

For PHA and microbial proteins accordingly estimated production potentials are provided in Annex 4.

3 Methodology for early estimates of environmental performance of residue valorisation options

The European Commission (EC, 2020) aims to achieve climate neutrality, for which synergies between circularity and reduction of greenhouse gas emissions need to be further exploited, specifically through:

- analysing how the impact of circularity on climate change mitigation and adaptation can be measured in a systematic way;
- improving modelling tools to capture the benefits of the circular economy on greenhouse gas emission reduction at EU and national levels.

For that purpose, two indicators for environmental performance are deployed in this deliverable:

- An indicator that expresses resource-use-efficiency[5] of a residual stream in a destination: measure the efficiency in the valorisation pathway, considering cascading and all byproduct valorisation in the pathway (e.g. in PHA production side streams are generated that may be anaerobically digestated, which delivers biomethane and digestate, which can be applied to the soil as fertilizer product that promotes crop production). We have named this indicator 'degree of circularity'. The concept for this indicator was developed by Broeze et al. (2024) and further extended in the AgriLoop project (task 1.2).

  This indicator was selected with an eye on the 'food vs. fuel' social debate. Resource-use solutions are essential in order to fulfil all demands with the limited available resources.

- An indicator for environmental sustainability impact: effects on greenhouse gas (GHG) emissions.

  This indicator was selected because in environmental policy, climate impact is considered the major sustainability concern. It is somewhat linked to resource-use efficiency (with high yields to main product, embedded impacts can be distributed over a relatively high volume). However, compared to 'degree of circularity' this indicator adds environmental impact due to use of fossil resources.

Many physical environmental indicators (like nitrogen pollution and water problems) are linked to local specific situations, and therefore not addressed in universal indicator here.

In following sections the methodologies for both indicator are explained. To quantify environmental benefits of novel destinations, next to the novel pathways (including production of PHA and microbial proteins) also metrics for a number of common processing/application pathways will be described.

[5] Efficiency seeks to optimize material and energy use to reach a higher level of productivity, aiming for relative or absolute reductions in environmental impact through technological improvements (Huber, 2000; Rudolf, 2025).

3.1 Degree of circularity: indicator for resource-use-efficiency

The existing methodologies for circularity assessment are not adequate for promoting effective use of bio-resources for all existing and future demands.

> A broad set of metrics for circular economy (CE) have been defined, mainly addressing environmental, economic and social issues. Most indicators focus on recycling, linking to resource-use efficiency (Vural Gursal et al., 2023).
> For monitoring circularity Eurostat has developed the 'circular material use rate' — in short 'circularity rate' — which measures the contribution of recycled materials towards the overall use of materials[6]. The circularity rate is the share of material resources used in the EU which came from recycled waste materials, thus saving primary raw materials from being extracted.
> For organic residue streams the material that is used as food and fodder is considered 'circular material use', and the share of residue streams in food and fodder of the total food and fodder use is counted as 'circularity rate'.
> The 'circularity rate' has some drawbacks, related to the inherent transformation and degradation of organic molecules in production and consumption:
> - Use for food and fodder are equally appreciated in the 'circularity rate'. This may seem logical from the market-demand perspective, but disregards that the resource use efficiency to food is significantly affected by the limited protein and energy conversion efficiency of livestock. This is underpinned by the food waste hierarchy (European Parliament Council, 2008; Papargyropoulou et al., 2014; Teigiserova et al., 2020), which appreciates use for food higher than use for fodder.
> - In transformations of organic material to food or feed losses may occur (e.g. in extraction processes); this seems not explicitly incorporated in the 'circularity rate' assessment.
> - The functionality of (components in) a residue stream in the application may vary amongst different applications. For example a stream that has high lignocellulose content is less suitable for pig feed than for dairy feed.
> - This approach neglects that also in other applications (e.g. when applied to the soil), a residue stream may contribute to crop production (through the supply of nutrients and persistent organic matter).
> - Valuable non-food uses are also overlooked by the indicator. Also 'organic recycling' (e.g. for biogas and/or fertilizer production) is not considered.
>
> After Vural Gursal et al. (2023): for increasing circularity of biomass use it is essential to monitor quality and to incorporate quality aspects in circularity evaluation. Here, quality refers to the potential resource utility or functionality based on the inherent and intrinsic material properties such as structure and chemical composition.

We propose to assess the 'degree of circularity' of a biomass valorisation pathway through a perspective that appreciates quality/functionality of the biomass in an application (introduced by Broeze et al., 2024). For that we propose to estimate the 'degree of circularity' as the yield efficiency via a processing pathway to final products. Here, 'final products' refers to food or biobased products; other applications (like feed, substrate for fermentation, etc.) are considered intermediate steps towards generation of the final products. Applications with highest 'degree of circularity' are promoted by this indicator.

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[6] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Circular_economy_-_material_flows#Circularity_rate (accessed 18 October 2024).

This perspective is largely consistent with Eurostat's 'circular material use rate' for fossil material s. This is because their contribution ratio to final products is proportional with their substitution ratio for material resources.

Essential feature – as in full LCA's – is the inclusion of destinations of co-products that are generated in a valorisation pathway next to the main/intended products. Considered main and co-products for a selection of potential destinations are listed in Table 6.

TABLE 6. CONSIDERED MAIN AND CO-PRODUCTS FOR A SUBSET OF THE PROCESSING/APPLICATION PATHWAYS ELABORATED IN CHAPTER 2

Destination/processing pathway	Considered effects: yields (products and co-products) to final products
Directly applied or left behind in the field	Fertilizer, indirectly contributing crop (food) production: • N: fertilizer nutrient (contributes to crop (protein) production), • Persistent organic matter: may contribute to physical soil fertility.
Feed (dairy cattle, pigs, layer hens, broilers)	Contributes to food production via the animal Manure: fertilizer function contributes indirectly to food production (fertilizer function, see above)
Anaerobic digestion	Bio-methane (energy carrier) Digestate indirectly contributes – through its fertilizer function – to food production
PHA production	PHA raisin (material) Through anaerobic digestion of the residue, biogas is produced (energy carrier) Digestate contributes through its fertilizer function to food production
Alkaline protein extraction	Extracted protein is used as food ingredient Through anaerobic digestion of the residue, biogas is produced (energy carrier) Digestate contributes through its fertilizer function to food production
Rubisco protein extraction	Food ingredient Through anaerobic digestion of the residue, biogas is produced (energy carrier) Digestate contributes through its fertilizer function to food production
Enzymatic protein extraction, combined with fermentative ethanol production	Extracted protein is used as food ingredient Through fermentation of the residue bio-ethanol is produced (energy carrier) The residue of the fermentation may be used as feed for livestock, that directly and indirectly contributes to food production (see above)
Microbial protein production	It is assumed here that the MP product is used as animal feed (e.g. for fish). The proteins are – with a 'retention ratio' – converted to food. Through anaerobic digestion of the residue, biogas is produced (energy carrier) Digestate contributes through its fertilizer function to food production

For a selection of destination specific yield factors as presented in Annex 5 of this report. Factors for various other destinations that are not elaborated in Annex 5 (amongst others animal feed) can be found in Broeze et al. (2024). For some pathways elaborated by Broeze et al. (2024) updates (based on progressing insights) were applied:

- for soil application of organic material (like crop residues, manure and digestate): the contribution to food production via persistent organic matter was taken out, considering that the marginal effect is highly dependent on the actual soil conditions, and not considered critical in large parts of Europe (Hijbeek et al. (2017), Oldfield et al. (2021));
- diverse valorisation pathways (a subset of those presented in chapter 2) were added.

Remark: in practice, all destinations (except for direct use as food) have net efficiency substantially lower than 100%. Consequentially the calculated degree of circularity of all applications are (substantially) lower than 100%. Striving for 100% degree of circularity is only realistic through direct use of the material in final products; any conversion and extraction process leads inevitably to reduction of degree of circularity. The indicator 'degree of circularity' can be used to compare different potential processing/application pathways, e.g. demonstrating benefit of adding a cascade step (e.g. PHA production prior to anaerobic digestion).

3.2 Estimating effects on GHG emissions

As in the methodology for estimating degree of circularity, in GHG emission accounting destinations of co-products that are generated in a valorisation pathway must be included next to the main/intended products if the fractionation process is in the scope of the assessment.

Whereas in the methodology for estimating the degree of circularity the complete pathway to final products is described (LCA: 'system expansion'), in GHG emission accounting a combination of 'system expansion' and 'substitution' is used:

- For destinations with an existing demand market (like energy carriers, animal feed and materials) 'substitution' approach is chosen. GHG emissions associated to substituted materials (based on calculated substitution ratios[7]) are prevented are counted as net negative GHG emissions.
- For other destinations (mostly with negative economic value), like composting and land application of manure and digestate as a fertilizer, a consequential ('system expansion') approach is chosen. Described effects include, amongst others, carbon sequestration (carbon sink) and emissions of methane and nitrous oxide.

Considered effects per destination/processing pathway are presented in **Erreur ! Source du renvoi introuvable.**.

TABLE 7. CONSIDERED MAIN AND CO-PRODUCTS FOR A SUBSET OF THE PROCESSING/APPLICATION PATHWAYS ELABORATED IN CHAPTER 2

Destination/processing pathway	Considered effects on GHG emissions
Directly applied or left behind in the field	N in the material substitutes synthetic fertilizer, where the substitution ratio is based on a typical utilization rate for N for the material.

[7] Ratio (substitution product) : (input material) in dry matter.

	a small fraction of N in the material is emitted as nitrogen dioxide. persistent organic matter: carbon sequestration.
Feed (dairy cattle, pigs, layer hens, broilers)	substitute common ingredients of animal feed (wheat + soybean meal); substitution ratio is based on estimated nutritional energy and protein content
Anaerobic digestion	energy use in anaerobic digestion and biogas upgrading produced bio-methane substitutes natural gas biogas slip results in methane emissions digestate is utilized as fertilizer: N in the material substitutes synthetic fertilizer, where the substitution ratio is based on a typical utilization rate for N from digestate. a small fraction of N in the digestate is emitted as nitrogen dioxide persistent organic matter: carbon sequestration
PHA production	produced PHA substitutes fossil plastics. use of energy and chemicals in the processing steps from feedstock up to PHA downstream processing (as shown in section 2.1). Remark: the actual result will strongly depend on the chosen processing pathways, as for instance shown by Rossi et al. (2022) for PHA downstream processing. As explained before, here prospective (optimized) factors are assumed. produced bio-methane from anaerobic digestion of the residue substitutes natural gas biogas slip results in methane emissions energy use in anaerobic digestion of the residue stream and biogas upgrading digestate is utilized as fertilizer: N in the material substitutes synthetic fertilizer, where the substitution ratio is based on a typical utilization rate for N from digestate. a small fraction of N in the digestate is emitted as nitrogen dioxide persistent organic matter: carbon sequestration
Alkaline protein extraction	extracted protein product substitutes food ingredient (soybean protein isolate and wheat starch); substitution ratio is based on estimated nutritional energy and protein content produced bio-methane from anaerobic digestion of the residue substitutes natural gas biogas slip results in methane emissions energy use in anaerobic digestion and biogas upgrading digestate is utilized as fertilizer: N in the material substitutes synthetic fertilizer, where the substitution ratio is based on a typical utilization rate for N from digestate. a small fraction of N in the digestate is emitted as nitrogen dioxide persistent organic matter: carbon sequestration
Rubisco protein extraction	food ingredient (protein product is assumed to substitute soybean protein isolate) produced bio-methane from anaerobic digestion of the residue substitutes natural gas biogas slip results in methane emissions energy use in anaerobic digestion and biogas upgrading digestate (utilized as fertilizer)
Enzymatic protein extraction, combined with fermentative ethanol production	extracted protein product substitutes food ingredient (soybean protein isolate and wheat starch); substitution ratio is based on estimated nutritional energy and protein content the residue is fermented for bio-ethanol production, which substitutes petrol the residue from fermentation is used as feed for livestock: substitute common ingredients of animal feed (wheat + soybean meal); substitution ratio is based on estimated nutritional energy and protein content

As for the indicator of 'degree of circularity', all factors are average/typical and for a few indicative; specific technology options may result in some deviations between the early estimates of yields, emissions and actual use of inputs. Furthermore, considering that transport intensity is very situation-specific, GHG emission effects due to transport are not described in the method. For a selection of destinations specific factors (for energy use, GHG emission intensities of substituted materials and for emissions of other greenhouse gases) are given in Annex 5.

4 Comparisons of estimated environmental impact of selected valorisation pathways

In this chapter early estimates of environmental performance (in terms of 'degree of circularity' and 'effect on GHG emissions') are presented based on the methodology introduced in chapter 3.

> Note: the method estimates the effect, assuming that the pathway is technically feasible and that yields are not hindered by physical material characteristics. Results for destinations that are considered practically unrealistic may be neglected.

Below, detailed results for a few residue-stream – destination combinations are presented. Next, in section 4.2 overall results for all residue streams in scope to a selection of destinations are discussed.

4.1 Detailed results for a few residue-stream – destination combinations

Below, early estimates of environmental impact of different valorisation pathways for three residue streams are compared (based on updated metrics compared to the results presented in Agriloop deliverable D1.5). Of the large set of residue streams in scope, brewers' spent grain, grey starch and rice bran are elaborated because of the relatively high protein content in the first, the high (and rather pure) starch carbohydrate content in the second and rather blended composition of the third material. Furthermore, potential valorisation options of sugar beet leaves are considered because of recent interest.

> The set of analyses partly overlaps with those presented in Agriloop deliverable D1.5. However, refinements of the destinations' processing pathways models and adjustments of factors have been accomplished as described in chapter 3, next to actualisations of emission factors for energy. Accordingly, below more details and updated results are presented based on actual insights.

Table 8, Table 9 and Table 11 present calculated detailed results in terms of reduction of greenhouse gas emissions and degree of circularity related to residue valorisation pathways for brewers' spent grain, grey starch and rice bran, respectively.

TABLE 8. SYNERGIES BETWEEN REDUCTION OF GREENHOUSE GAS EMISSIONS (KG CO_2-EQ. PER KG DRY MATTER VALORISED RESIDUE) AND DEGREE OF CIRCULARITY RELATED TO RESIDUE VALORISATION PATHWAYS FOR BREWERS' SPENT GRAIN.

Product & co-products	Associated net GHG emissions savings	Degree of circularity	GHG emissions savings	Degree of circularity
			Benefit relative to Reference application	
Reference application: feed for cattle				
Food (GHGe effect: subst. feed)	1.19	20%		
Manure: N		7%		
TOTAL	**1.19**	**27%**		
PHA production				
PHA	0.81	7%		
Bio-methane	0.37	4%		
Methane slip	-0.06			
Digestate: N fertilizer	0.12	6%		
Digestate: N_2O emissions	-0.07			
Carbon sequestration	0.12			
Energy use in PHA process	-0.29			

Energy use in digestion + gas upgr.	-0.06			
TOTAL	**0.94**	**17%**	**-0.25**	**-10%**
Enzymatic extraction of protein and bioethanol				
Food (protein product)	2.00	44%		
Bioethanol	0.92	4%		
Food (from cattle, substitute feed)	0.28	7%		
Manure: N		1%		
Energy/inputs: protein extraction	-0.61			
Energy: ethanol fermentation	-0.45			
TOTAL	**2.15**	**56%**	**0.96**	**29%**
Microbial protein production for fish feed				
Food (fish)	0.88	11%		
Bio-methane	0.28	3%		
Methane slip	-0.05			
Energy/inputs: MP production	-0.26			
Energy: waste water tr.; gas upgr.	-0.10			
TOTAL	**0.75**	**14%**	**-0.44**	**-13%**

Table 8, comparing environmental performance of different valorisation pathways for brewer's spent grain, shows that for this residue stream PHA production is not a beneficial option compared to the current common use (animal feed). This can be explained by the fact that in the PHA destination the relatively high protein content of the residue stream is poorly valorised.

A biorefinery pathway (protein extraction combined with bioethanol production, from which the residue is utilized as animal feed) seems more environmental beneficial than the current use. This is consistently concluded from both sustainability indicators. In this pathway the estimated impact of energy and processing inputs use is quite substantial; however these emissions are compensated by substantial environmental benefits of residue-derived food proteins and bioethanol.

> Note: practical relevancy of this pathway may be limited because protein rich fractions can be more easily obtained from grain fractionation.

The valorisation via microbial protein production and fish feed is (logically) less beneficial: little amount of carbohydrates is available for conversion to proteins; not all proteins end in the MP product. This results in reduced protein yield to feed compared to direct feeding.

TABLE 9. SYNERGIES BETWEEN REDUCTION OF GREENHOUSE GAS EMISSIONS (KG CO_2-EQ. PER KG DRY MATTER VALORISED RESIDUE) AND DEGREE OF CIRCULARITY RELATED TO RESIDUE VALORISATION PATHWAYS FOR GREY STARCH.

Product & co-products	Associated net GHG emissions savings	Degree of circularity	GHG emissions savings	Degree of circularity
			Benefit relative to Reference application	
Reference application: feed for cattle				
Food (GHGe effect: subst. feed)	0.48	26%		
Manure: N		3%		
TOTAL	**0.48**	**29%**		
PHA production				
PHA	1.37	20%		
Bio-methane	0.10	2%		
Methane slip	-0.02			
Digestate: N fertilizer	0.03	2%		
Digestate: N_2O emissions	-0.02			
Carbon sequestration	0.01			
Energy use in PHA process	-0.49			
Energy use in digestion + gas upgr.	-0.05			

TOTAL	**0.95**	**24%**	**0.47**	**-5%**
Enzymatic extraction of protein and bioethanol				
Food (protein product)	0.51	18%		
Bioethanol	0.47	3%		
Food (from cattle, substitute feed)	0.06	1%		
Manure: N		1%		
Energy/inputs: protein extraction	-0.61			
Energy: ethanol fermentation	-0.45			
TOTAL	**-0.02**	**23%**	**-0.50**	**-6%**
Microbial protein production for fish feed				
Food (fish)	0.94	19%		
Bio-methane	0.17	3%		
Methane slip	-0.03			
Energy/inputs: MP production	-0.34			
Energy: waste water tr.; gas upgr.	-0.09			
TOTAL	**0.65**	**22%**	**0.17**	**-7%**

For 'grey starch' – characterized by a relatively high starch content – destinations in which starch is converted to highly appreciated product (like PHA or proteins) are quite beneficial in terms of GHG emission reduction. This is due to the relatively high GHG emission intensity of substituted products, compared to the 'energy' crop substitution when used as animal feed. Because of the limited yields to final products, these alternative destinations score lower than direct use as animal feed.

The (hypothetic) pathway including protein extraction for food scores less beneficial. This is a (logical) consequence of the low protein content of the material.

TABLE 10. SYNERGIES BETWEEN REDUCTION OF GREENHOUSE GAS EMISSIONS (KG CO_2-EQ. PER KG DRY MATTER VALORISED RESIDUE) AND DEGREE OF CIRCULARITY RELATED TO RESIDUE VALORISATION PATHWAYS FOR RICE BRAN.

Product & co-products	Associated net GHG emissions savings	Degree of circularity	GHG emissions savings	Degree of circularity
			Benefit relative to Reference application	
Reference application: feed for cattle				
Food (GHGe effect: subst. feed)	0.72	22%		
Manure: N		4%		
TOTAL	**0.72**	**26%**		
PHA production				
PHA	1.16	13%		
Bio-methane	0.20	3%		
Methane slip	-0.03			
Digestate: N fertilizer	0.06	3%		
Digestate: N_2O emissions	-0.04			
Carbon sequestration	0.09			
Energy use in PHA process	-0.42			
Energy use in digestion + gas upgr.	-0.05			
TOTAL	**0.98**	**19%**	**0.26**	**-7%**
Enzymatic extraction of protein and bioethanol				
Food (protein product)	1.01	27%		
Bioethanol	0.62	3%		
Food (from cattle, substitute feed)	0.20	9%		
Manure: N		1%		
Energy/inputs: protein extraction	-0.61			
Energy: ethanol fermentation	-0.45			
TOTAL	**0.77**	**39%**	**0.05**	**13%**
Microbial protein production for fish feed				
Food (fish)	0.72	11%		
Bio-methane	0.21	3%		
Methane slip	-0.03			
Energy/inputs: MP production	-0.27			
Energy: waste water tr.; gas upgr.	-0.09			

TOTAL	**0.54**	**14%**	**-0.18**	**-12%**

Apparently, for this product the destination *enzymatic extraction of protein and bioethanol* scores best on degree of circularity. This is due to the relatively high appreciation of food.

In terms of GHG emission effect, PHA production is the preferred destination. This is due to the rather high yield to PHA and high GHG emission intensity of substituted plastic.

As final example, potential destinations of sugar beet leaves are compared (Table 11) because this stream is often considered a promising, underexploited residue stream. Currently this stream is largely left behind in the field (from which nutrients and organic matter contribute to soil health). An obvious alternative to the current destination is feed for cattle. This option seems beneficial compared to the current destination in terms of circularity as well as in terms of GHG emissions effect (Table 11). This option was practiced in the past, but was largely discontinued because of practical (handling) issues and effects on milk attributes.

Another option that is considered promising, extraction of Rubisco protein, scores higher on both environmental indicators compared to the reference destination. However, the benefit on GHG emission is small (due to relatively high impact of energy use in the extraction process) and may become negative if GHG emissions of harvest/collection and transport would be included.

Finally, also the option of enzymatic protein extraction is presented in the table. This option seems more beneficial in terms of environmental benefits, but may be hindered by hurdles in appreciation of the food proteins by consumers, short seasonal availability of the fresh residue and challenging collection logistics.

TABLE 11. SYNERGIES BETWEEN REDUCTION OF GREENHOUSE GAS EMISSIONS (KG CO_2-EQ. PER KG DRY MATTER VALORISED RESIDUE) AND DEGREE OF CIRCULARITY RELATED TO RESIDUE VALORISATION PATHWAYS FOR SUGAR BEET LEAVES.

Product & co-products	Associated net GHG emissions savings	Degree of circularity	GHG emissions savings	Degree of circularity
			Benefit relative to Reference application	
Reference application: left behind in the field/soil				
Fertilizer: N	0.08	4%		
Carbon sequestration	0.18			
N_2O emissions	-0.13			
TOTAL	**0.13**	**4%**		
Feed for cattle				
Food	0.96	20%		
Manure: N		6%		
TOTAL	**0.96**	**26%**	**0.83**	**22%**
Rubisco protein production				
Food (Rubisco protein product)	0.59	25%		
Biomethane	0.57	7%		
Methane slip	-0.09			
Digestate: N fertilizer	0.13	7%		
Digestate: N_2O emissions	-0.08			
Carbon sequestration	0.11			
Energy use in protein extraction	-0.94			
Energy use in digestion + gas upgr.	-0.06			
TOTAL	**0.22**	**38%**	**0.09**	**26%**
Enzymatic production of protein and bioethanol				
Food (protein product)	1.56	40%		
Bioethanol	0.66	3%		

Food (via cattle)	0.19	4%		
Manure: N		1%		
Energy/inputs: protein extraction	-0.61			
Energy: ethanol fermentation	-0.45			
TOTAL	**1.35**	**48%**	**1.22**	**35%**

Some observations based on above case studies:

The priority ranking of destinations in terms of environmental benefit for agri-residues varies amongst residue streams, dependent on their chemical composition. Rigid rankings (like in food waste hierarchy) neglect specific functionalities of ingredients in destinations.

Although the use of a residue stream is considered sustainable, an intensive processing process can have a relatively large negative impact on the environmental sustainability of the processing route/application. When making choices regarding the processing route, the impact of the (process) chain must also be taken into account.

Utilization of a side-stream generated in a destination pathway may substantially contribute to net environmental benefit of the destination. In process development – next to 'optimizing' yield to the main intended product – also the potential valorisation of side-streams should be taken in consideration.

4.2 Net results for all residue streams

Net scores for 'degree of circularity' and 'effect on GHG emissions' for all residue streams in scope to a selection of destinations are provided in Annex 6 of this deliverable. Some reflections on these results:

- Preferences by the 'food waste hierarchy' (from high to low preference: food – animal feed – anaerobic digestion – composting) are largely confirmed in the results for degree of circularity and GHG emission effect.

  Example: Alkaline protein extraction for most residues streams seems to score better than animal feed (direct use as feed as well as via microbial proteins). This is due to the fact that extracted proteins are considered food ingredient, whereas yield to food via feed has limited efficiency.

  Adding an extra cascade step contributes to increasing degree of circularity if the material is highly functional in the extra cascade step. E.g. PHA production prior to anaerobic digestion has higher degree of circularity than direct anaerobic digestion for materials with high content of simple carbohydrates like grey starch and molasses.

  In terms of GHG emission effects, for all materials that provide significant yield to PHA and have low content of hemicellulose the extra cascade step of PHA production seems beneficial. This is also observed for a residue stream that may commonly be anaerobically co-digested (like surplus maize silage; in scope of AgriLoop WP4): adding a PHA production step prior to anaerobic digestion adds to total degree of circularity as well as GHG emission reduction.

- Pathways that include substantial production of PHA and bioenergy (e.g. alkaline protein extraction and bioethanol fermentation) deliver relatively high GHG emission reduction. This is due to the relatively high conversion yield to the simple biomolecules, combined with relatively high GHG emission intensity of fossil energy carriers compared to plant-based substitution materials in other destinations.

- In general the pathway via MP (fish feeds) scores lower on environmental benefits than alkaline protein extraction. The latter benefits from direct use as food of extracted proteins, whereas the MP product contributes to food production via fish feed, which has a protein retention ratio << 1. This conclusion, however, overlooks that fish proteins is commonly higher appreciated in food than extracted plant-based proteins.

- For lignocellulose residue streams (straws and branches from trees) the environmental benefits of mushroom production seem rather small. However, practical yields (and consequentially environmental benefits) for presented destinations in Annex 6 are overrated by the early estimates for such materials because the most digestible are poorly accessible in these materials. More realistically, for these residue streams comparisons with destinations 'soil application' and 'composting' applies. In comparison with these destinations [8] mushroom production is substantially more beneficial in terms of degree of circularity, because of the more direct contribution to food production (whereas a significant fraction of the valuable contribution for the soil is retained in the spent mushroom substrate). This conclusion is (though less sizeable) confirmed in the effects on GHG emissions. This observation underpins the choices of such materials for mushroom production WP4.
In practice – e.g. button mushroom production – other residue-derived N sources are added (manure); from the combined (pre-processed) feedstock higher mushroom production yields are obtained than from the un-enriched residue stream. Because effects of such enrichments are very situation-specific, these are not described in the presented methodology.

- For all residue streams the destination 'cattle feed' scores higher than 'anaerobic digestion' on 'degree of circularity'. This is due to the methodological choice for lower appreciation of energy carriers relative to food (see section 3.1). However, the effects on GHG emission are less consistent: especially for protein-rich streams substantially higher GHG emissions savings are achieved through application as cattle feed compared to anaerobic digestion. This is due to the substantial higher climate impact factor for substituted protein-rich feed ingredient than for substituted energy-rich feed ingredient.

Comment: Estimated yields in mushroom production for some protein-rich streams (like brewer's yeast and peanut meal) are – based on assumed yield factors – very high. This due to the methodological assumption that protein

[8] Results for 'soil application' and 'composting' are not presented in this deliverable.

content in the substrate for mushroom production is limiting, which is not valid for such materials.

5 Conclusions and recommendations

In this report completed methodologies, heuristics and essential data were presented for early estimating potential yields and environmental performance of utilizing selected agro-residue streams for producing biopolymers, proteins and some other relevant products. The methodology combines:

- estimates of chemical composition (in terms of macro-nutrients) per residue stream;
- heuristics for estimating conversion/extraction yields to diverse biobased and protein products, including destinations of side-streams that are generated in the valorisation pathway, based on literature-derived yield factors for macro-nutrients;
- estimates of volumes of selected agri-residues streams in EU per country, UK and CN, from which (through the heuristics for conversion/extraction) the potential yields to selected products can be estimated;
- appreciation factors for different destinations, facilitating the comparison of 'degree of circularity' of potential uses/destinations per residue stream;
- further parameter factors for the valorisation pathways, including estimates of energy and other inputs as well as estimates of methane and nitrous oxide emissions, These factors are – including factors for substituting conventional materials through the residue-derived products - applied in heuristics for estimating GHG emissions of residue valorisation in described pathways.

> Remark: All early estimates are based on yield derived from various references. Whereas for common destinations, like anaerobic digestion, strong underpinning is available – newer destinations, like PHA and microbial proteins, are still subject of process development and optimisation. Consequently for those newer destinations limited underpinning is available, and the early estimates may be less accurate to what can be achieved in practice.
>
> For the 'new' pathways prospective factors were assumed (assuming, for instance, that the use of chemicals is at the lower end of reported values and that higher yield factors for diverse components can be combined in an application) considering that these destinations are still subject to substantial technological progress.

The methodology is an integration and extension of the work presented in Broeze et al. (2024) (yield factors for common destinations) and Agriloop deliverable D1.5 (which enriched Broeze et al.'s approach with amongst others biopolymer production pathways and added a draft approach for estimating GHG emission effects). Compared to this earlier work, diverse extraction and conversion factors were updated based on further underpinning from recent references; furthermore the descriptions of destination pathways were completed with other GHG emission effects.

The heuristics were elaborated in an excel-based calculator, which facilitates rapid assessments of valorisation pathways based on a residue-stream's composition. In order to make comparisons with common valorisation pathways (like feed or land application), also these reference application pathways are described in the method.

From the early estimates quantitative results the following generic conclusions were drawn:

- An adequate combination of material – processing pathway – product application is crucial for effective circular and environmental beneficial valorisation of a residue stream.

- Residue streams with relatively high content of simple carbohydrates seem most favourable for novel destinations (considered in this report: PHA and microbial proteins). Further development of these pathways, e.g. with improved or more dedicated microbial strains, may make them even more beneficial in terms of environmental performance.
  For streams with moderate to high contents of simple carbohydrates (including common substrates in anaerobic co-digestion), production of PHA can be considered extra cascading step prior to anaerobic digestion. This contributes to increasing resource use efficiency and reducing total GHG emissions.

  Remark: It is broadly recognized in the scientific domain that substituting fossil-derived by PHA is environmentally beneficial. However, that also counts for other products that can be generated from residue streams (like biomethane). The question remains which destination is most beneficial. In scientific literature comparisons of (environmental) performance for different biobased applications are rare. Identified references that do actually make such comparisons focus on one feedstock (e.g. Rossi et al., (2022) who concluded that for the organic fraction of solid municipal waste the destination PHA scores lower in GHG emission reduction than anaerobic digestion). The results presented in this deliverable show that conclusion may not be translated to all residue streams, but that the actually preferent destination (in terms of considered environmental performance) depends on characteristics of the residue stream.

- Although the use of a residue stream is commonly considered environmentally beneficial, energy use in intensive processing can have relatively large negative impact on the environmental sustainability of the processing route/application. When making choices regarding the processing route, the impact of the processing inputs and emissions must be taken into account.

- The environmental impact of a valorisation option can be significantly influenced by the possibilities and limitations for applications of processing residues. These potential applications should be included in the sustainability evaluation of alternative valorisation options. In the design of valorisation pathways potential cascading options should be maximally exploited.

PHA production can be considered an extra cascade step prior to anaerobic digestion. The extra cascade step is beneficial (in terms of environmental performance) if the substrate is functional for PHA production. (functional = with significant yield, substantial 'nutritional' value for the processes)

MP production can be considered 'upcycling'. Upcycling is beneficial (environmental performance) if the substrate has limited value in current destination and is functional protein production.

Based on above global conclusions for Agriloop work in WP3 and WP4 it is concluded/confirmed/recommended that:

- When designing biorefinery pathways the potential beneficial use of all fractions should be considered. For an intervention that benefits yield to the main (intended) product, the effect on yield and usability of side streams should be taken in account.
- Residue streams with high contents of simple carbohydrates, like grey starch and molasses, seem promising for microbial protein production.
- Based on the early assessments, also adding PHA production prior to anaerobic digestion is considered beneficial in terms of environmental performance, especially for such residue streams.
- In case of lacking demands for feed and biobased application, for lignocellulose residue streams mushroom production seems more (environmental) beneficial than soil application (direct or via composting).

The next step in developing more dedicated estimates of yields and environmental impact of biopolymer and protein production from residues is estimating parameters for the specific technology options and processing pathways explored in the technical research in the Agriloop project (Agriloop WPs 2, 3 and 4). For that, insights in processing steps (as explored in the technical research) must be translated to complete (biorefinery) processing pathways. Global understanding of the pathways – as described in this report – will facilitate the description of whole valorisation pathways including the elements that are beyond scope of the dedicated technical research activities.

Literature

Arapoglou, D., Varzakas, T., Vlyssides, A., & Israilides, C. J. W. M. (2010). Ethanol production from potato peel waste (PPW). Waste management, 30(10), 1898-1902.

Arya, S. S., Salve, A. R., & Chauhan, S. (2016). Peanuts as functional food: a review. Journal of food science and technology, 53(1), 31-41.

Bastos, J.; F. Monforti-Ferrario; G. Melica (2024): GHG Emission Factors for Local Energy Use. European Commission, Joint Research Centre (JRC) [Dataset] PID: http://data.europa.eu/89h/72fac2b2-aa63-4dc1-ade3-4e56b37e4b7c

Bos, H.L. & J.P.M. Sanders (2013) Raw material demand and sourcing options for the development of a bio-based chemical industry in Europe. Part 1: Estimation of maximum demand, Biofuels, Bioprod. Bioref. 7:246–259, DOI: 10.1002/bbb.1388.

Burniol-Figols, A., C. Varrone, S.B. Le, A.E. Daugaard, I.V. Skiadas, H.N. Gavala (2018) Combined polyhydroxyalkanoates (PHA) and 1,3-propanediol production from crude glycerol: Selective conversion of volatile fatty acids into PHA by mixed microbial consortia, Water Research, Vol. 136, pp. 180-191, https://doi.org/10.1016/j.watres.2018.02.029.

Broeze, J.; W. Elbersen; J. Voogt; H. Soethoudt (2024) Circulariteit van reststroombenutting. Wageningen Food & Biobased Research, Report 2584. DOI: 10.18174/672425. https://edepot.wur.nl/672425.

Bruggen, C. van, A. Bannink, A. Bleeker, D.W. Bussink, H.J.C. van Dooren, C.M. Groenestein, J.F.M. Huijsmans, J. Kros, L.A. Lagerwerf, K. Oltmer, M.B.H. Ros, M.W. van Schijndel, L. Schulte-Uebbing, G.L. Velthof en T.C. van der Zee (2023). Emissies naar lucht uit de landbouw berekend met NEMA voor 1990-2021. Wageningen, WOT Natuur & Milieu, WOt-technical report 242.

Carré, P.; Quinsac, A.; Citeau, M.; Fine, F., 2015. A re-examination of the technical feasibility and economic viability of rapeseed dehulling. OCL, 22(3) D304

Casa, M., Miccio, M., De Feo, G., Paulillo, A., Chirone, R., Paulillo, D., ... & Chirone, R. (2021). A brief overview on valorization of industrial tomato by-products using the biorefinery cascade approach. Detritus, (15), 31-39.

CLO (2025). Stroomschema voor stikstof en fosfor in de landbouw, 2023 (indicator 0094, versie 24, 11 maart 2025), www.clo.nl. Centraal Bureau voor de Statistiek (CBS), Den Haag; PBL Planbureau voor de Leefomgeving, Den Haag; RIVM Rijksinstituut voor Volksgezondheid en Milieu, Bilthoven; en Wageningen University and Research, Wageningen. https://www.clo.nl/indicatoren/nl009424-stroomschema-voor-stikstof-en-fosfor-in-de-landbouw-2023 (accessed 4 June 2025).

Cosun (2019) Protein from beet leaves (in Dutch), Cosun Magazine, 6, p. 2.

CVB (2023) CVB Feed Table 2023. Chemical composition and nutritional values of feedstuffs, Stichting CVB, The Netherlands, https://www.cvbdiervoeding.nl/bestand/10901/cvb-feed-table-20232.pdf.ashx, accessed 28 February, 2024.

Del Valle, M., CÃ¡mara, M., & Torija, M. E. (2006, June). The nutritional and functional potential of tomato by-products. In X International Symposium on the Processing Tomato 758 (pp. 165-172).

Duong, T.H., M. van Eekert, K. Grolle, T.T.V. Nga, G. Zeeman, H. Temmink (2021) Effect of solid retention time (SRT) on protein hydrolysis and acidogenesis at pH 5 and pH 7 using gelatine as a model protein, Journal of Water Process Engineering, Vol. 44, 102398, https://doi.org/10.1016/j.jwpe.2021.102398.

EC (2020) Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions 'A new circular economy action plan for a cleaner and more competitive Europe', COM(2020)/ 2020/98 final, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2020:98:FIN (accessed 18 October 2024).

Elbersen, W., B. Janssens & J. Koppejan, 2011, De beschikbaarheid van biomassa voor energie in de agro-industrie (in Dutch), Wageningen UR Food & Biobased Research, Report 1200.

ETC WMGE (2021) Greenhouse gas emissions and natural capital implications of plastics (including biobased plastics), European Topic Centre Waste and Materials in a Green Economy, I. Vanderreydt, T Rommens, A Tenhunen (authors), https://www.eionet.europa.eu/etcs/etc-wmge/products/etc-wmge-reports/greenhouse-gas-emissions-and-natural-capital-implications-of-plastics-including-biobased-plastics (accessed 2022-04-01).

Eubia (2022) https://www.eubia.org/cms/wiki-biomass/biofuels/bioethanol/, accessed 7 December 2022.

European Parliament Council, 2008. Directive 2008/1/EC of the European Parliament and of the Council of 15 January 2008 Concerning Integrated Pollution Prevention and Control. Brussels.

Eurostat. (2023). Annual crop statistics. Handbook. 2023 Edition. Crop statistics working group. European Commission, Brussels, Belgium.

FAO. Crops and livestock products. License: CC BY-NC-SA 3.0 IGO. Extracted from: https://www.fao.org/faostat/en/#data/QCL. Data of Access: 21-07-2023.

Fillaudeau L, Blanpain-Avet P, Daufin G (2006). Water, wastewater and waste management in brewing industries. J. Cleaner Production, 14:463-471.

Fischer, G.; Prieler, S.; van Velthuizen, H.; Berndes, G.; Faaij, A.; Londo, M.; de Wit, M. Biofuel production potentials in Europe: Sustainable use of cultivated land and pastures, Part II: Land use scenarios. Biomass Bioenergy 2010, 34, 173–187.

Fischer, G.; Hizsnyik, E.; Prieler, S.; Shah, M.; van Velthuizen, H. Biofuels and Food Security. OFID Study Prepared by IIASA; IIASA—Intenational Institute for Applied Systems Analysis: Vienna, Austria, 2009.

Fischer, G.; Hizsnyik, E.; Prieler, S.; van Velthuizen, H. Assessment of Biomass Potentials for Biofuel Feedstock Production in Europe: Methodology and Results; IIASA—International Institute for Applied Systems Analysis, 2007. Available online: https://ec.europa.eu/energy/intelligent/projects/sites/iee-projects/files/projects/documents/refuel_assessment_of_biomass_potentials.pdf (accessed on 28 February 2019).

Fry, J.P.; Mailloux, M.A.; Love, D.C.; Milli, M.C.; Cao, L. (2018) Feed conversion efficiency in aquaculture: do we measure it correctly?, Environ. Res. Lett. 13 024017, doi 10.1088/1748-9326/aaa273

Fujihara, S., Kasuga, A., Aoyagi, Y. and Sugahara, T. (1995), Nitrogen-to-Protein Conversion Factors for Some Common Edible Mushrooms. Journal of Food Science, 60: 1045-1047. https://doi.org/10.1111/j.1365-2621.1995.tb06289.x

García-Condado S, López-Lozano R, Panarello L, et al. (2019) Assessing lignocellulosic biomass production from crop residues in the European Union: Modelling, analysis of the current scenario and drivers of interannual variability. GCB Bioenergy. 11:809–831. https://doi.org/10.1111/gcbb.12604

García-Galindo, D.; Dyjakon, A.; Cay Villa-Ceballos, F. Building Variable Productivity Ratios for Improving Large Scale Spatially Explicit Pruning Biomass Assessments. Energies 2019, 12, 957. https://doi.org/10.3390/en12050957

GFLI (2022) GFLI 2.0 feed database, www.globalfeedlca.org (accessed 2023-02-22).

Golkowska, K. & M. Greger (2013) Anaerobic digestion of maize and cellulose under thermophilic and mesophilic conditions – A case study, Biomass and Bioenergy 56, 545-554

Grimm D, Sonntag E, Rahmann G. 2024. Oyster mushroom cultivation on cereal and legume straw of poor feed quality. Studies in Fungi 9: e010, https://doi.org/10.48130/sif-0024-0010

Harmsen, P., Lips, S., Bos, H., Smit, B., Van Berkum, S., Helming, J., & Jongeneel, R. (2014). Suiker als grondstof voor de Nederlandse chemische industrie: gewassen, processen, beleid (in Dutch) Wageningen UR Food & Biobased Research Report 1494. https://doi.org/10.13140/RG.2.1.2296.9441

Hijbeek, R., van Ittersum, M., ten Berge, H. et al. Do organic inputs matter – a meta-analysis of additional yield effects for arable crops in Europe. Plant Soil 411, 293–303 (2017), https://doi.org/10.1007/s11104-016-3031-x

Huber, J. (2000), Towards industrial ecology: sustainable development as a concept of ecological modernization. J. Environ. Policy Plann., 2: 269-285. https://doi.org/10.1002/1522-7200(200010/12)2:4<269::AID-JEPP58>3.0.CO;2-UIfBB, 2025, Biopolymers facts and statistics 2024. IfBB Institute for bioplastics and biocomposites, https://www.ifbb-hannover.de/en/facts-and-statistics.html.

Iglesias, R.; Muñoz, R.; Polanco, M.; Díaz, I.; Susmozas, A.; Moreno, A.D.; Guirado, M.; Carreras, N.; Ballesteros, M. Biogas from Anaerobic Digestion as an Energy Vector: Current Upgrading Development. Energies 2021, 14, 2742. https://doi.org/10.3390/en14102742.

Koffi, B., Cerutti, A., Duerr, M., Iancu, A., Kona, A. and Janssens-Maenhout, G., Covenant of Mayors for Climate and Energy: Default emission factors for local emission inventories – Version 2017, EUR 28718 EN, Publications Office of the European Union, Luxembourg, 2017, ISBN 978-92-79-71479-5, doi:10.2760/290197, JRC107518.

Kumla, J.; Suwannarach, N.; Sujarit, K.; Penkhrue, W.; Kakumyan, P.; Jatuwong, K.; Vadthanarat, S.; Lumyong, S. (2020) Cultivation of Mushrooms and Their Lignocellulolytic Enzyme Production Through the Utilization of Agro-Industrial Waste. Molecules, 25, 2811. https://doi.org/10.3390/molecules25122811

Ladakis, D., Papapostolou, H., Vlysidis, A., & Koutinas, A. (2020). Inventory of food processing side streams in European Union and prospects for biorefinery development. In Food industry wastes (pp. 181-199). Academic Press.

Le Clef, E., T. Kemper (2015) 8 - Sunflower Seed Preparation and Oil Extraction, In: Editor(s): Enrique Martínez-Force, Nurhan Turgut Dunford, Joaquín J. Salas, Sunflower, AOCS Press, pp. 187-226, https://doi.org/10.1016/B978-1-893997-94-3.50014-3.

Li, W., H. Khalida, Z. Zhu, R. Zhang, G. Liu, C. Chen & E. Thorin (2018) Methane production through anaerobic digestion: Participation and digestion characteristics of cellulose, hemicellulose and lignin, Applied Energy, 226, 1219-1228.

Lijó, L.; González-García, S.; Bacenetti, J.; Fiala, M.; Feijoo, G.; Lema, J.M.; Moreira, M.T. (2014) Life Cycle Assessment of electricity production in Italy from anaerobic co-digestion of pig slurry and energy crops. Renew. Energy, 68, 625–635, http://dx.doi.org/10.1016/j.renene.2014.03.005.

Locker, C.K. (2021) Residual biomass utilisation in the potato and sugar beet processing industry: evaluation from a circular perspective, MSc Thesis Plant Production Systems, Wageningen University, https://edepot.wur.nl/559806 (accessed 2025-10-08).

Lopes, T. A. d. S., Queiroz, L. M., & Kiperstok, A. (2018). Environmental performance of a full-scale wastewater treatment plant applying life cycle assessment. Ambiente E Agua - An Interdisciplinary Journal of Applied Science, 13(4), 1. https://doi.org/10.4136/ambi-agua.2216

Lovett J., Bie F. Sustainable sourcing of feedstocks for bioplastics. Corbion, 2016.

Mathias, T., V. Alexandre, M. Cammarota, P. Mello & E. Servulo. (2015). Characterization and determination of brewer's solid wastes composition. Journal of the Institute of Brewing. 121. 10.1002/jib.229.

Molina-Alcaide, E., Moumen, A. and Martín-García, A.I. (2008), By-products from viticulture and the wine industry: potential as sources of nutrients for ruminants. J. Sci. Food Agric., 88: 597-604. https://doi.org/10.1002/jsfa.3123.

Nivtem (nd) Model Detailed Project Report, Groundnut Oil, https://uphorticulture.in/DPR/Fat%20and%20oil/Ground%20Nut%20Oil%20New.pdf (accessed 2024-10-07).

Nivtem (nda), Detailed project report groundnut oil unit under PMFME scheme, https://www.niftem.ac.in/site/pmfme/dprnew/peanutoildpr.pdf (accessed 2024-10-07).

Nova (2015) Definition, Calculation and Comparison of the "Biomass Utilization Efficiency (BUE)" of Various Bio-based Chemicals, Polymers and Fuels, Nova institute, paper #8 on bio-based economy 2015-11.

Olajire, A.A. (2020) The brewing industry and environmental challenges, Journal of Cleaner Production, Vol. 256, 102817, https://doi.org/10.1016/j.jclepro.2012.03.003.

Oldfield, E. E., Bradford, M. A., and Wood, S. A. (2019): Global meta-analysis of the relationship between soil organic matter and crop yields, SOIL, 5, 15–32, https://doi.org/10.5194/soil-5-15-2019.

Padilla-Rascón, C., E. Ruiz, I. Romero, E. Castro, J.M. Oliva, I. Ballesteros, P. Manzanares (2020) Valorisation of olive stone by-product for sugar production using a sequential acid/steam explosion pretreatment, Industrial Crops and Products, Volume 148, 112279, https://doi.org/10.1016/j.indcrop.2020.112279

Papargyropoulou, E., Lozano, R., Steinberger, J. K., Wright, N., bin Ujang, Z., (2014). The food waste hierarchy as a framework for the management of food surplus and food waste, Journal of Cleaner Production, Volume 76, Pages 106–115.

Rossi, E., F. Pasciucco, R. Iannelli, I. Pecorini (2022) Environmental impacts of dry anaerobic biorefineries in a Life Cycle Assessment (LCA) approach, Journal of Cleaner Production, Vol. 371, 133692, https://doi.org/10.1016/j.jclepro.2022.133692.

Rudolf, M., M. Schmidt, (2025) Efficiency, sufficiency and consistency in sustainable development: Reassessing strategies for reaching overarching goals, Ecological Economics, Volume 227, 108426, https://doi.org/10.1016/j.ecolecon.2024.108426.

Saavedra del Oso, M., Mauricio-Iglesias, M., Hospido, A., Steubing, B., 2023. Prospective LCA to provide environmental guidance for developing waste-to-PHA biorefineries. J. Clean. Prod. 383, 135331 https://doi.org/10.1016/J.JCLEPRO.2022.135331.

Sadhukhan, J., E. Martinez-Hernandez, M.A. Amezcua-Allieri, J. Aburto, J.A. Honorato S (2019) Economic and environmental impact evaluation of various biomass feedstock for bioethanol production and correlations to lignocellulosic composition, Bioresource Technology Reports, 7, 100230.

Scarlat, N., M. Martinov & J.-F. Dallemand (2010) Assessment of the availability of agricultural crop residues in the European Union: Potential and limitations for bioenergy use, Waste Management, 30, 1889–1897

Scarlat, N., F. Fahl, E. Lugato, F. Monforti-Ferrario, J.F. Dallemand, (2019) Integrated and spatially explicit assessment of sustainable crop residues potential in Europe, Biomass and Bioenergy, Volume 122, Pages 257-269.

Schröder, J.J., W. van Dijk (2019) Stikstofwerking van organische meststoffen en hun relatie met gebruiksnormen, Report WPR-916, Wageningen Research, Wageningen, The Netherlands, https://dio.org/10.18174/477978.

Selin Noren, I., Kooistra, K., van Geel, W., de Haan, J. (2022) Reference values for arable crop residues: organic matter and C:N ratio, Wageningen Research, Report WPR-OT 928. https://doi.org/10.18174/566378

Shalini, R. and Gupta, D.K. (2010) Utilization of Pomace from Apple Processing Industries: A Review. Journal of Food Science and Technology, 47, 365-371. https://doi.org/10.1007/s13197-010-0061-x

Shawky, E., W. Zhu, J. Tian (2025) A review of innovative extraction technologies for protein recovery from plant-based by-products: A step toward zero-waste processing, International Journal of Biological Macromolecules, Volume 315, Part 1, 144301, https://doi.org/10.1016/j.ijbiomac.2025.144301.

Spiller, M., M. Muys, G. Papini, M. Sakarika, M. Buyle, S.E. Vlaeminck (2020) Environmental impact of microbial protein from potato wastewater as feed ingredient: Comparative consequential life cycle assessment of three production systems and soybean meal, Water Research, Vol. 171, 115406, https://doi.org/10.1016/j.watres.2019.115406.

Teigiserova, D.A., L. Hamelin, M. Thomsen (2020) Towards transparent valorization of food surplus waste and loss: clarifying definitions food waste hierarchy and role in the circular economy, Sci. Total Environ., 706, Article 136033

Tian, Y., J. Li, J. Meng, J. Li (2023) High-yield production of single-cell protein from starch processing wastewater using co-cultivation of yeasts, Bioresource Technology, Vol. 370, 128527, https://doi.org/10.1016/j.biortech.2022.128527.

Turk, M. F., Vorobiev, E., & Baron, A. (2012). Improving apple juice expression and quality by pulsed electric field on an industrial scale. LWT-Food Science and Technology, 49(2), 245-250.

Vidovic, D., Marmier, A., Zore, L. and Moya, J., Greenhouse gas emission intensities of the steel, fertilisers, aluminium and cement industries in the EU and its main trading partners, Publications Office of the European Union, Luxembourg, 2023, doi:10.2760/359533, JRC134682.

Voudouris, P., A. Tamayo Tenorio, J.P. Lesschen, W.J. Mulder, K. Kyriakopoulou, J.P.M. Sanders, A.J. van der Goot, M.E. Bruins (2017) Sustainable Protein Technology : an evaluation on the STW Protein programme and an outlook for the future, Wageningen Food & Biobased Research, https://edepot.wur.nl/429443.

Vukušić, J. L., Millenautzki, T., Cieplik, R., Obst, V., Saaid, A. M., Clavijo, L., ... & Barbe, S. (2021). Reshaping apple juice production into a zero discharge biorefinery process. Waste and Biomass Valorization, 12(7), 3617-3627.

Vural Gursel, I, B. Elbersen, K.P.H. Meesters (2023) Monitoring circular biobased economy – Systematic review of circularity indicators at the micro level, Resources, Conservation and Recycling, Volume 197, 107104, https://doi.org/10.1016/j.resconrec.2023.107104.

Zee, T.C. van der, A. Bannink, C. van Bruggen, C.M. Groenestein, J.F.M. Huijsmans, J.W.H. van der Kolk, Lagerwerf, L.A., H.H. Luesink, G.L. Velthof & J. Vonk (2021). Methodology for estimating emissions from agriculture in the Netherlands. Calculations of CH4, NH3, N2O, NOx, NMVOC, PM10, PM2.5 and CO2 using the National Emission Model for Agriculture (NEMA) – update 2021. RIVM Report 2021-Voogt, J, W. Mulder & C. Safi (2021): Virtual Biorefinery, BRISK II deliverable 7.5.

Zotarelli, L., J.M. Scholberg, M.D. Dukes, R. Muñoz-Carpena, J. Icerman (2009) Tomato yield, biomass accumulation, root distribution and irrigation water use efficiency on a sandy soil, as affected by nitrogen rate and irrigation scheduling, Agricultural Water Management, Volume 96, Issue 1, pp. 23-34, https://doi.org/10.1016/j.agwat.2008.06.007.

Zwart, K., A. Pronk, L. Kater (2004) Extraction of crop residues from open field cultivation (in Dutch), PPO Praktijkonderzoek Plant & Omgeving, Wageningen UR, Lelystad, report 530133.

N°	Dataset name	Open Data	Closed Data	Means of dissemination	Maximum delay before access	Data set access
1	WP1.2_WR_JB	Estimates of volumes of agri-residues streams, their composition, potential yields to protein, biopolymers and other biobased products, estimated degree of circularity and GHG emission effects through application to destinations	-	Scientific and popularized publications, conferences, various dissemination and capacity-building events. Will be updated and enhanced with sustainability estimates in D1..6	Once published and at the latest 2 years after the end of the project	

Above 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	PR issues	Use of third-party	Restrictions on data sharing (Y/N)
1	WP1.2_WR_JB	WR	Jan Broeze	-	no	N

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

Annex 1. Chemical composition of selected agri-residues

TABLE 12. COLLECTED MACRO-NUTRIENT COMPOSITION AND FEEDING VALUE ESTIMATES OF SELECTED AGRI-RESIDUES (FROM AGRILOOP DELIVERABLE D1.5)

Residual stream	*DM content (g/kg)*	*Org. M (g/kg DM).*	*Ash (g/kg DM)*	*Protein (g/kg DM)*	*Lipids (g/kg DM)*	*Lignin (g/kg DM)*	*Cellulose (g/kg DM)*	*Hemi-cell. (g/kg DM)*	*Starch (g/kg DM)*	*Sugar (g/kg DM)*	*Others (g/kg DM)*
Wheat straw	907	931	69	45	15	76	471	270	17	16	21
Barley straw	909	925	75	38	14	65	418	322	10	12	46
Oat straw	896	921	79	39	16	69	402	292	12	32	60
Rye straw	920	923	77	41	14	90	413	276	10	12	67
Maize (corn) stover	296	932	68	68	18	56	340	303	10	12	125
Corn cobs (excl. grain)	915	964	36	44	6	63	400	315	107	0	29
Rice straw	928	819	181	42	14	48	376	267	10	12	50
Sunflower straw	898	883	117	73	14	66	390	250	10	12	68
Rapeseed straw	921	930	70	57	14	130	459	153	3	12	102
Tomato crop residues	563	945	55	46	17	171	189	121	10	12	379
Grape branches and leaves	563	945	55	46	17	171	189	121	10	12	379
Olive pruning leaves	501	910	90	98	-	201	140	120	-	-	351
Olive pruning branches	898	928	72	78	-	179	208	138	-	-	325
Potato crop residues	187	845	155	73	19	203	355	134	16	36	8
Sugar beet leaves	120	811	189	195	24	46	130	145	45	161	64
Sugar beet tops	279	859	141	116	13	55	155	137	18	76	87
Triticale straw	240	956	44	250	92	58	160	286	26	13	71
Broken rice	885	993	7	78	8	5	8	22	715	9	148
Discoloured rice	883	949	52	78	20	54	70	108	561	13	45
Unripe rice	883	949	52	78	20	54	70	108	561	13	45

Residual stream	DM content (g/kg)	Org. M (g/kg DM).	Ash (g/kg DM)	Protein (g/kg DM)	Lipids (g/kg DM)	Lignin (g/kg DM)	Cellulose (g/kg DM)	Hemi-cell. (g/kg DM)	Starch (g/kg DM)	Sugar (g/kg DM)	Others (g/kg DM)
Brewer's spent grain	240	956	44	250	92	58	160	286	26	13	71
Brewer's yeast	907	938	62	383	84	33	142	54	94	30	119
Rice husk	919	825	175	37	-	142	375	161	53	-	57
Rice bran	905	894	106	126	138	58	109	135	270	26	33
Rice bran, defatted	901	848	152	133	33	75	144	150	243	24	45
Olive pomace	885	920	80	123	42	244	179	127	-	43	162
Olive stones	879	973	27	172	304	-	-		21	-	476
Tomato pomace	935	948	52	210	119	254	189	106	-	-	70
Tomato skins	900	978	22	119	31	491	225	48	-	-	64
Grape pomace	397	922	79	148		298	148	116	18	142	52
Grape seeds	450	920	46	91	114	332	201	161	9		11
Potato peels	142	937	63	127	10	13	53	33	476	15	212
Potato pulp (starch industry)	156	947	53	95	2	49	113	170	208	11	300
Grey starch	380	955	45	104	13	-	-	-	590	27	222
Apple pomace	208	1111	25	68	42	157	185	109	-	62	352
Sugar beet pulp	248	923	77	82	8	9	220	251	10	53	290
Molasses	787	910	90	98	2	-	-	-	-	512	298
Defatted peanut meal (from mechanical extraction)	900	945	55	530	11	8	55	14	118	144	22
Defatted peanut meal (from solvent extraction)	920	933	67	489	16	14	49	77	110	134	33
Peanut meal	910	939	61	510	14	11	52	46	114	139	28
Peanut skins	913	961	39	164	199	128	186	75	175	33	2
Peanut hulls	916	948	52	70	20	224	340	100	0	0	194
Rice	885	993	7	78	8	5	8	22	715	9	148

Residual stream	DM content (g/kg)	Org. M (g/kg DM).	Ash (g/kg DM)	Protein (g/kg DM)	Lipids (g/kg DM)	Lignin (g/kg DM)	Cellulose (g/kg DM)	Hemi-cell. (g/kg DM)	Starch (g/kg DM)	Sugar (g/kg DM)	Others (g/kg DM)
DDGS from maize	903	956	44	268	125	35	84	169	29	17	229
DDGS from wheat	916	954	46	324	68	77	89	139	11	49	197

Annex 2. Estimated extraction and conversion yields to biopolymers and proteins

Table 13. Estimates of yields from selected agri-residue streams to biobased products and proteins (kg product per ton dry matter)

	Bio-methane	Bio-ethanol (incl. hydrolysis)	Bio-ethanol (first generation)	Bio-diesel	PHA	Bio-PE	Bio-PET	PLA	Protein extraction based on hydrolysis	Rubisco protein extraction	Microbial proteins (crude proteins in MP product)	Mushroom production (protein yield)
Apple pomace	192.0	279.7	130.0	37.8	128.9	18.6	22.0	45.9	47.6	20.4	64.8	16.3
Barley straw	168.0	284.8	23.9	12.6	36.1	6.3	7.4	15.5	26.6	11.4	33.4	9.1
Brewer's spent grain	234.6	212.0	39.1	82.8	166.1	10.7	12.7	26.5	175.2	75.1	196.3	60.1
Brewer's yeast	281.1	209.7	159.7	75.6	271.4	34.4	40.6	84.8	267.8	114.8	314.4	91.8
Broken rice	255.6	436.1	403.6	7.2	291.0	195.8	231.4	482.9	54.6	23.4	219.2	18.7
DDGS from maize	262.4	213.1	87.4	112.5	225.2	12.9	15.3	31.9	187.6	80.4	211.2	64.3
DDGS from wheat	242.1	196.0	85.4	61.2	195.8	17.7	20.9	43.6	226.8	97.2	256.3	77.8
Discoloured rice	226.1	370.2	299.7	18.0	233.6	155.4	183.7	383.2	54.6	23.4	185.9	18.7
Grape branches and leaves	168.8	277.2	117.5	15.3	96.1	6.3	7.4	15.5	32.2	13.8	39.4	11.0
Grape pomace	148.6	192.6	94.6	0.0	99.5	47.4	56.1	117.0	103.5	44.4	146.4	35.5
Grape seeds	163.0	134.1	7.7	102.6	118.2	2.5	3.0	6.3	63.4	27.2	70.1	21.7
Grey starch	246.7	431.9	400.5	3.4	281.7	196.5	232.3	484.7	44.6	19.1	209.0	15.3
Maize (corn) stover	178.9	287.3	46.1	16.2	60.9	6.3	7.4	15.5	47.6	20.4	55.9	16.3
Molasses	231.4	382.7	339.8	1.8	233.5	153.6	181.6	378.9	68.6	29.4	187.2	23.5
Oat straw	170.3	284.5	38.5	14.6	46.8	12.6	14.9	31.1	27.0	11.6	38.6	9.3
Olive pomace	165.4	194.9	67.0	37.8	107.2	12.9	15.2	31.8	86.1	36.9	101.8	29.5
Olive pruning branches	158.7	255.7	91.4	0.0	76.3	0.0	0.0	0.0	54.6	23.4	58.5	18.7
Olive pruning leaves	154.7	239.2	98.7	0.0	86.3	0.0	0.0	0.0	68.6	29.4	73.5	23.5
Olive stones	336.0	212.8	144.3	273.6	368.6	5.7	6.7	14.0	120.4	51.6	133.7	41.3
Peanut hulls	159.5	224.5	54.5	18.0	67.6	0.0	0.0	0.0	49.0	21.0	52.5	16.8
Peanut meal	264.7	172.0	134.2	12.2	239.7	72.5	85.7	178.8	356.7	152.9	438.3	122.3

Peanut skins	268.4	190.5	104.3	179.3	267.3	56.9	67.3	140.4	114.5	49.1	168.7	39.2
Potato crop residues	141.2	189.7	28.3	17.1	52.9	15.2	17.9	37.5	51.2	21.9	66.5	17.6
Potato peels	236.3	364.6	305.2	8.6	239.9	133.2	157.4	328.4	88.6	38.0	204.0	30.4
Potato pulp (starch industry)	202.8	338.7	193.9	1.9	150.4	59.5	70.3	146.7	66.6	28.5	119.9	22.8
Rapeseed hulls	210.6	159.3	45.2	118.8	176.2	24.0	28.4	59.2	112.7	48.3	139.8	38.6
Rapeseed meal	226.8	172.0	83.6	21.6	177.7	35.8	42.3	88.4	266.7	114.3	312.6	91.4
Rapeseed straw	167.5	249.8	36.2	12.6	48.6	4.4	5.2	10.9	39.9	17.1	46.1	13.7
Rice bran	244.9	248.5	157.1	124.0	243.8	80.6	95.3	198.9	88.4	37.9	160.3	30.3
Rice bran, defatted	193.0	256.2	146.4	29.7	158.0	72.9	86.2	179.8	92.9	39.8	158.8	31.8
Rice husk	137.5	227.6	42.5	0.0	37.5	14.3	16.9	35.3	25.9	11.1	39.5	8.9
Rice straw	153.5	251.9	25.1	12.6	38.0	6.3	7.4	15.5	29.4	12.6	36.4	10.1
Rye straw	165.7	273.8	29.8	12.6	40.5	6.3	7.4	15.5	28.7	12.3	35.6	9.8
Sugar beet leaves	193.3	227.2	120.8	21.9	148.3	60.3	71.3	148.9	136.6	58.5	192.0	46.8
Sugar beet pulp	192.6	321.2	113.0	7.2	97.0	18.6	22.0	45.9	57.4	24.6	75.5	19.7
Sunflower meal	205.3	186.4	56.9	0.0	126.4	18.3	21.6	45.1	226.8	97.2	256.5	77.8
Sunflower straw	168.0	257.1	30.1	12.6	49.8	6.3	7.4	15.5	51.1	21.9	59.6	17.5
Tomato crop residues	168.8	277.2	117.5	15.3	96.1	6.3	7.4	15.5	32.2	13.8	39.4	11.0
Tomato pomace	204.9	128.9	19.7	107.1	162.9	0.0	0.0	0.0	147.0	63.0	157.5	50.4
Tomato skins	122.8	113.9	18.0	27.9	68.4	0.0	0.0	0.0	83.3	35.7	89.3	28.6
Triticale straw	234.6	212.0	39.1	82.8	166.1	10.7	12.7	26.5	175.2	75.1	196.3	60.1
Unripe rice	226.1	370.2	299.7	18.0	233.6	155.4	183.7	383.2	54.6	23.4	185.9	18.7
Wheat straw	171.2	274.6	22.3	13.8	38.4	9.3	11.0	23.0	31.5	13.5	41.0	10.8

Annex 3. Estimated volumes of selected agri-residues streams per country

Estimations of volumes of selected agri-residues streams, as explained in chapter 2.7, are presented in below tables.

TABLE 14. ESTIMATED ANNUAL VOLUMES (TONNES) OF CROP RESIDUES FROM CEREALS INCLUDING RICE

	Wheat straw	Maize (corn) stover	Barley straw	Rye straw	Oat straw	Triticale straw	Rice straw
Total EU27	72,090,372	32,391,299	24,253,127	4,457,824	4,287,586	6,733,968	0
Belgium	750,923	193,505	120,260	1,894	8,457	16,030	0
Bulgaria	3,735,046	1,597,501	314,805	10,974	13,840	34,806	72,090
Croatia	483,242	997,214	139,185	1,176	31,990	24,507	0
Cyprus	20,007	0	15,018	0	201	983	0
Czechia	2,485,667	422,315	791,664	66,867	105,274	108,809	0
Denmark	1,891,070	20,486	1,548,379	334,309	167,778	23,441	0
Estonia	439,073	0	206,032	24,810	45,867	17,102	0
Finland	450,093	0	570,517	38,878	454,716	5,864	0
France	17,658,410	6,530,607	4,816,005	105,890	246,865	946,122	76,186
Germany	10,149,714	1,881,490	4,382,120	1,734,069	396,785	988,879	0
Greece	759,498	560,370	177,180	11,777	46,241	27,257	281,498
Hungary	2,720,106	2,985,012	734,246	50,197	42,141	159,488	12,618
Ireland	261,152	0	594,933	0	105,502	0	0
Italy	4,294,211	2,564,993	525,397	6,615	136,949	35,577	1,705,769
Latvia	1,384,376	0	115,686	78,639	106,901	15,916	0
Lithuania	2,438,871	48,969	256,142	40,376	101,548	143,735	0
Luxembourg	39,175	211	13,059	3,762	3,543	13,995	0
Malta	0	0	0	0	0	0	0
Netherlands	431,562	72,815	83,291	4,539	3,631	3,178	0
Norway	156,826	0	295,354	21,008	141,645	0	0

	Wheat straw	Maize (corn) stover	Barley straw	Rye straw	Oat straw	Triticale straw	Rice straw
Poland	6,558,276	3,292,016	1,446,927	1,467,016	892,091	3,164,396	0
Portugal	51,060	318,799	26,403	12,320	24,884	18,316	208,617
Romania	5,837,948	6,944,671	948,808	21,413	119,948	155,724	20,863
Slovenia	80,291	167,033	53,630	1,427	2,220	14,381	0
Slovakia	1,052,369	702,547	272,853	20,923	21,179	19,747	0
Spain	5,141,123	1,858,875	4,666,800	196,449	684,677	535,794	702,913
Sweden	1,517,272	6,512	524,752	73,642	299,001	83,309	0
United Kingdom	6,438,733	0	3,034,599	107,211	554,204	36,354	0
China	70,127,195	121,375,453	1,002,514	311,102	319,530	301,194	242,736,505

TABLE 15. ESTIMATED ANNUAL VOLUMES (TONNES) OF CROP RESIDUES FROM OTHER CROPS THAN CEREALS

	Olive pruning branches	Olive pruning leaves	Tomato crop residues	Grape branches and leaves	Sunflower straw	Rapeseed straw	Potato crop residues	Sugar beet leaves
Total EU27	6,872,072	754,252	809,862	9,048,058	7,584,883	7,937,062	7,799,558	4,256,161
Belgium	0	0	2,205	1,624	0	12,868	564,430	170,892
Bulgaria	0	0	10,745	82,737	1,457,549	181,141	39,221	0
Croatia	13,701	1,504	1,015	61,509	80,304	37,078	28,434	26,554
Cyprus	9,729	1,068	875	17,864	0	0	16,162	0
Czechia	0	0	910	47,444	34,487	488,289	110,096	155,684
Denmark	0	0	105	0	0	284,354	347,960	96,643
Estonia	0	0	35	0	0	105,534	12,305	0
Finland	0	0	315	0	0	24,726	93,840	15,135
France	15,819	1,736	21,665	2,197,707	1,303,248	1,521,760	1,315,064	1,290,730
Germany	0	0	1,400	292,059	69,683	1,595,239	1,641,746	1,199,837
Greece	0	0	45,990	260,536	161,080	5,466	61,535	1,080
Hungary	0	0	6,790	171,303	1,209,714	354,600	40,352	25,465
Ireland	0	0	35	0	0	21,474	58,510	0

	Olive pruning branches	Olive pruning leaves	Tomato crop residues	Grape branches and leaves	Sunflower straw	Rapeseed straw	Potato crop residues	Sugar beet leaves
Italy	1,303,342	143,050	357,210	2,037,743	204,757	26,055	223,940	56,741
Latvia	0	0	0	0	0	205,649	24,568	0
Lithuania	0	0	2,520	0	0	435,944	47,159	32,168
Luxembourg	0	0	0	3,567	230	2,162	2,791	0
Malta	11	1	0	1,334	0	0	1,719	0
Netherlands	0	0	6,475	551	0	2,085	979,966	246,235
Norway	0	0	137	0	0	4,019	58,913	0
Poland	0	0	26,950	2,900	24,354	1,442,973	1,152,517	573,671
Portugal	789,681	86,672	62,230	509,298	7,997	0	72,377	0
Romania	0	0	63,455	474,469	2,015,508	649,601	291,422	29,429
Slovenia	528	58	735	43,210	780	3,476	11,428	317
Slovakia	0	0	840	22,475	135,676	199,904	26,339	51,245
Spain	4,739,260	520,163	196,385	2,695,231	739,207	118,364	328,561	94,134
Sweden	0	0	140	261	0	159,940	128,108	76,868
United Kingdom	0	0	683	1,322	0	458,701	54,939,719	276,584
China	0	0	3,992,506	2,256,084	1,810,881	7,399,926	19,630,078	450,107

TABLE 16. ESTIMATED ANNUAL VOLUMES (TONNES) OF SECONDARY RESIDUES (1)

	DDGS from wheat	DDGS from maize	Brewer's spent grain	Brewer's yeast	Potato peels	Grey starch	Potato pulp (starch industry)	Sugar beet pulp	Molasses
Total EU27	1,637,362	3,188,895	1,284,214	82,111	127,516	17,787	126,293	4,834,067	2,320,352
Belgium	106,116	206,669	1,284,214	82,111	46,413	6,474	0	221,033	106,096
Bulgaria	32,719	63,723	17,417	1,114	41	6	0	0	0
Croatia	0	0	10,016	640	0	0	0	36,817	17,672
Cyprus	0	0	0	0	0	0	0	0	0
Czechia	34,311	66,823	71,865	4,595	0	0	1,943	197,000	94,560

	DDGS from wheat	DDGS from maize	Brewer's spent grain	Brewer's yeast	Potato peels	Grey starch	Potato pulp (starch industry)	Sugar beet pulp	Molasses
Denmark	0	0	20,650	1,320	25	3	25,022	117,117	56,216
Estonia	3,891	7,578	5,454	349	0	0	0	0	0
Finland	12,380	24,111	14,509	928	198	28	0	18,967	9,104
France	355,487	692,340	80,666	5,158	0	0	0	1,285,033	616,816
Germany	199,320	388,192	295,257	18,878	12,596	1757	41,646	1,362,100	653,808
Greece	5,306	10,333	17,974	1,149	0	0	0	1,417	680
Hungary	197,552	384,748	21,025	1,344	3	0	0	30,300	14,544
Ireland	1,769	3,444	6,261	400	0	0	0	0	0
Italy	26,706	52,012	61,408	3,926	43	6	194	70,083	33,640
Latvia	4,598	8,956	3,056	195	0	0	0	0	0
Lithuania	5,659	11,022	12,841	821	0	0	0	42,667	20,480
Luxembourg	0	0	0	0	0	0	0	0	0
Malta	0	0	0	0	0	0	0	0	0
Netherlands	132,644	258,336	97,347	6,224	40,636	5668	23,218	328,483	157,672
Norway	0	0	9,673	618	497	69	0	0	0
Poland	71,097	138,468	148,390	9,488	5,582	779	18,198	725,567	348,272
Portugal	531	1,033	29,040	1,857	41	6	0	0	0
Romania	2,122	4,133	66,143	4,229	0	0	0	27,467	13,184
Slovenia	0	0	0	0	0	0	0	0	0
Slovakia	38,025	74,056	7,149	457	0	0	53	56,817	27,272
Spain	105,585	205,635	142,254	9,096	7	1	0	93,733	44,992
Sweden	73,397	142,946	18,979	1,214	272	0	1,503	94,067	45,152
United Kingdom	182,165	354,781	1,470,160	94,000	9,873	1377	1,453	269,950	129,576
China	816,774	1,590,734	1,407,600	90,000	9,099	1269	40,487	340,000	163,200

TABLE 17. ESTIMATED ANNUAL VOLUMES (TONNES) OF SECONDARY RESIDUES (2)

	Rapeseed meal	Rapeseed hulls	Sunflower meal
Total EU27	7,443,398	3,932,874	3,895,308
Belgium	446,967	236,165	434
Bulgaria	21,975	11,611	809,546
Croatia	17,959	9,489	12,571
Cyprus	0	0	0
Czechia	360,073	190,252	0
Denmark	224,209	118,465	289
Estonia	50,977	26,935	0
Finland	44,842	23,693	0
France	1,398,907	739,141	617,953
Germany	3,058,610	1,616,080	73,506
Greece	5,354	2,829	62,269
Hungary	84,887	44,852	437,281
Ireland	10,151	5,363	0
Italy	20,971	11,080	104,350
Latvia	48,746	25,756	0
Lithuania	77,636	41,021	5,841
Luxembourg	0	0	0
Malta	0	0	0
Netherlands	0	0	0
Norway	3,458	1,827	0
Poland	1,004,812	530,914	0
Portugal	50,531	26,699	20,342
Romania	133,187	70,372	221,065
Slovenia	223	118	0
Slovakia	75,406	39,842	0
Spain	72,617	38,369	84,652

	Rapeseed meal	Rapeseed hulls	Sunflower meal
Sweden	113,889	60,176	0
United Kingdom	539,105	284,847	0
China	2,565,127	1,355,338	506,000

TABLE 18. ESTIMATED ANNUAL VOLUMES (TONNES) OF SECONDARY RESIDUES (3)

	Apple pomace	Olive pomace	Olive stones	Tomato skins	Tomato pomace (from juice)	Tomato pomace (from unconcentrated puree)	Tomato pomace (from concentrated puree)	Grape pomace	Grape seeds
Total EU27	197,938	510,175	259,602	7,607	997	9,998	27,053	340,160	101,730
Belgium	3,407	0	0	0	0	0	0	0	0
Bulgaria	623	0	0	10	0	10	122	1,598	478
Croatia	78	1,052	535	0	0	0	182	1,200	359
Cyprus	0	0	0	0	0	0	0	232	69
Czechia	1,059	0	0	0	0	16	27	1,227	367
Denmark	2,781	0	0	0	6	0	0	0	0
Estonia	152	0	0	0	16	0	0	0	0
Finland	1,615	0	0	0	0	0	0	0	0
France	14,756	1,383	704	41	96	333	246	94,921	28,388
Germany	66,930	0	0	1	172	0	0	18,299	5,473
Greece	626	73,269	37,283	173	0	193	1,085	4,459	1,334
Hungary	6,632	0	0	0	26	0	363	5,325	1,593
Ireland	0	0	0	0	0	0	0	0	0
Italy	9,694	89,417	45,500	6,291	54	7,766	7,424	106,663	31,899
Latvia	0	0	0	0	0	0	0	0	0
Lithuania	428	0	0	23	17	0	0	0	0
Luxembourg	0	0	0	0	0	0	0	184	55
Malta	0	0	0	0	0	0	0	32	9

	Apple pomace	Olive pomace	Olive stones	Tomato skins	Tomato pomace (from juice)	Tomato pomace (from unconcentrated puree)	Tomato pomace (from concentrated puree)	Grape pomace	Grape seeds
Netherlands	5,739	0	0	0	33	0	1	21	6
Norway	2,418	0	0	0	0	0	0	0	0
Poland	61,236	0	0	78	345	1	981	0	0
Portugal	914	48,227	24,540	84	0	1,074	6,501	13,818	4,133
Romania	901	0	0	4	0	22	302	8,323	2,489
Slovenia	0	149	76	0	0	0	0	1,169	350
Slovakia	0	0	0	0	0	0	0	709	212
Spain	12,635	295,805	150,520	896	39	729	9,386	76,571	22,900
Sweden	2,293	0	0	0	0	0	3	0	0
United Kingdom	18,000	0	0	0	0	0	0	0	0
China	0	0	0	8,346	1,094	10,969	29,680	6,848	2,048

TABLE 19. ESTIMATED ANNUAL VOLUMES (TONNES) OF SECONDARY RESIDUES (4)

	Peanut meal	Peanut skins	Rice husk	Rice bran	Rice bran, defatted
Total EU27	0	0	0	0	0
Belgium	12,533	213	0	0	0
Bulgaria	0	680	11,624	4,359	0
Croatia	0	400	0	0	0
Cyprus	0	0	0	0	0
Czechia	1,880	1,293	0	0	0
Denmark	1,880	547	0	0	0
Estonia	0	100	0	0	0
Finland	0	787	0	0	0
France	0	11,787	12,468	4,676	0
Germany	0	8,013	0	0	0

Greece	8,147	200	49,068	18,401	0
Hungary	0	187	1,904	714	0
Ireland	0	1,187	0	0	0
Italy	8,773	1,707	291,862	109,448	0
Latvia	0	107	0	0	0
Lithuania	0	187	0	0	0
Luxembourg	0	40	0	0	0
Malta	0	80	0	0	0
Netherlands	0	1,147	0	0	0
Norway	0	933	0	0	0
Poland	36,347	427	0	0	0
Portugal	6,267	240	35,180	13,193	0
Romania	0	1,307	2,996	1,124	0
Slovenia	0	213	0	0	0
Slovakia	0	333	0	0	0
Spain	0	3,587	123,436	46,289	0
Sweden	0	2,053	0	0	0
United Kingdom	0	7,827	0	0	0
China	6,016,000	409,693	42,372,000	15,889,500	2,880,000

Annex 4. Estimations of potential production volumes of selected products per country

TABLE 20. ESTIMATED PRODUCTION POTENTIAL OF SELECTED RESIDUAL STREAMS PER COUNTRY TO PHA (TONNES/Y) (1)

	Total EU27	Belgium	Bulgaria	Croatia	Cyprus	Czechia	Denmark	Estonia	Finland	France	Germany	Greece	Hungary	Ireland	Italy	Latvia
Apple pomace	25,514	439	80	10		137	358	20	208	1,902	8,627	81	855		1,250	
Barley straw	876,735	4,347	11,380	5,031	543	28,618	55,973	7,448	20,624	174,095	158,411	6,405	26,543	21,506	18,993	4,182
Brewer's spent grain	213,336	213,336	2,893	1,664		11,938	3,430	906	2,410	13,400	49,049	2,986	3,493	1,040	10,201	508
Brewer's yeast	22,283	22,283	302	174		1,247	358	95	252	1,400	5,123	312	365	109	1,065	53
DDGS from maize	718,056	46,536	14,349			15,047		1,706	5,429	155,897	87,411	2,327	86,635	776	11,712	2,017
DDGS from wheat	320,571	20,776	6,406			6,718		762	2,424	69,599	39,024	1,039	38,678	346	5,229	900
Grape branches and leaves	869,807	156	7,954	5,913	1,717	4,561				211,270	28,076	25,046	16,468		195,892	
Grape pomace	33,853		159	119	23	122				9,447	1,821	444	530		10,615	
Grape seeds	12,027		56	42	8	43				3,356	647	158	188		3,771	
Grey starch	5,011	1,824	2				1		8		495		0		2	
Maize (corn) stover	1,973,233	11,788	97,318	60,749		25,727	1,248			397,835	114,618	34,137	181,843		156,256	
Molasses	541,800	24,773		4,126		22,080	13,126		2,126	144,026	152,664	159	3,396		7,855	
Oat straw	200,853	396	648	1,499	9	4,932	7,860	2,149	21,301	11,564	18,588	2,166	1,974	4,942	6,415	5,008
Olive pomace	54,715			113						148		7,858			9,590	
Olive pruning branches	524,418			1,046	742					1,207					99,460	
Olive pruning leaves	65,122			130	92					150					12,351	
Olive stones	95,680			197						259		13,741			16,770	
Peanut meal		3,004				451	451					1,953			2,103	
Peanut skins		57	182	107		346	146	27	210	3,151	2,142	53	50	317	456	29
Potato crop residues	412,836	29,876	2,076	1,505	855	5,827	18,418	651	4,967	69,607	86,899	3,257	2,136	3,097	11,853	1,300
Potato peels	30,586	11,133	10				6		47		3,021		1		10	

	Total EU27	Belgium	Bulgaria	Croatia	Cyprus	Czechia	Denmark	Estonia	Finland	France	Germany	Greece	Hungary	Ireland	Italy	Latvia
Potato pulp (starch industry)	18,997					292	3,764				6,265				29	
Rapeseed hulls	692,908	41,608	2,046	1,672		33,519	20,872	4,745	4,174	130,225	284,727	498	7,902	945	1,952	4,538
Rapeseed meal	1,322,414	79,409	3,904	3,191		63,971	39,834	9,057	7,967	248,534	543,401	951	15,081	1,803	3,726	8,660
Rapeseed straw	385,587	625	8,800	1,801		23,721	13,814	5,127	1,201	73,928	77,498	266	17,227	1,043	1,266	9,991
Rice bran			1,063							1,140		4,487	174		26,686	
Rice bran, defatted																
Rice husk			436							467		1,839	71		10,937	
Rice straw			2,736							2,892		10,684	479		64,743	
Rye straw	180,535	77	444	48		2,708	13,539	1,005	1,575	4,288	70,227	477	2,033		268	3,185
Sugar beet leaves	631,096	25,340		3,937		23,085	14,330		2,244	191,387	177,910	160	3,776		8,413	
Sugar beet pulp	469,145	21,451		3,573		19,119	11,366		1,841	124,712	132,191	137	2,941		6,802	
Sunflower meal	492,517	55	102,358	1,589			37			78,133	9,294	7,873	55,289		13,194	
Sunflower straw	377,779		72,596	4,000		1,718				64,911	3,471	8,023	60,252		10,198	
Tomato crop residues	77,854	212	1,033	98	84	87	10	3	30	2,083	135	4,421	653	3	34,339	
Tomato pomace	6,198		21	30		7	1	3		110	28	208	63		2,483	
Tomato skins	520		1	0						3	0	12			430	
Triticale straw	1,118,661	2,663	5,782	4,071	163	18,076	3,894	2,841	974	157,172	164,275	4,528	26,494		5,910	2,644
Wheat straw	2,769,662	28,850	143,498	18,566	769	95,498	72,654	16,869	17,292	678,424	389,945	29,179	104,505	10,033	164,981	53,187

TABLE 21. ESTIMATED PRODUCTION POTENTIAL OF SELECTED RESIDUAL STREAMS PER COUNTRY TO PHA (TONNES/Y) (2)

	Lithuania	Luxembourg	Malta	Netherlands	Norway	Poland	Portugal	Romania	Slovenia	Slovakia	Spain	Sweden	United Kingdom	China
Apple pomace	55			740	312	7,893	118	116			1,629	296	2,320	
Barley straw	9,259	472		3,011	10,677	52,305	954	34,299	1,939	9,863	168,702	18,969	109,699	36,240
Brewer's spent grain	2,133			16,172	1,607	24,651	4,824	10,988		1,188	23,632	3,153	244,226	233,833
Brewer's yeast	223			1,689	168	2,575	504	1,148		124	2,468	329	25,509	24,423
DDGS from maize	2,482			58,170		31,179	233	931		16,676	46,304	32,188	79,887	358,192
DDGS from wheat	1,108			25,970		13,920	104	416		7,445	20,672	14,370	35,665	159,912
Grape branches and leaves		343	128	53		279	48,960	45,612	4,154	2,161	259,098	25	127	216,882
Grape pomace		18	3	2			1,375	828	116	71	7,620			682
Grape seeds		6	1	1			489	294	41	25	2,707			242
Grey starch				1,597	20	219	2				0	11	388	358
Maize (corn) stover	2,983	13		4,436		200,545	19,421	423,060	10,175	42,798	113,240	397		7,394,024
Molasses	4,782			36,816		81,321		3,078		6,368	10,506	10,543	30,256	38,107
Oat straw	4,757	166		170	6,635	41,790	1,166	5,619	104	992	32,074	14,007	25,962	14,968
Olive pomace							5,172		16		31,724			
Olive pruning branches			1				60,262		40		361,660			
Olive pruning leaves			0				7,483		5		44,911			
Olive stones							9,045		28		55,476			
Peanut meal						8,712	1,502							1,441,942
Peanut skins	50	11	21	307	249	114	64	349	57	89	959	549	2,092	109,515
Potato crop residues	2,496	148	91	51,870	3,118	61,004	3,831	15,425	605	1,394	17,391	6,781	2,907,999	1,039,034
Potato peels				9,747	119	1,339	10				2	65	2,368	2,182
Potato pulp (starch industry)				3,492		2,737				8		226	219	6,090
Rapeseed hulls	7,227				322	93,538	4,704	12,398	21	7,020	6,760	10,602	50,185	238,789
Rapeseed meal	13,793				614	178,518	8,977	23,662	40	13,397	12,901	20,234	95,779	455,727

	Lithuania	Luxembourg	Malta	Netherlands	Norway	Poland	Portugal	Romania	Slovenia	Slovakia	Spain	Sweden	United Kingdom	China
Rapeseed straw	21,178	105		101	195	70,100		31,558	169	9,711	5,750	7,770	22,284	359,493
Rice bran							3,217	274			11,286			3,874,283
Rice bran, defatted														455,087
Rice husk							1,318	112			4,626			1,587,879
Rice straw							7,918	792			26,679			9,213,193
Rye straw	1,635	152		184	851	59,412	499	867	58	847	7,956	2,982	4,342	12,599
Sugar beet leaves	4,770			36,511		85,063		4,364	47	7,598	13,958	11,398	41,011	66,741
Sugar beet pulp	4,141			31,879		70,416		2,666		5,514	9,097	9,129	26,199	32,997
Sunflower meal	739						2,572	27,951			10,703			63,978
Sunflower straw		11				1,213	398	100,386	39	6,758	36,818			90,194
Tomato crop residues	242			622	13	2,591	5,982	6,100	71	81	18,879	13	66	383,807
Tomato pomace	3			6		216	1,234	53			1,654	0		6,800
Tomato skins	2					5	6	0			61			571
Triticale straw	23,878	2,325		528		525,676	3,043	25,869	2,389	3,280	89,007	13,839	6,039	50,035
Wheat straw	93,700	1,505		16,580	6,025	251,964	1,962	224,290	3,085	40,431	197,518	58,293	247,372	2,694,238

TABLE 22. ESTIMATED PRODUCTION POTENTIAL OF SELECTED RESIDUAL STREAMS PER COUNTRY TO MICROBIAL PROTEINS (TONNES CRUDE PROTEIN IN MP, PER YEAR) (1)

	Total EU27	Belgium	Bulgaria	Croatia	Cyprus	Czechia	Denmark	Estonia	Finland	France	Germany	Greece	Hungary	Ireland	Italy
Apple pomace	12,819	221	40	5		69	180	10	105	956	4,335	41	430		628
Barley straw	809,666	4,015	10,509	4,647	501	26,429	51,691	6,878	19,046	160,778	146,293	5,915	24,512	19,861	17,540
Brewer's spent grain	252,040	252,040	3,418	1,966		14,104	4,053	1,070	2,848	15,832	57,947	3,528	4,126	1,229	12,052
Brewer's yeast	25,816	25,816	350	201		1,445	415	110	292	1,622	5,935	361	423	126	1,234
DDGS from maize	673,533	43,651	13,459			14,114		1,601	5,093	146,230	81,991	2,183	81,263	728	10,985
DDGS from wheat	419,689	27,200	8,387			8,795		997	3,173	91,118	51,090	1,360	50,636	453	6,845
Grape branches and leaves	356,349	64	3,259	2,422	704	1,869				86,554	11,502	10,261	6,747		80,254
Grape pomace	49,789		234	176	34	180				13,893	2,678	653	779		15,612
Grape seeds	7,127		33	25	5	26				1,989	383	93	112		2,235
Grey starch	3,717	1,353	1				1		6		367		0		1
Maize (corn) stover	1,810,155	10,814	89,275	55,728		23,601	1,145			364,956	105,145	31,316	166,814		143,342
Molasses	434,286	19,857		3,308		17,698	10,522		1,704	115,446	122,369	127	2,722		6,296
Oat straw	165,378	326	534	1,234	8	4,061	6,471	1,769	17,539	9,522	15,305	1,784	1,625	4,069	5,282
Olive pomace	51,934			107						141		7,458			9,102
Olive pruning branches	402,016			802	569					925					76,245
Olive pruning leaves	55,438			111	78					128					10,514
Olive stones	34,699			72						94		4,983			6,082
Peanut meal		5,493				824	824					3,571			3,845
Peanut skins		36	115	67		218	92	17	133	1,988	1,351	34	31	200	288
Potato crop residues	518,323	37,509	2,606	1,890	1,074	7,316	23,124	818	6,236	87,393	109,103	4,089	2,682	3,888	14,882
Potato peels	26,010	9,467	8				5		40		2,569		1		9
Potato pulp (starch industry)	15,147					233	3,001				4,995				23

	Total EU27	Belgium	Bulgaria	Croatia	Cyprus	Czechia	Denmark	Estonia	Finland	France	Germany	Greece	Hungary	Ireland	Italy
Rapeseed hulls	549,981	33,026	1,624	1,327		26,605	16,566	3,767	3,313	103,363	225,996	396	6,272	750	1,549
Rapeseed meal	2,326,895	139,727	6,870	5,614		112,563	70,090	15,936	14,018	437,315	956,158	1,674	26,537	3,173	6,556
Rapeseed straw	365,740	593	8,347	1,709		22,500	13,103	4,863	1,139	70,123	73,509	252	16,340	990	1,201
Rice bran			699							750		2,950	114		17,549
Rice bran, defatted															
Rice husk			459							493		1,939	75		11,533
Rice straw			2,623							2,772		10,242	459		62,063
Rye straw	158,850	67	391	42		2,383	11,913	884	1,385	3,773	61,792	420	1,789		236
Sugar beet leaves	817,093	32,808		5,098		29,888	18,553		2,906	247,793	230,343	207	4,889		10,893
Sugar beet pulp	364,904	16,685		2,779		14,871	8,841		1,432	97,002	102,819	107	2,287		5,290
Sunflower meal	999,310	111	207,683	3,225			74			158,531	18,857	15,975	112,181		26,770
Sunflower straw	452,317		86,920	4,789		2,057				77,718	4,155	9,606	72,140		12,210
Tomato crop residues	31,896	87	423	40	34	36	4	1	12	853	55	1,811	267	1	14,068
Tomato pomace	5,992		21	29		7	1	2		106	27	201	61		2,401
Tomato skins	679		1	0						4	0	15			561
Triticale straw	1,321,609	3,146	6,831	4,810	193	21,355	4,600	3,357	1,151	185,686	194,077	5,350	31,301		6,982
Wheat straw	2,955,429	30,785	153,123	19,811	820	101,903	77,527	18,000	18,452	723,927	416,099	31,137	111,514	10,706	176,046

TABLE 23. ESTIMATED PRODUCTION POTENTIAL OF SELECTED RESIDUAL STREAMS PER COUNTRY TO MICROBIAL PROTEINS (TONNES CRUDE PROTEIN IN MP, PER YEAR) (2)

	Latvia	Lithuania	Luxembourg	Malta	Netherlands	Norway	Poland	Portugal	Romania	Slovenia	Slovakia	Spain	Sweden	United Kingdom	China
Apple pomace		28			372	157	3,966	59	58			818	148	1,166	
Barley straw	3,862	8,551	436		2,781	9,860	48,304	881	31,675	1,790	9,109	155,796	17,518	101,307	33,468
Brewer's spent grain	600	2,520			19,105	1,898	29,123	5,699	12,981		1,403	27,919	3,725	288,534	276,256
Brewer's yeast	61	258			1,957	194	2,983	584	1,330		144	2,860	382	29,554	28,296
DDGS from maize	1,892	2,328			54,564		29,246	218	873		15,642	43,433	30,192	74,934	335,982
DDGS from wheat	1,179	1,451			33,999		18,224	136	544		9,746	27,064	18,813	46,693	209,356
Grape branches and leaves			140	53	22		114	20,058	18,686	1,702	885	106,149	10	52	88,854
Grape pomace			27	5	3			2,023	1,218	171	104	11,208			1,002
Grape seeds			4	1	0			290	174	24	15	1,604			143
Grey starch					1,185	14	163	1				0	8	288	265
Maize (corn) stover		2,737	12		4,069		183,971	17,816	388,096	9,334	39,261	103,881	364		6,782,946
Molasses		3,833			29,511		65,184		2,468		5,104	8,421	8,451	24,252	30,545
Oat straw	4,123	3,917	137		140	5,463	34,409	960	4,627	86	817	26,409	11,533	21,376	12,325
Olive pomace								4,909		15		30,112			
Olive pruning branches				1				46,196		31		277,247			
Olive pruning leaves				0				6,370		4		38,232			
Olive stones								3,280		10		20,119			
Peanut meal							15,930	2,747							2,636,759
Peanut skins	18	31	7	13	193	157	72	40	220	36	56	605	346	1,320	69,095
Potato crop residues	1,633	3,134	185	114	65,124	3,915	76,591	4,810	19,367	759	1,750	21,835	8,513	3,651,041	1,304,525
Potato peels					8,289	101	1,139	8				1	55	2,014	1,856
Potato pulp (starch industry)					2,785		2,183				6		180	174	4,856

	Latvia	Lithuania	Luxembourg	Malta	Netherlands	Norway	Poland	Portugal	Romania	Slovenia	Slovakia	Spain	Sweden	United Kingdom	China
Rapeseed hulls	3,602	5,736				256	74,244	3,734	9,841	16	5,572	5,366	8,415	39,834	189,533
Rapeseed meal	15,239	24,270				1,081	314,116	15,796	41,636	70	23,573	22,701	35,603	168,531	801,890
Rapeseed straw	9,476	20,088	100		96	185	66,492		29,934	160	9,212	5,454	7,370	21,137	340,989
Rice bran								2,115	180			7,422			2,547,786
Rice bran, defatted															457,482
Rice husk								1,390	118			4,878			1,674,372
Rice straw								7,590	759			25,575			8,831,725
Rye straw	2,802	1,439	134		162	749	52,276	439	763	51	746	7,000	2,624	3,820	11,086
Sugar beet leaves		6,176			47,272		110,133		5,650	61	9,838	18,072	14,757	53,098	86,411
Sugar beet pulp		3,221			24,796		54,770		2,073		4,289	7,076	7,101	20,377	25,665
Sunflower meal		1,498						5,219	56,712			21,717			129,810
Sunflower straw			14				1,452	477	120,193	47	8,091	44,082			107,990
Tomato crop residues		99			255	5	1,061	2,451	2,499	29	33	7,734	6	27	157,241
Tomato pomace		3			5		209	1,193	51			1,599	0		6,575
Tomato skins		2					7	7	0			80			745
Triticale straw	3,124	28,210	2,747		624		621,044	3,595	30,562	2,822	3,876	105,155	16,350	7,135	59,112
Wheat straw	56,754	99,984	1,606		17,692	6,429	268,864	2,093	239,333	3,292	43,143	210,766	62,202	263,963	2,874,946

Annex 5. Formula for degree of circularity, yield factors and substitution rules for a selection of destinations/effects

Formula for *Degree of circularity*

The degree of circularity is calculated with following formula (upgraded from Broeze et al., 2024):

$$Degree\ of\ circularity\ (\%) = \frac{\sum_{products\ k} A_k \times \sum_{components\ j}\left(\sum_{components\ i}\left(y_{i,j,k} \times K_{j,k} \times \Delta H^0_{c,j} \times m_i\right)\right)}{\sum_{components\ i}\left(K_{i,food} \times \Delta H^0_{c,i} \times m_i\right)}$$

where the expression in the denominator expresses the value of the material and the nominator refers to the produced product(s) in a valorisation pathway. Meaning of the variables:

- m_i stands for the mass share of macro-nutrient i in the material on dry matter basis (kg/kg).
- $y_{i,j,k}$ stands for the yield factor of macro-nutrient i to component j in product k (kg/kg).
  Often (like in extraction processes) $y_{i,j,k} = 0$ for all $j \neq i$; in conversion processes $y_{i,j,k} \neq 0$ is possible for $j \neq i$.
- $\Delta H^0_{c,i}$ stands for the specific heat of combustion of macro-nutrient i (MJ/kg).
- $K_{j,k}$ is a multiplication factor for component j in product k, intended for expressing higher value of proteins compared to carbohydrates in food. The default value for $K_{j,k} = 1$ in all products (meaning that the products are valued at their specific heat of combustion), except for proteins in food. The higher valuation of proteins is reflected by:
  - more appreciated nutritional value;
  - higher land use intensity of protein compared to carbohydrate production; from comparisons of land productivity and composition of diverse commodity crops it is concluded that proteins require around 3 to 5 times the land required for carbohydrates (in m^2/MJ);
  - elevated prices of protein-rich feed ingredients compared to carbohydrate-rich ingredients; proteins are appreciated (in terms of €/MJ) around 2 to 3 times higher than other macro-nutrients[9].

  Based on these arguments, it was decided that in the method proteins in food are valued 3x higher than other macronutrients: $K_{protein,food} = 3$.
- A_k stands for the appreciation of product k.

[9] Derived from https://www.wur.nl/nl/onderzoek-resultaten/onderzoeksinstituten/livestock-research/producten/voederwaardeprijzen-rundvee.htm

The factor A_k was introduced to accommodate (societal) preferences for destinations.

The use of food-grade materials for non-food application is sometimes contested. In order to prioritize food application, the appreciation factor A for non-food products may be set to a lower value than for food (with reference appreciation factor: $A = 1$).

In the quantitative results presented in this deliverable, for bio-energy carriers – considering the relatively high yield factors of oil extraction, ethanol fermentation and anaerobic digestion compared to the yield to food via animal feed and the lower (up to comparable) pricing of substrate material for anaerobic digestion compared to pricing of animal feed – the appreciation factor is set to $A = 0.2$.

For biobased final products (like purified PHA) the appreciation factor is derived from the factor for energy carriers. Since the product may be recycled – with multiple use cycles – the factor is multiplied by the estimated number of uses. Considering that the recycling ratio of plastics through chemical recycling is approximately 50%, and that recycling ratio of mechanical recycling can reach levels of 90%, but that mechanical recycling of e.g. PHA faces a number of challenges, here an average recycling ratio of 60% is assumed. The cumulative effect (of the endless recycling, each time with 60%, each carbon molecule in total is used $1 + 0.6 + 0.6^2 + 0.6^3 + \cdots = 1/(1 - 0.6) = 2.5$ times. From this, the appreciation factor for biomaterials is estimated at $A = 0.2 \times 1/(1 - 0.6) = 0.5$.

> Remark: proposed appreciation factors are somewhat arbitrary, based on current economic appreciation and a recycling factor that is not realistic in the current practice (where recycling of bioplastics is not yet institutionalized). It is anticipated that in a more mature circular bio-economy this value is adequate.

Heuristics for assessing degree of circularity for destination 'anaerobic (co-)digestion'

Conversion yield to biomethane

Yield to biomethane (kg biomethane per kg dry matter material) is estimated based on chemical (in terms of macro-nutrients) composition of the material and yield factors (Table 1).

Digestate: fertilizer function of nutrients

Digestate is commonly used as a fertilizer, contribution to crop productivity through provision of nutrients (most essential: N, P and K) and organic matter.

Of the nutrients, only N is in scope of this study. In anaerobic digestion the nitrogen is retained in the digestate. The contribution to crop production is estimated as follows:

- The utilization rate of nitrogen from digestate is estimated at 80% (Schröder et al., 2019).

- The fraction of nitrogen that ends in the crop (relative to the amount of 'utilized' nitrogen), which is estimated at ¾ (derived from nitrogen balance in utilized agricultural areas (CLO, 2025), with correction of the sources for utilization rates of organic sources).

  In total, approximately 80% x ¾ = 60% of the nitrogen in applied material ends in crops.
- Of produced crops, 22.5% are marketed as consumer products (like food and ornamental products), and 75% is used as animal feed (CLO, 2025). In animal production approximately 30% of nitrogen ends in food proteins, and 60% in manure. Since manure is circularly applied as fertilizer, also this contributes to production of food and other products. Altogether, the cumulative net yield from crops to food is estimated at 50%.

The combined effect is estimated at 60% x 50% = 30%.

> Comment: this result is based on data for The Netherlands. In many other countries, larger part of the crops is destined as food, which promotes the effect. However, in many countries the nutrient utilization rate may lower. Altogether, the above effect is considered representative for the average situation.

Digestate: organic matter

Organic matter is considered highly relevant for soil health, amongst other for retaining moisture and for structure. Consequently, the application of persistent organic matter may contribute to crop productivity.

It is assumed that all lignin and part of cellulose and hemi-cellulose (corrected for degradation fractions estimated from Table 1) are retained in the digestate.

Marginal contribution of a material to soil organic matter depends on the persistence of the material. The most persistent macro-nutrients in organic material are lignin, cellulose and hemicellulose. The actual rate of decay depends on many situation factors (like agricultural soil management, soil humidity and pH). Based on the rule-of-thumb that effective organic matter from compost is broken down at a rate of 2% per year, here it is assumed that lignin breaks down at a rate of 1% per year, and (hemi)cellulose at 4% per year. Consequently, over its lifespan, a kg lignin is expected to contribute 100 kg x years organic matter and (hemi)cellulose 25 kg x years.

The actual contribution of soil organic matter to crop production also depends strongly on situation conditions (like soil type and actual organic matter content). For a situation with low soil organic matter content (Oldfield et al., 2021)., the marginal benefit of extra organic matter was estimated at approximately $^{1}/_{40}$ kg crop yield (in dry matter) per kg extra organic matter.

For situations where soil organic matter content is not a limiting factor (roughly where the organic matter content is around or above 2%, which is largely the case in North-Western Europe), the marginal effect of extra organic matter is not significant (Hijbeek et al., 2017).

The combined marginal effect (also taking in consideration yield from crops to final products as pointed out above) is – dependent on the situation estimated for

- lignin: between 0 and 100 x $^1/40$ x ½ = 0 to 1¼ kg extra food (dry matter) production per kg lignin.
- cellulose: between 0 and 25% x 25 x $^1/40$ x ½ = 0 to 0.08 kg extra food (dry matter) production per kg cellulose.
- hemicellulose: between 0 and 42% x 25 x $^1/40$ x ½ = 0 to 0.13 kg extra food (dry matter) production per kg hemicellulose.

By default, the contribution from persistent organic matter is assumed 0.

Heuristics for assessing degree of circularity for destination 'PHA'

Conversion yield to PHA

Yield to PHA (kg PHA per kg dry matter material) is estimated based on chemical (in terms of macro-nutrients) composition of the material and yield factors (Table 1).

Yield via anaerobic digestion of residue stream

Burniol-Figols et al. (2018) suggest that approximately 20% of the feedstock's COD ends in the residue stream that is anaerobically digested. Based on that 20% of the yield factors for destination *anaerobic digestion* are added to the result.

Heuristics for assessing degree of circularity for destination 'Microbial Proteins'

Conversion yield to Microbial Proteins

Yield to MP (kg protein in the MP per kg dry matter material) is estimated based on chemical (in terms of macro-nutrients) composition of the material and yield factors (section 2.3). It is assumed that the MP product is used as fish feed, for which a protein retention ratio to food of 28% is assumed (value estimated for Atlantic salmon by Fry et al. (2018)).

Yield to biomethane in waste water treatment

Again, for this application it is assumed that approximately 20% of the feedstock's COD ends in the residue stream (Spiller et al., 2020; Tian et al., 2023), with destination waste water treatment. A UASB system is assumed. The yield (ton biomethane per ton dry matter material) is estimated at 80% of biomethane potential (IPCC, 2019, Chapter 6). The biomethane potential is derived from Table 1. Biomethane substitutes natural gas: 1.25 ton natural gas per ton biomethane.

Heuristics for assessing GHG emission effects of destination 'anaerobic (co-)digestion'

Yield to biomethane (ton biomethane per ton dry matter material) is estimated based on chemical (in terms of macro-nutrients) composition of the material and yield factors (Table 1). Biomethane substitutes natural gas: 1.25 ton natural gas per ton biomethane.

Energy use in anaerobic digestion: 9 kWh electricity + 550MJ heat per ton DM substrate (estimated from Lijo et al., 2014).

Energy use in biogas upgrading: 700 kWh per ton methane (estimated from Iglesias et al. (2021) and Francisco López et al., 2024)).

Methane leakage from anaerobic digestion and biogas upgrading: 2% of produced methane leaks to the atmosphere (estimated from Francisco López et al., 2024)

Digestate: fertilizer function of nutrients (N): Nitrogen in the material is considered to substitute synthetic nitrogen fertilizer, with substitution factor 80% (Schröder et al., 2019).
GHG emissions associated to 1 kg of synthetic fertilizer-N is estimated from:

- average GHG emission intensity of production in Europe (Vidovic et al., 2023): 3 kg CO_2e/kg N.
- Effect of N_2O emissions: emission factor for artificial fertilizers: 1.3% N2O-N of applied N. This means 13 x 44 / 36 ≈ 15.9 g N_2O per kg applied N. Climate impact of 16 g N_2O is 15.9 x 273 / 1000 ≈ 4.34 kg CO_2e.

The total effect is 7.34 kg CO_2e per kg substituted synthetic fertilizer-N. Thus, a kg N in the digestate mitigates 80% x 7.34 = 5.87 kg CO_2e GHG emissions.

Digestate: organic matter: • Supplied persistent organic matter (in digestate) may contribute to food production (as explained in the 'Degree of circularity' section above). It is assumed that the produced food substitutes wheat flour.

Carbon sequestration through persistent organic matter in the soil: Based on assumed annual break down rates of 1% for lignin and 4% for (hemi)cellulose, the GWP-100 effect is estimated at 0.39 kg CO_2e per kg lignin and 0.11 kg CO_2e per kg (hemi)cellulose in the digestate.

Nitrous oxide emissions from digestate applied in the field: Emission factor for N_2O from digestate applied to the soil is estimated at 0.8% N_2O-N of the N in the digestate (Van der Zee et al., 2021; Van Bruggen et al., 2023).

Heuristics for assessing GHG emission effects of destination 'PHA'

Yield to PHA (ton PHA per ton dry matter material) is estimated based on chemical (in terms of macro-nutrients) composition of the material and yield factors (Table 1). PHA substitutes fossil-derived plastics (assumed polyethylene or polypropylene) with estimated GHG emission intensity – production + released CO2 from the fossil carbon at end-of-life – of 2 + 2.7 = 4.7 kg CO_2e per kg plastic (ETC WMGE, 2021).

Energy use in PHA production: 1.28 kWh electricity and 1.65MJ heat per kg produced PHA (estimated from Saavedra del Oso et al., (2023) scenario 2).

Other inputs in PHA production: estimated contribution 0.19 kg CO_2e per kg produced PHA (estimated from Saavedra del Oso et al., (2023) scenario 2).

GHG emissions effect of anaerobic digestion of residue stream: as explained above it is assumed that 20% of the feedstock's COD ends in the residue stream that is anaerobically digested. Based on that 20% of the factors for destination *anaerobic digestion* are added to the result.

Heuristics for assessing GHG emission effects of destination 'Microbial Proteins'

The *yield to MP crude proteins* is estimated based on chemical (in terms of macro-nutrients) composition of the material and yield factors (section 2.3). It is assumed that the MP product substitutes soybean meal and wheat flour in fish feed, with substitution ratios based on protein content and nutritional energy.

Energy use in MP production: 0.6 kWh electricity per kg DM feedstock and 8.8MJ heat per kg protein in the MP product (estimated from Spiller et al. (2020)).

Use of N-source (di-ammonium sulphate) in MP production: estimated at 0.16 kg di-ammonium sulphate per kg simple carbohydrate in the material.

Yield to biomethane in waste water treatment: explained above in the 'Degree of circularity' section above.

Methane leakage from anaerobic digestion and biogas upgrading: 2% of produced methane leaks to the atmosphere (as explained above for anaerobic digestion).

Energy use in waste water treatment: Electricity use is estimated at 0.3 kWh per kg dry matter (Lopes et al., 2018). The heat demand strongly depends on the specific conditions (especially temperature of the waste water and COD content). Here a typical situation is assumed (waste water has dry matter content of 10g per litre, it must be heated from average 15° to approximately 25°, with 20% heat loss) with estimated heat demand 5MJ per kg dry matter. Other GHG emissions are relatively small (Lopes et al., 2018).

Nitrous oxide emissions linked to the waste water: emission factor of 1.1% kg N_2O-N per kg N in the waste water. The amount of N in the waste water fraction is estimated at 1/3 of the amount in the MP product (for which yield parameters are given in section 2.3).

GHG emission factors for inputs and substituted materials

- Produced electricity: 0.213 kg CO2-eq/kWh

Derived from https://ember-energy.org/data/yearly-electricity-data/ (accessed 2025-08-18), value for EU, 2024.

- Consumed electricity: 0.233 kg CO2-eq/kWh

  Based on production-associated GHG emission factor, with 8.4% T&D losses (derived from Eurostat Supply, transformation and consumption of electricity data))
- Heat: 0.0726 kg CO2-eq/MJ (Bastos et al., 2024)
- Natural gas: 2.67 kg CO2-eq/kg

  Derived from https://eu-mayors.ec.europa.eu/sites/default/files/2022-10/JRC-CoM-EF-CoMW-EF-2017.pdf.
- Substituted food ingredients (carboncloud.com):
  - Soybean protein isolate: 8.76 kg CO2e/kg
  - Wheat starch: 0.69 kg CO2e/kg
- Substituted feed ingredients: estimated average for Europe from GFLI (2022).
- di-ammonium sulphate: 0.62 (Vidovic et al., 2023).

Annex 6. Environmental impact effects of destinations of residue flows

TABLE 24. ESTIMATED DEGREE OF CIRCULARITY FOR SELECTED DESTINATIONS FOR AGRI-RESIDUES

Degree of CIRCULARITY	Anaerobic (co-)digestion	PHA + anaer. digestion	Feed (dairy cattle)	Ethanol + cattle feed	Alkaline protein extraction	Microbial Proteins - > Fish Feed	Mushroom production (spent substrate: fertilizer)
Apple pomace	14.0%	17.3%	20.4%	19.5%	25.8%	11.2%	9.9%
Barley straw	12.1%	10.8%	16.6%	16.3%	19.4%	9.8%	6.2%
Brewer's spent grain	18.7%	16.7%	26.8%	27.3%	47.4%	14.0%	24.3%
Brewer's yeast	21.4%	20.6%	28.8%	30.6%	57.5%	16.8%	30.6%
Broken rice	18.0%	24.1%	28.0%	22.6%	31.6%	21.7%	11.5%
Corn cobs (excl. grain)	13.1%	12.1%	18.2%	17.3%	21.5%	11.6%	7.1%
DDGS from maize	19.4%	19.1%	29.9%	28.5%	48.6%	14.3%	24.8%
DDGS from wheat	20.0%	18.1%	30.2%	28.7%	53.6%	15.5%	28.4%
Discoloured rice	16.3%	20.0%	22.9%	21.1%	29.8%	18.5%	11.4%
Grape branches and leaves	12.4%	15.9%	17.3%	16.8%	21.1%	9.9%	7.3%
Grape pomace	14.8%	13.0%	21.1%	20.1%	36.8%	13.1%	18.7%
Grape seeds	12.8%	12.9%	19.5%	19.4%	27.0%	8.5%	12.0%
Grey starch	17.3%	23.7%	29.1%	21.4%	28.9%	21.5%	9.8%
Maize (corn) stover	13.7%	13.1%	19.1%	18.9%	25.7%	10.9%	10.2%
Maize silage	15.9%	19.0%	24.6%	21.0%	27.6%	16.0%	9.9%
Molasses	17.4%	21.7%	23.6%	22.3%	33.7%	18.8%	13.8%
Oat straw	12.2%	11.4%	16.8%	16.4%	19.6%	10.0%	6.3%
Olive pomace	14.4%	14.2%	20.6%	20.3%	33.0%	11.2%	15.8%
Olive pruning branches	13.3%	14.6%	18.1%	17.9%	26.9%	10.6%	11.6%
Olive pruning leaves	13.7%	15.0%	19.0%	18.7%	30.1%	10.9%	13.9%
Olive stones	18.5%	24.1%	29.3%	29.0%	38.0%	11.5%	16.5%
Peanut hulls	12.8%	13.0%	17.3%	17.1%	25.1%	9.9%	10.4%

Degree of CIRCULARITY	Anaerobic (co-)digestion	PHA + anaer. digestion	Feed (dairy cattle)	Ethanol + cattle feed	Alkaline protein extraction	Microbial Proteins -> Fish Feed	Mushroom production (spent substrate: fertilizer)
Peanut meal	22.7%	18.5%	32.7%	31.7%	65.5%	19.0%	36.3%
Peanut skins	17.3%	18.8%	27.1%	25.9%	37.5%	12.8%	17.1%
Potato crop residues	12.0%	10.3%	16.4%	16.0%	24.7%	9.8%	10.8%
Potato peels	18.0%	21.3%	29.2%	23.6%	37.6%	18.7%	16.6%
Potato pulp (starch industry)	15.9%	18.5%	27.5%	21.3%	31.9%	14.8%	13.5%
Rapeseed hulls	15.9%	15.7%	24.2%	23.7%	37.0%	11.6%	17.8%
Rapeseed meal	20.6%	17.0%	29.5%	29.0%	57.9%	16.7%	31.6%
Rapeseed straw	12.8%	11.9%	17.0%	16.8%	23.2%	10.2%	8.8%
Rice bran	16.5%	18.7%	26.1%	24.2%	34.1%	13.7%	14.9%
Rice bran, defatted	15.9%	15.9%	23.7%	21.9%	35.8%	14.5%	16.8%
Rice husk	10.5%	9.7%	14.0%	13.5%	17.8%	9.1%	6.1%
Rice straw	11.5%	10.3%	15.7%	15.5%	19.5%	9.2%	6.8%
Rye straw	12.1%	11.1%	16.4%	16.2%	19.9%	9.7%	6.6%
Sugar beet leaves	17.3%	15.7%	26.2%	24.0%	43.2%	14.9%	21.9%
Sugar beet pulp	15.0%	16.2%	25.3%	20.5%	29.1%	12.5%	12.0%
Sunflower meal	19.7%	15.9%	27.7%	27.4%	54.7%	15.9%	29.6%
Sunflower straw	13.4%	11.9%	18.3%	18.1%	26.2%	10.7%	10.8%
Tomato crop residues	12.4%	15.9%	17.3%	16.8%	21.1%	9.9%	7.3%
Tomato pomace	16.8%	15.6%	24.8%	24.8%	42.1%	11.9%	21.4%
Tomato skins	12.5%	11.0%	17.5%	17.4%	30.9%	9.4%	15.6%
Triticale straw	18.7%	16.7%	26.8%	27.3%	47.4%	14.0%	24.3%
Unripe rice	16.3%	20.0%	22.9%	21.1%	29.8%	18.5%	11.4%
Wheat straw	12.5%	10.9%	16.9%	16.6%	21.0%	10.2%	7.2%
Cattle manure	15.4%	12.4%					

TABLE 25. ESTIMATED GHG EMISSION EFFECTS FOR SELECTED DESTINATIONS FOR AGRI-RESIDUES

GHGe Effect (DM basis)	Anaerobic (co-)digestion	PHA + anaer. digestion	Cattle feed	Ethanol + cattle feed	Alkaline protein extraction	Microbial Proteins -> Fish Feed	Mushroom production (spent substrate: fertilizer)
Apple pomace	-0.76	-0.92	-0.42	-0.83	-1.13	-0.31	-0.40
Barley straw	-0.60	-0.55	-0.27	-0.34	-0.82	-0.21	-0.36
Brewer's spent grain	-0.82	-0.94	-1.19	-1.33	-2.21	-0.75	-0.80
Brewer's yeast	-0.84	-1.22	-1.73	-2.28	-2.97	-1.17	-0.94
Broken rice	-0.67	-0.99	-0.53	-1.78	-1.10	-0.69	-0.20
Corn cobs (excl. grain)	-0.63	-0.59	-0.30	-0.50	-0.88	-0.28	-0.37
DDGS from maize	-0.84	-1.10	-1.32	-1.58	-2.33	-0.82	-0.76
DDGS from wheat	-0.86	-1.07	-1.53	-1.78	-2.67	-0.96	-0.94
Discoloured rice	-0.69	-0.89	-0.48	-1.43	-1.12	-0.58	-0.29
Grape branches and leaves	-0.71	-0.84	-0.30	-0.68	-0.97	-0.23	-0.37
Grape pomace	-0.88	-0.86	-0.71	-1.00	-1.70	-0.46	-0.73
Grape seeds	-0.96	-0.95	-0.50	-0.53	-1.46	-0.22	-0.65
Grey starch	-0.64	-0.95	-0.48	-1.70	-1.00	-0.65	-0.17
Maize (corn) stover	-0.62	-0.63	-0.40	-0.55	-1.00	-0.30	-0.40
Maize silage	-0.65	-0.82	-0.46	-1.14	-1.02	-0.48	-0.28
Molasses	-0.60	-0.89	-0.55	-1.64	-1.15	-0.63	-0.24
Oat straw	-0.61	-0.57	-0.27	-0.40	-0.82	-0.22	-0.35
Olive pomace	-0.84	-0.89	-0.62	-0.84	-1.52	-0.37	-0.63
Olive pruning branches	-0.71	-0.80	-0.42	-0.72	-1.15	-0.29	-0.46
Olive pruning leaves	-0.73	-0.84	-0.51	-0.82	-1.28	-0.32	-0.51
Olive stones	-0.90	-1.46	-0.99	-1.45	-1.86	-0.60	-0.42
Peanut hulls	-0.78	-0.80	-0.39	-0.57	-1.17	-0.25	-0.51
Peanut meal	-0.88	-1.08	-2.28	-2.69	-3.72	-1.51	-1.29
Peanut skins	-0.94	-1.16	-0.89	-1.22	-1.85	-0.59	-0.60

GHGe Effect (DM basis)	Anaerobic (co-)digestion	PHA + anaer. digestion	Cattle feed	Ethanol + cattle feed	Alkaline protein extraction	Microbial Proteins -> Fish Feed	Mushroom production (spent substrate: fertilizer)
Potato crop residues	-0.71	-0.65	-0.39	-0.48	-1.12	-0.24	-0.51
Potato peels	-0.65	-0.94	-0.73	-1.65	-1.36	-0.69	-0.35
Potato pulp (starch industry)	-0.64	-0.83	-0.58	-1.15	-1.17	-0.48	-0.36
Rapeseed hulls	-0.95	-1.03	-0.83	-0.97	-1.85	-0.48	-0.71
Rapeseed meal	-0.87	-1.01	-1.72	-1.98	-2.99	-1.10	-1.09
Rapeseed straw	-0.68	-0.65	-0.34	-0.46	-1.00	-0.25	-0.43
Rice bran	-0.77	-0.98	-0.72	-1.21	-1.47	-0.54	-0.43
Rice bran, defatted	-0.67	-0.78	-0.69	-1.14	-1.40	-0.52	-0.48
Rice husk	-0.61	-0.55	-0.24	-0.37	-0.81	-0.17	-0.38
Rice straw	-0.53	-0.49	-0.28	-0.35	-0.76	-0.19	-0.32
Rye straw	-0.63	-0.58	-0.28	-0.37	-0.86	-0.21	-0.38
Sugar beet leaves	-0.65	-0.75	-0.96	-1.32	-1.73	-0.65	-0.60
Sugar beet pulp	-0.57	-0.70	-0.51	-0.83	-1.03	-0.38	-0.34
Sunflower meal	-0.82	-0.89	-1.46	-1.64	-2.63	-0.94	-1.00
Sunflower straw	-0.60	-0.58	-0.41	-0.51	-1.01	-0.29	-0.42
Tomato crop residues	-0.71	-0.84	-0.30	-0.68	-0.97	-0.23	-0.37
Tomato pomace	-0.99	-1.07	-1.02	-1.08	-2.16	-0.56	-0.85
Tomato skins	-1.08	-0.99	-0.57	-0.63	-1.75	-0.27	-0.85
Triticale straw	-0.82	-0.94	-1.19	-1.33	-2.21	-0.75	-0.80
Unripe rice	-0.69	-0.89	-0.48	-1.43	-1.12	-0.58	-0.29
Wheat straw	-0.63	-0.56	-0.30	-0.37	-0.88	-0.24	-0.39
Cattle manure	-0.68	-0.67					