high-value products from agricultural residues through sustainable chains

Project number: 101081776

Deliverable D1.4

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

Workpackage(s) concerned: WP1

Workpackage leader: Jan Broeze (WR)

Deliverable Leader: Marta Rodriguez-Illera (WR)

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Executive Summary

In this deliverable, a first step has been taken to address the environmental impact of agricultural and food production practices by efficiently utilizing agricultural residues. The methodology involves developing a dataset estimating the volumes and compositions of major agricultural residues in Europe. This dataset is created through the synthesis of existing data sources, literature reviews, and correlations from the literature. It covers primary residues generated close to fields as well as secondary residues from plant processing sites. Furthermore, the deliverable explores potential pathways for converting these residues into valuable products, such as biopolymers, proteins, and other high-value applications. The methodology quantitatively analyses composition-dependent yields, drawing from relevant literature. The primary goal of this work is to generalize the quantitative findings from technological work packages (Agriloop WPs 2 and 3) to a broader range of agricultural residues. The results achieved in this deliverable provide a more detailed inventory of agricultural residues in Europe, including primary residues and various processing pathways for different crops. The ultimate objective is to promote sustainable practices, reduce waste, and contribute to the development of a circular (bio-)economy in Europe by maximizing the use of agricultural residues.

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1 Introduction

Agricultural and food production practices are associated with considerable environmental burdens through the consumption of resources such as land, water, energy etc. 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 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). Persistent fibre components and minerals will end in the residues, which is still functional for soil health.

This deliverable aims at generating a dataset estimating the volumes and compositions of major residues in Europe, together with potential yields to biopolymers, proteins and other value-added products, with the intention of screening the routes with a higher environmental performance. Consequently the quantitative findings of the technological work packages (WPs 2 and 3) are generalized to a broad set of agri-residues.

To achieve this deliverable, we have first created a framework and dataset for estimation of biomass residue volumes and compositions in Europe. This is based on combinations of available datasets and literature review as well as some correlations from literature. First estimates of volumes of large secondary residues were also provided in Agriloop Deliverable 1.1; here a more detailed inventory is presented (addressing also primary residues and distinguishing different processing pathways per crop).

Secondly, we have gathered and quantitatively elaborated pathways and yields to common biobased applications, derived from literature as a function of composition. In the following phases of the research (Deliverables 1.5 and 1.6) these data will be completed with yields to products intended in Agriloop and indicators for environmental performance assessment.

Part of the elaborations described in this deliverable were derived from the Agriloop milestone document M7, in which the data management framework and a glance on the content were introduced.

In next deliverables (D1.5 and D1.6) also data on Chinese residue streams will be included; due to different timing of the Chinese Agriloop consortium (start in October 2023) the scope of D1.4 is limited to Europe.

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2 Setup of data framework

The data framework was introduced in the milestone document (Agriloop MS7) and further elaborated in this Deliverable document.

To produce the quantitative dataset addressed in this deliverable, we have followed a step-by-step approach. The main approach has been previously described in the Milestone MS7 and the resulting data framework and dataset is shown in Figure 1. The first step was the selection of relevant agri-residual streams for EU27 based on a screening related to their crop production level in the EU. This selection was done to further examine the potential of primary residues such as straws and residues left on the field on top of secondary residues already in scope of the project. Secondly, based on the production level of the crop per country, and correlations or residue factors from literature, we obtained the residues due volumes per country. Thirdly, we collected the composition of residues to express the amount of nutrients available per country. And finally, based on the nutrients and macronutrient from residues and the conversion factors and extraction yields from literature, product yields per country and per ton of residues are estimated.

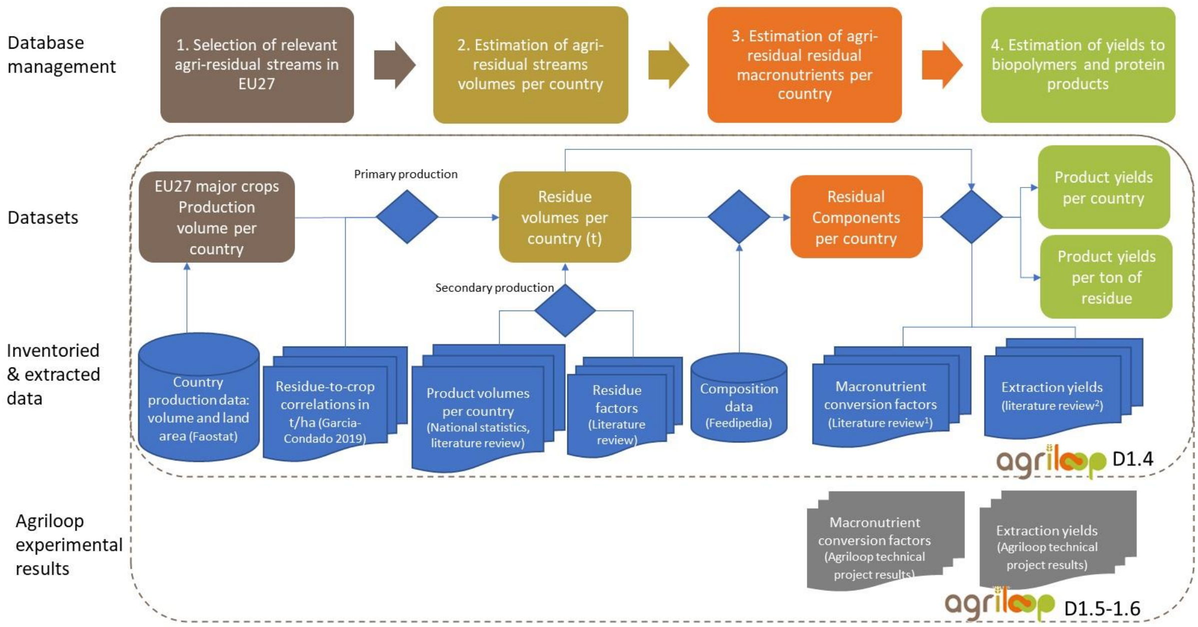

FIGURE 1. OVERVIEW OF DATA FRAMEWORK FOR DELIVERABLE D1.4 (AND DELIVERABLES D1.5 AND D1.6).

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3 Data collection on agri-residues and on extraction and conversion efficiencies

In this deliverable the generation of datasets on volumes of generated agri-residues, their composition and yields of extraction and efficiencies of conversion to products (protein products, biopolymers and other biobased products) is presented. Through combining these data, the production potentials per residue stream and per country can be estimated.

3.1 Identification and selection major agri-residual streams

To identify and select the most relevant residual streams in scope for the EU27 we followed different approaches for the primary residues (crop residues, from agricultural production) and secondary residues (from processing).

As stated in the Milestone document MS7, the crop residues were selected based on a screening of crop production in the EU (with cut-off 4Mt (mega tons) per year for the year 2021); for these the 10 crops with highest volumes of crop residues will be selected.

Figure 2 shows the overview of crops with annual production above the specified cut-off volume.

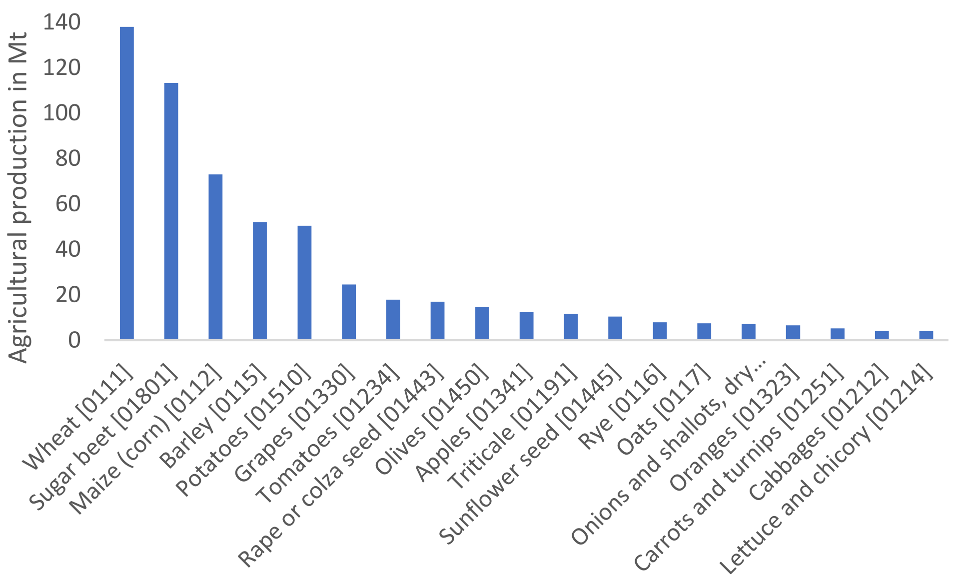

FIGURE 2. AGRICULTURAL PRODUCTION PER CROP IN MEGATONS (MT) IN THE EU27 COUNTRIES FOR CROPS WITH HIGHEST CROP PRODUCTION (ABOVE 4MT) FOR THE YEAR 2021, RETRIEVED AND FILTERED FROM THE FAOSTAT DATABASE (FAO, 2023).

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Based on crop-to-residue ratio, volumes of crop residues can be estimated. For that, heuristics are provided by amongst others Scarlat et al. (2010). Based on their heuristics, the order of cereal and oil crops in terms of residue volume estimated in the EU27 is: wheat, barley and maize, rapeseed, sunflower, rye, oats and rice (Figure 3).

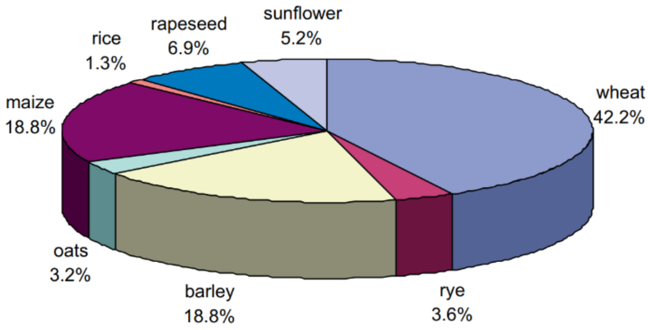

FIGURE 3. SHARE OF CROP RESIDUES PRODUCED IN THE EU27, BASED ON HEURISTICS OF SCARLAT ET AL. 2010.

This set is complemented with a number of other crops with substantial production volumes according to Figure 2: sugar beet, potatoes, grapes, tomatoes, apples and triticale.

Selection of secondary residues on scope in the Agriloop project was done based on the by-products of major consumer products and ingredients in scope which are also partly covering the spectrum of major crops listed in Figure 2. These are by-products generated during the production of apple juice, wine, beer, tomato, potato products, oil (from rapeseed, sunflower and olive) and sugar (from sugar beet). From this list, some residues are skipped such as the brewers yeast for being obtained in relative low amount and with already an application in food.

Table 1 lists the major EU27 crops residues selected and in scope in the project for both primary and secondary residues. In Table 2 we have gathered the definitions based on the assumptions used by the data sources used for the volume and composition estimation. Residues from 'smaller' crops such oranges, carrots and turnips, cabbages, lettuce and chicory are assumed to have very little (both considering its specific volume and overall volume based on crop production), to no residues. We therefore neglect for the sake of simplicity in this current deliverable the possible rootlets or leaves generated.

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TABLE 1. OVERVIEW OF IDENTIFIED AND SELECTED RESIDUES IN SCOPE OF THE AGRILOOP PROJECT

FAOstat crop code	Crops	Agricultural production		Processing	
		Primary residue 1	Primary residue 2	Secondary residue 1	Secondary residue 2
111	Wheat	*Wheat straw*		NiS	NiS
112	Maize (corn)	*Maize (or corn) stover*		NiS	NiS
115	Barley	*Barley straw*		*Brewer's grains*	*Brewer's yeast*[1]
116	Rye	*Rye straw*		NiS	NiS
117	Oats	*Oat straw*		NiS	NiS
1191	Triticale	*Triticale straw*		NiS	NiS
1234	Tomatoes	*Tomato crop residues (leaves and stems/tomato plant)*	*Culled tomatoes*[2]	*Tomato pomace*	*Culled tomatoes*[2]
1330	Grapes	*Branches and leaves*		*Grape pomace*	
1341	Apples	*Culled apples*[2]		*Apple pomace*	*Culled apples*[2]
1443	Rape seed	*Rape straw*		*Rapeseed hulls*	*Rapeseed meal*
1450	Sunflower seed	*Sunflower stalks (straw)*		*Sunflower meal*	
1450	Olives	*Olive tree pruning biomass, Olive leaves*	*Olive pits*	*Extracted Olive Pomace*	*Olive oil vegetation water*
1510	Potatoes	*Potato leaves*	*Discarded potatoes*	*Potato pulp*	*Potato peels*
1801	Sugar beet	*Sugar beet leaves*	*Sugar beet tops*	*Sugar beet pulp*	*Molasses*

NiS: not in scope; [1]skipped from the analysis, [2]combined primary (from agricultural production and postharvest operations) and secondary (from processing) residues as a secondary residue.

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TABLE 2. . DEFINITIONS OF CROP RESIDUES ADAPTED FROM LITERATURE SOURCES WHICH ARE SCOPING THE RESIDUE PARTS OF THIS DELIVERABLE

FAOstat crop code	Residue	Definitions
111	*Wheat straw*	Highly fibrous crop residue consisting of the dry stems, leaves left after harvest.
112	*Maize (or corn) stover*	Maize stover consists of the residues left in the field following the harvest of corn grains. It includes stalks, leaves, husks, and cobs. Maize stover contains different plant parts in variable proportions. Stalks are the main component (40-60%), followed by leaves (20-30%), cobs (15-20%) and husks (10-15%).
115	*Barley straw*	Highly fibrous crop residue consisting of the dry stems, leaves left after harvest.
115	*Brewer's grains*	Brewers grains are the solid residue left after the processing of germinated and dried cereal grains (malt) for the production of beer and other malt products. Though in this deliverable we only consider the residue from the beer production. This residue is produced after fractionation of the stream generated after the malt mashing process, the grains are separated during the *lautering* from the wort. Though barley is the main grain used for brewing, beers are also made from wheat, maize, rice, sorghum and millet.
115	*Brewer's yeast*	Brewer's yeast is the solid residue separated after fermentation from the fermented liquor happening during the beer production process. It contains the yeast which is made from a one-celled fungus called Saccharomyces cerevisiae. This by-product has a high nutritional profile and is generally used as a food supplement.
116	*Rye straw*	Highly fibrous crop residue consisting of the dry stems, leaves left after harvest.
117	*Oat straw*	Highly fibrous crop residue consisting of the dry stems, leaves left after harvest.
1191	*Triticale straw*	Highly fibrous crop residue consisting of the dry stems, leaves left after harvest.
1234	*Culled tomatoes*	Culled, dropped and damaged tomatoes (broken, injured during picking, unfit for packing) together with tomatoes discarded from postharvest and processing operations.
1234	*Tomato crop residues (leaves and stems/tomato plant)*	Tomato crop residues such as leaves and stems are produced from the tomato plant during harvesting operations.
1234	*Tomato pomace*	Consists of seeds and peels from the tomato.
1330	*Branches and leaves*	Vine shoot
1330	*Grape pomace*	Also called, grape pulp. Includes skins and grape seeds that are separated from the juice (must) after pressing. This side stream also includes in some cases also the stem. Composition considers all types: with or without stems, with or without seeds, from wineries, distillation, or juice production.
1341	*Culled apples*	Culled, dropped and damaged apples (broken, injured during picking, unfit for packing) especially available during the apple harvest season together with apples from postharvest operations and processing.
1341	*Apple pomace*	Solid residue that remains after milling and pressing of apples for cider or apple juice (or even in some cases puree production). Apple pomace contains peel, flesh, stem, core, seeds and juice residues. A typical sample of apple pomace contains 54% pulp, 34% peel, 7% seeds, 4% seed core and 2% stem.
1443	*Rape straw*	Highly fibrous crop residue consisting of the dry stems, leaves left after harvest.
1443	*Rapeseed hulls*	Rapeseed hulls are the teguments (a fibrous by-product) of the seeds of the oilseed rape plant, resulting from the extraction of rapeseed oil. Rapeseed hulls account for 12-20% of seed weight., the hull may content fraction contains kernel fragments. It is rich in fibre, notably lignin, but also in residual oil and protein.
1443	*Rapeseed meal*	Rapeseed meal is the residue left after oil extraction from the rapeseed. This residue is high in protein and there is a patented process, the Burcon process that is already in use to extract protein.
1445	*Sunflower stalks (straw)*	This stream considers the stalks from the sunflower. Although they look dry, their water content is quite high and around 80%.
1445	*Sunflower meal*	The Sunflower meal is the residue and by-product from the extraction of sunflower oil. It is considered high in fibre and in protein, with a lower content than soybean meal. It is also use for feed. The composition can vary depending on the degree of dehulling. We consider both hulled and non-dehulled sunflowers.
1450	*Olive tree pruning biomass*	The olive tree pruning biomass comprises leaves (~ 25% dry weight basis, dwb), thin branches (~ 50% dwb) and wood of different thickness (~ 25% dwb) (Romero-García et al., 2014
	Olive leaves	Leafy residue from initial olive cleaning operations and separated by density in olive mills.
1450	*Olive pits*	Olive residue, also called olives stones
1450	*Extracted Olive Pomace*	The final solid residue generated in pomace olive oil extracting industries after pomace oil recovery
1450	*Olive oil vegetation water*	The alpechin or vegetation water is a liquid residue produced from the extraction of oil from olives. This aqueous phase (mainly water) is a constituent part of the olive fruit and of the oily juice released when olives are pressed and is rich in organic matter.
1510	*Potato leaves*	Leafy residue separated from potatoes.
1510	*Discarded potatoes*	Damaged potatoes (broken, injured during picking, unfit for packing) together with tomatoes discarded from postharvest and processing operations.
1510	*Potato pulp*	Pulp generated in the process of extracting starch from potatoes
1510	*Potato peels*	Residue from the peeling process of potatoes. The produced side streams include earthy water (produced during washing), peel mass (pure potato), starch and Potato juice. It consists of potato skins (~56% on fresh weight basis , fwb), starch (~33% fwb) and inert material (~ 0.1% fwb).
1801	*Sugar beet leaves*	Leaves from the sugar beet cut off after harvesting
1801	*Sugar beet pulp*	Pulp generated in the process of extracting sugar from sugar beets.
1801	*Molasses*	This residue is the syrupy by-product yielded after the crystallisation of sugar from concentrated sugar juice extracted from the roots of sugar beets

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3.2 Estimation of agri-residual streams volumes per country

To estimate the volumes of the residual streams at country level we used different approaches for the agricultural residues (primary residues) and processing residues (secondary residues). For the primary residues, we estimated the volume of residues from crop production data, and crop-to-residues correlations (when available) and factors from literature to estimate the yield of residues. 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 the residue factors gathered for each type of residue in combination with crop yield data, volume processed or product generated following some heuristics derived from information gathered from literature. In case of overlap/inconsistency of information a critical review is made to discriminate for the more valid information. In all situations, country specific information, such as country statistics data prevails when available.

3.2.1 Estimations of volumes from primary production

For the primary residues of selected crops, we exported crop production data (including the producing amounts and harvest areas) of 2020 at country level and per crop type from the Faostat database "Crops and livestock products" and estimated the residue volume for each crop and country based on the yield and estimated residue-to-crop ratios. Residue-to-crop ratios were obtained from the widely accepted study of Scarlat et al. 2010 and Fischer and co-workers (Fischer et al. 2010, Fischer et al. 2007, and Fischer et al. 2009). Because of poor correlations in the equations of Scarlat 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 (García-Condado et al. 2019, García-Galindo et al. 2019). When correlations were not available we have included factors from literature as an approximation, especially when it comes to parts of the plant (and its residue-to-crop ratio), which can be regarded as a good approximation. Table 3 shows the collected correlations and factors gathered from literature.

Table 3. Correlations and factors available in literature for the residue to yield ratio from primary production for the different crops selected (where RPR: residue to crop yield ratio, R: residue yield in t/ha, CY: crop yield in t/ha). Y: economic yield in t dry matter/ha

Crop	Crop residue	Equation	R^2	Reference
Wheat	*Wheat straw*	R = 2.1248·Y^0.8629	0.6829	García-Condado et al. 2019
Maize	*Maize (or corn) stalk straw*	RPR = −0.1807 · Ln(CY) + 1.3373	0.1732	Scarlat et al. 2010
Barley	*Barley straw*	R = 1.5242·(Y)^0.3481[a]	0.856	García-Condado et al. 2019
Rye	*Rye straw*	RPR= 0.3007 Ln(CY) + 1.5142	0.2198	Scarlat et al. 2010
Oat	*Oat straw*	RPR = −0.1874 · Ln(CY) + 1.3002	0.2121	Scarlat et al. 2010
Triticale	*Triticale straw*	R= 2.1248·Y^0.8629	0.6829	García-Condado et al. 2019
Tomatoes	*Tomato crop residues (leaves and stems/tomato plant)*	R= 3.5	-	Zotarelli et al. 2009
Grapes	*Branches and leaves*	R= 2.9	-	Molina-Alcaide et al. 2008

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Rape or colza seed	*Rape straw*	R = 3.6753· (Y)^0.7963[a]	0.6859	García-Condado et al. 2019
Sunflower	***Sunflower stalks (straw)***	R = 1.9444 · Y + 0.386[a]	0.8242	García-Condado et al. 2019
Olives	***Olive tree pruning biomass***	R = 57.4·Y	-	Padilla- Rascón et al. 2020
	Olive leaves	R = 6.3·Y	-	Padilla- Rascón et al. 2020
Potatoes	*Potato leaves*	R = 0.1067·Y+1.6831	0.0619	García-Condado et al. 2019
Rice	*Rice straw*	R = 1.7171(Y)^0.7933	0.8718	García-Condado et al. 2019
Sugar beet	*Sugar beet leaves*	RPR = 0.3266·CY	-	Zwart et al. 2004, Krijnse Locker 2021, greenproteinproject.eu
	Sugar beet tops	RPR = 0.1516·CY	-	

[a]The relationship is highly heteroscedastic: the error variance is increasing dramatically with CY; RMSE: Model root mean squared error.

Table 4 shows the dry matter as the percentage of the harvested crop product. These percentages are used for calculating the crop residuals in the primary production, using the formulas presented in Table 3.

TABLE 4. DRY MATTER VALUES USED IN THE CORRELATIONS BASED ON AVERAGE VALUES FROM LITERATURE

Crop	Crop seed	Dry matter (% w/w)
Wheat	Wheat grain	87
Maize	Maize grain	86.3
Barley	Barley grain	87.1
Rye	Rye grain	86.6
Oats	Oats	87.9
Triticale	Triticale grain	87.1
Tomatoes	Tomato fruit (fresh)	7.3
Grapes	Grapes	19.7
Apples	Apple fruit	14.7
Rapeseed	Rapeseeds	92.3
Sunflower	Sunflower seed	92.8
Olives	Olive fruit	50
Potatoes	Potato tuber (raw)	20.6
Sugar beet	Sugar beet root	18.8
Rice	Rice bean seeds	91.1

3.2.2 Estimations of volumes of secondary residues

Table 5 summarizes the residue factors gathered from literature for the different secondary residues expressed per economic yield (fresh produced sold to the market), crop yield (derived from crop production data) and volume of data of produce processed. Some values such as for processed tomatoes, beer, wine and apple juice main residues were also reported as part of deliverable 1.1.

TABLE 5. SECONDARY RESIDUES RESIDUE FACTORS FROM LITERATURE. Y: ECONOMIC YIELD IN TONS FRESH WEIGHT, CY: CROP YIELD (IN TONS FRESH WEIGHT), V: VOLUME OF PRODUCT IN HL.

Crop	Product(s)- processing	Residue name	Residue factor (equation)	Reference
Barley/Wheat	*Beer*	***Brewer's grain***	R=0.02·V	Gupta et al. 2010
		Brewer's yeast	-	-
Tomatoes		***Culled tomatoes***	R = 0.36[a]·CY	Calculation

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	Processed tomatoes	*Tomato pomace*	R= 0.04·Y	Del Valle et al. 2006
		Tomato skins	-	-
Grapes	*Wine*	*Grape pomace*	R=0.0357·V	Ladakis et al. 2020
Apples		*Culled apples*	R = 0.27[a]·CY	Meyer et al. 2017
	Apple juice	*Apple pomace*	R=0.4· Y	Golebiewska et al. 2022
Rape or colza seed	*Rapeseed oil*	*Rapeseed hulls*	R= 0.19·CY	Carré et al. 2015
		Rapeseed meal	R= 0.605·Y[b]	Calculation
Sunflower seed	*Sunflower oil*	*Sunflower meal*	Tbd	-
Olives	*Olive oil*	*Olive pits (or stones)*	R=0.115·CY	Padilla- Rascón et al. 2020
		Extractive Olive Pomace	R=0.226·CY	Padilla- Rascón et al. 2020
		Olive oil vegetation water	Tbd	-
Potatoes		*Discarded potatoes*	R = 0.2·Y	Porter et al. 2006
	Starch production	*Potato pulp*	Tbd	-
	Potato Pre-processing (prepared potatoes, fries and other potato derived snacks)	*Potato peels*	R=0.09·CY	Arapoglou et al. 2010
Sugar beet	*Sugar*	*Sugar beet pulp (pressed)* *Molasses*	R = 0.2200·CY R = 0.0346·CY	Chouinard, 2021

[a]Derived from calculation from Porter et al. 2006. [b]Derived from calculation based on dry matter of the rapeseed starting material reported in Erreur ! Source du renvoi introuvable. and results from the Canola Council of Canada "Lifecycle Analysis Canola Biodiesel" 2010. Tbd: to be determined.

3.3 Estimations of agri-residual macronutrients composition

The specified attributes/components currently described are: dry matter, sugars, starch, crude protein, fat, NDF (Neutral detergent fibre), ADF (Acid determined fibre), lignin, crude fibre, polyphenols, tannins and ash.

Estimates for moisture content of the agricultural residues are obtained from the study of Scarlat et al. 2010. The moisture content of the residual streams generated from secondary residues, as well as missing composition data from the other streams are obtained after literature search and data extraction from Feedipedia.org.

Further compositional estimates different primary and secondary agri-residual streams were extracted from Feedipedia.org. Missing values in that information (such as for potato leaves) were collected from other sources.

3.4 Estimations of yields to biopolymers, protein and other biobased products

Yields of extraction and conversion pathways from agricultural residues to biopolymers and protein products were estimated through heuristic rules. These rules describe mass balances, based on macro-nutrient composition of the agricultural residues. For the conversion processes addressed in this deliverable rules derived from literature study were used.

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3.4.1 Wet anaerobic digestion

Wet anaerobic digestion, as applied in amongst others manure fermentation and co-fermentation, provides biogas (biomethane and carbon dioxide) and digestate (which may be used as fertilizers). Estimates of yield from simple carbohydrates, fat/oil and proteins to biomethane (derived Baserga, 1998) are shown in Table 6. The contribution of complex carbohydrates varies amongst type of carbohydrate and depends on the degree of hydrolyzation, which depends on the chosen pre-treatment. Here it is assumed that no hydrolysation (pre-)treatment is applied and consequently complex carbohydrates are not converted.

TABLE 6. ESTIMATES FOR METHANE YIELD IN WET ANAEROBIC DIGESTION FROM MACRONUTRIENTS IN A BIOMATERIAL

Category	Methane yield Maximum yields based on stochiometrics	Typical measured data	Value implemented in the dataset	Energy yield (kJ/kg)
Simple carbohydrate	0.27 g/g	0.26 g/g	0.26 g/g	13×10^3
Fat/oil	0.72 g/g	0.56 g/g	0.60 g/g	30×10^3
Protein	0.34 g/g	0.33 g/g	0.33 g/g	16.5×10^3

For materials with significant complex carbohydrates degradation, predicted biogas yield may be specified in the biomass properties table. Alternatively, estimates may be derived through a model that takes digestibility in consideration .

In extended digestion processes, larger parts of the complex carbohydrates are digested, although contribution to biogas productivity may be limited due to acidification (as Molinuevo-Salces et al., 2013, demonstrate for retention times over 80 days).

3.4.2 Dry anaerobic digestion

Dry anaerobic digestion generally delivers a lower methane yield than wet anaerobic digestion:

- Angelonidi et al. (2015) compared biogas yield of dry and wet digesters. Their results showed about 60% reduced methane yield per kg volatile solids. Remark: the wet digesters considered in their study used substrates with higher biogas potencies than commonly used dry digesters, so the found differences are higher than they would be with equal substrates.
- Rocamora et al. (2020) show comparison of biogas yields for feedstocks treated by dry and wet digestion in various case studies. Methane yield per kg volatile solids was 0 to 50% lower in dry digestion compared to wet digestion.

Altogether we estimate conversion of macronutrients to biogas from dry digestion at 70% of wet digesters methane yield.

3.4.3 Typical yields for production of biofuels, chemicals and plastics

Through fermentation and other conversion processes, nutrients can be converted to various biobased materials. Since diverse pathways exist, in this preliminary phase of the

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project typical yields are used (quantitative estimates based on technical research in AgriLoop will be presented in forthcoming deliverables 1.5 and 16). For the current dataset, we have estimated conversion parameters ("macronutrient conversion factors") based on stochiometric analysis (chemical reaction equations) as presented by e.g. Linke et al. (2003) and various published experimental findings in Table 7.

TABLE 7. MACRONUTRIENT CONVERSION FACTORS, KG PRODUCT PER KG FEEDSTOCK (T: THEORETICAL, POTENTIAL YIELD DERIVED FROM AMONGST OTHERS STOCHIOMETRICS; P: PRACTICAL/TYPICAL VALUES, OR RANGE OF VALUES, ENCOUNTERED IN LITERATURE)

Product / Macro-nutrient	Biomethane	Bio-ethanol (fermentation)	Biodiesel (FAME)	Bio-PE	Bio-PET (30%)	PEF	PHA/PHB
Protein	0.34 (T)[2] 0.33 (P)[2]						
Fat/oil	0.72 (T)[2] 0.56 (P)[2]		1.0 (T)[2] 0.73-0.98 (P)[2]				
Sugar	0.27 (T)[2] 0.26 (P)[2]	0.51 (T)[1,2] 0.47 (P)[2]		0.25-0.29 (P)[2,3]	0.20[2]	0.56 (T)[2] 0.51-0.55 (P)[2]	0.48 (T)[2] 0.40 (P)[2]
Starch	0.27 (T)[2] 0.26 (P)[2]	0.57 (T)[1] 0.42 (P)[4]		0.20 (P)[2]			0.31 (P)[4]
Cellulose	0.30-0.35 (T)[2,7] 0.18-0.25 (P)[2,5 6]	0.51-0.57 (T)[2,6] 0.35-0.38 (P)[2]					
Hemicellulose	0.29 (T)[7] 0.13-0.16 (P)[6]	±0.4 (T)					
Lignin	(negative)						

Remark: presented yields for bio-ethanol from (hemi)cellulose to bioethanol through fermentation are based on second generation technologies.

[1] https://www.eubia.org/cms/wiki-biomass/biofuels/bioethanol/, accessed 7 December 2022; Duncan (2013).
[2] Nova (2015).
[3] Lovett et al. (2016).
[4] IfBB (2021)
[5] 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.
[6] Sadhukhan et al. (2019).
[7] 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.

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Based on above, combined with estimates from Bos & Sanders (2013), typical conversion yields are presented in **Erreur ! Source du renvoi introuvable.**.

TABLE 8. TYPICAL MACRONUTRIENT CONVERSION FACTORS, KG PRODUCT PER KG FEEDSTOCK

Product / Macro-nutrient	Biomethane	Bio-ethanol (fermentation)	Bio-ethanol (BTL) (pyrolysis or Fisher Trops)	Biodiesel	PHA/PHB
Protein	0.33				
Fat/oil	0.56			0.9	
Sugar	0.26	0.5	0.27		0.4
Starch	0.26	0.5	0.27		0.3
Cellulose	0.20	0.4	0.12		
Hemicellulose	0.15	0.3			
Lignin					

3.4.4 Protein extraction combined with bioethanol production from residue

This pathway describes a wet extraction process as described by Voogt et al. (2021) for brewers' spent grain and palm kernel meal.

TABLE 9. YIELDS OF PROTEIN EXTRACTION PROCESS, BASED ON VALUES PRESENTED BY VOOGT ET AL. (2021)

Component	Yield in protein powder	Yield in residue (feed)	Conversion ratio to ethanol
protein	80%	20%	
fat	0	100%	
sugar	80%		0.17
starch	0		0.87
fibres	0	100%	
ash	80%	20%	
other compounds			0.43

3.4.5 Rubisco protein extraction

The protein yield of Rubisco was estimated from Cosun (2019), assuming beet leaves dry matter content around 11 to 12%, of which 25% protein: about 30% of the protein ends in the Rubisco extract.

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3.5 Environmental performance

3.5.1 Parameters and indicators for environmental sustainability analysis

Provisions have also been made for adding dedicated indicators per agri-residual – processing pathway combination. Heuristics for these will be developed/provided by Task 1.4 and addressed in deliverable 1.5 and 1.6.

3.5.2 Environmental prospects for residue valorization

Based on results and scores from the different indicators performances from available residue amounts, prospects can be made to maximize the environmental performance of the residue valorization. This availability should consider also potential competing uses (e.g. feed, food, soil health), including potential synergies (e.g. residues after extracting proteins or short carbohydrates may retain essentials functions – persistent organic material and nutrients – for the soil).

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4 Resulting dataset and quantitative results

4.1 Agri-Residue volumes generated in EU27

4.1.1 From Primary production

Based on the methodology described in previous chapter, with recent data on crop production from the FAOSTAT database Figure 4, estimates of volumes of primary residues for the selected crops are shown in per country in Figure 5. As expected, the largest volumes of agricultural residues (in terms of dry matter) are generated in countries such as France and Germany (that also have highest crop production volumes for the selected crops, as shown in Figure 4). This conclusion is in line with previous results by Scarlat et al. 2010.

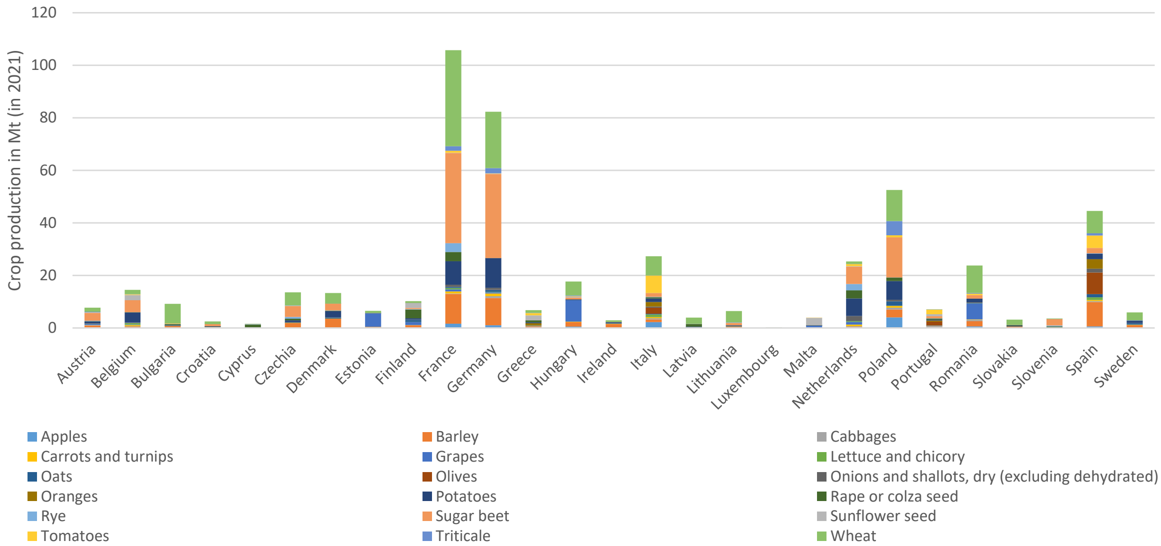

FIGURE 4. CROP PRODUCTION DATA (MEGATON PER YEAR) PER COUNTRY PER CROP FOR THE CROPS AND FOR THE YEAR 2021(FAO, 2023).

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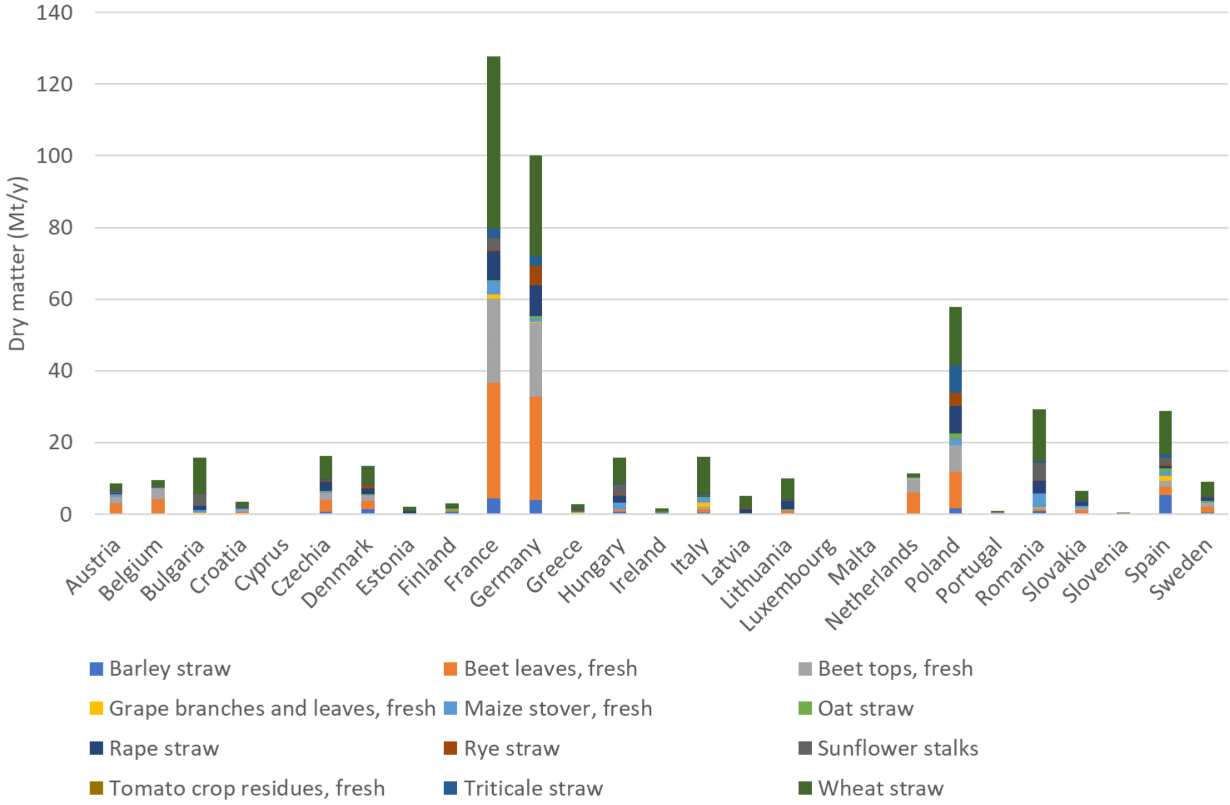

FIGURE 5. PRIMARY RESIDUE PRODUCTION PER COUNTRY OF SELECTED RESIDUES IN MEGATON PER YEAR (RESIDUES OF OLIVES NOT INCLUDED).

Note: data for olive production are left out of the data presented in Figure 5 because they seem excessively high (see Figure 6); likewise the volume of residues from tomato production seems unrealistic low. Further analysis of the data/assumptions is needed.

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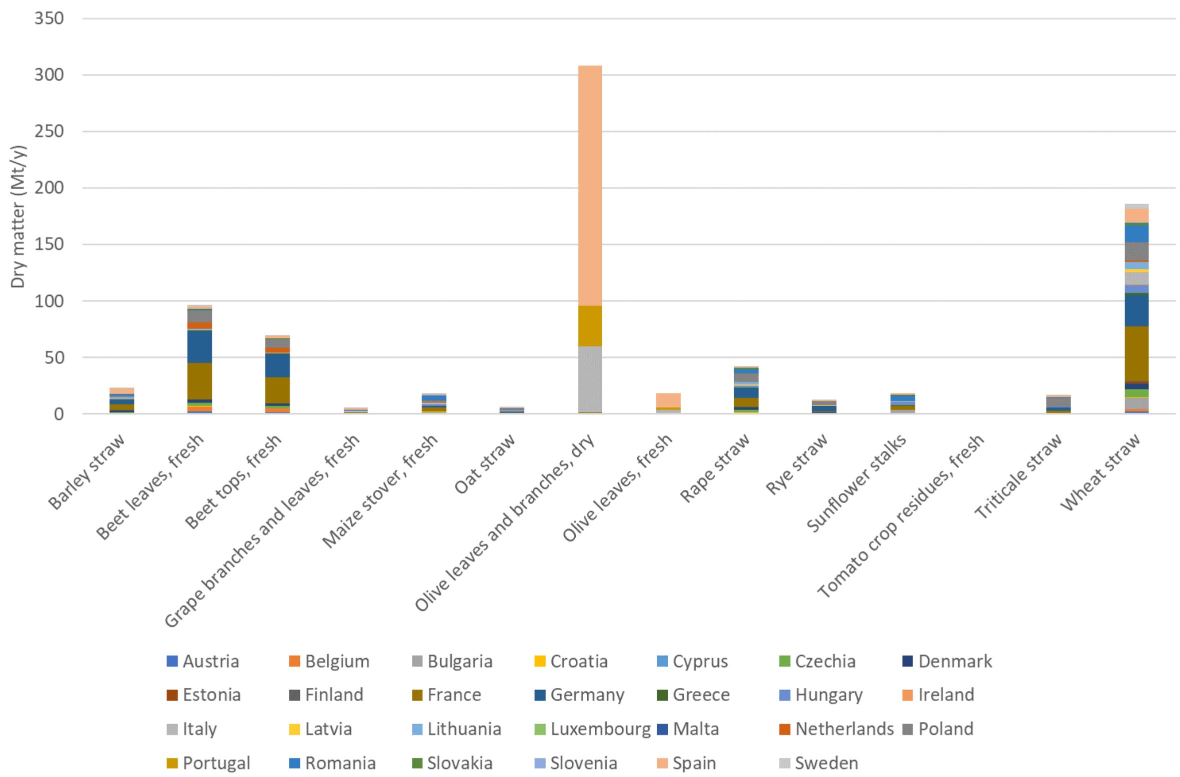

FIGURE 6. PRIMARY RESIDUE PRODUCTION PER SELECTED RESIDUE PER COUNTRY, SHOWING LARGE AMOUNTS OF OLIVE RESIDUES AND SMALL AMOUNTS OF TOMATO RESIDUES.

Estimates as shown in above figures still suffer from a systemic inaccuracy: For some crops different harvesting and post-harvesting systems are used, which results in different crop residues volumes and compositions (for example maize/corn, which in some situations is harvested as full crops for silage feed with very little crop residue, whereas in other situations only the grains are harvested as product and relatively large amount of residues is generated). In the current system only 1 data point for crop-to-residue ratio is used per crop; this will inevitably lead to inaccuracy which will be addressed in forthcoming updates of the dataset (Deliverables 1.5 and 1.6).

4.1.2 Secondary residues

As part of the deliverable 1.1 and in collaboration production with DSS volumes of secondary residues (i.e. from processing of selected crops) have been estimated for the selected secondary residue streams. Figure 7 shows an overview of such secondary residues generated in Europe (further details given in deliverable 1.1).

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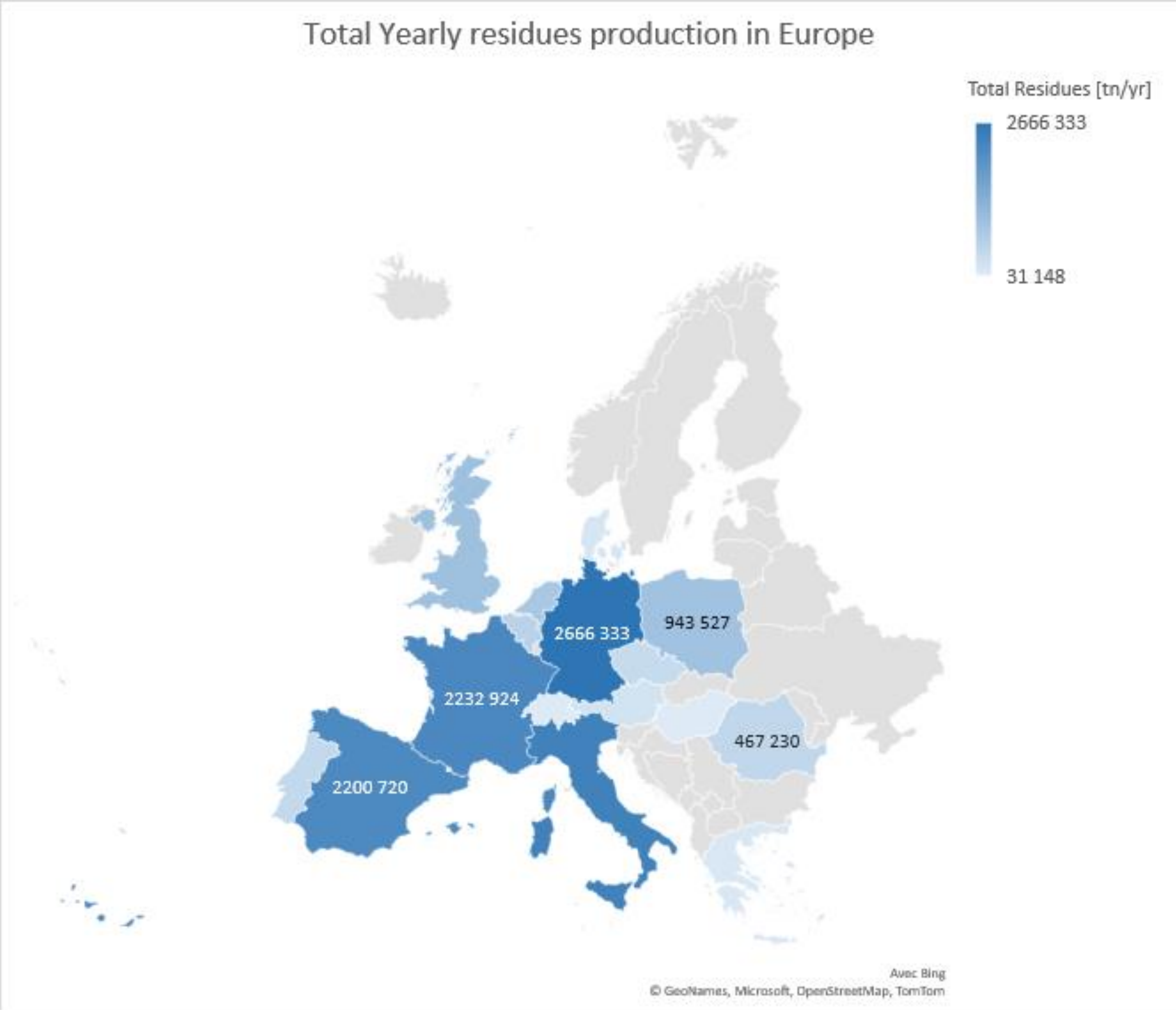

FIGURE 7 ESTIMATED YEARLY PRODUCTION OF RESIDUES RELATED TO PROCESSING IN COUNTRIES WITH LARGEST VOLUMES OF SECONDARY RESIDUES (SOURCE: AGRILOOP D1.1).

As for primary residues, also for secondary residues a system inaccuracy is recognized: different processing pathways will result in different product-to-residue ratios (think of processing potatoes to frozen potato products vs. starch extraction). Further detailing to such differences will be addressed in forthcoming updates of the dataset (Deliverables 1.5 and 1.6).

4.2 Nutrients available in residue volumes

Based on the volumes of agri-residues and their composition as explained in section Erreur ! Source du renvoi introuvable., the availability of nutrients per residue stream, as well as totals, per country can be quantified.

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Contents (on dry matter basis) of main macro-nutrients as derived from feedipedia.org are summarized in Table 10. Apparently, essential data are lacking for amongst others conversion to biopolymers: sugar and starch content (this may be explained by the fact that in common applications of the primary residues these components are not important). From this it is concluded that additional information must be searched; this will be addressed in forthcoming updates of the dataset (Deliverables 1.5 and 1.6).

TABLE 10. MACRO-NUTRIENT CONTENT (G PER G DRY MATTER) OF SELECTED PRIMARY RESIDUES ACCORDING DERIVED FROM FEEDIPEDIA.ORG

Primary residues	*Protein*	*Fat*	*Crude fibre*	*Sugar*	*Starch*
Barley straw	0.038	0	0.405	0	0
Beet leaves, fresh	0.167	0	0.123	0	0
Beet tops, fresh	0.116	0	0.109	0	0
Grape branches and leaves, fresh	0.046	0	0.394	0	0
Maize stover, fresh	0.068	0	0.3	0	0
Oat straw	0.036	0	0.398	0	0
Olive leaves and branches, dry	0.078	0.046	0.251	0	0
Olive leaves, fresh	0.098	0.063	0.179	0	0
Rape straw	0.057	0	0.482	0	0.003
Rye straw	0.041	0	0.419	0	0
Sunflower stalks	0.073	0	0.378	0	0
Tomato crop residues, fresh	0.126	0	0.268	0	0
Triticale straw	0.032	0	0.392	0	0
Wheat straw	0.042	0	0.415	0.012	0.01

Based on the compositional information and estimated volumes of agri-residues the total amount of nutrients in the primary agri-residues can be estimated per geographic area (or for instance factory location). This is illustrated for primary residues per country in Figure 8.

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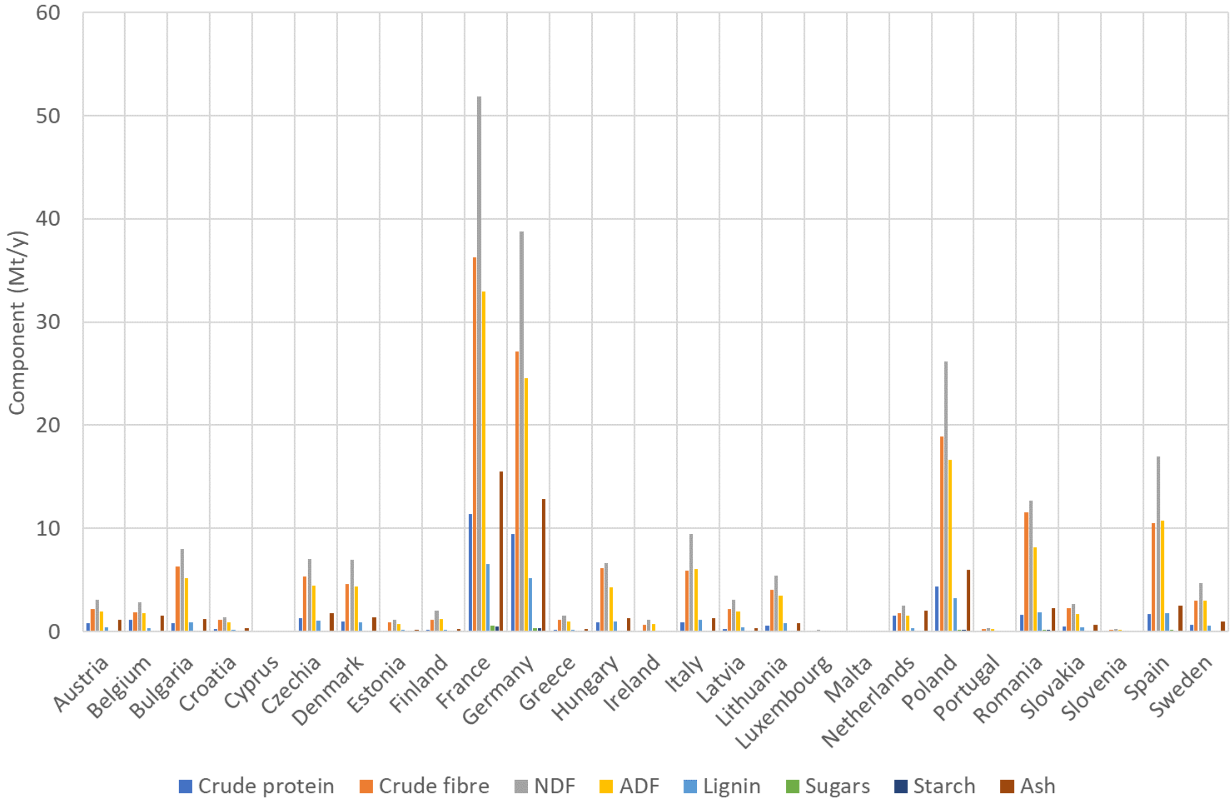

FIGURE 8 COMPONENTS FROM PRODUCED PRIMARY RESIDUES PER COUNTRY OF SELECTED RESIDUES IN MEGATON PER YEAR (RESIDUES OF OLIVES NOT INCLUDED).

4.3 Extraction and conversion yield to products

Based on the compositional information and volume of a residue stream and heuristics as presented in section Erreur ! Source du renvoi introuvable. the yields to diverse products can be estimated. For illustration, estimated yields to biobased products of the selected primary residue streams generated in The Netherlands are presented in Table 11.

TABLE 11. ESTIMATED POTENTIAL YIELDS TO DIVERS BIOBASED PRODUCTS OF SELECTED PRIMARY RESIDUES IN THE NETHERLANDS (IN KTON/YEAR).

residue stream	avail-ability	dry matter	bio-methane	bio-ethanol (fermentation)	bio-ethanol (btl)	pha/ phb
barley straw	83	76	6.1	7.6	2.0	0
beet leaves, fresh	32706	5854	2406	905	241	0
beet tops, fresh	15181	4236	829	372	99	0
grape branches and leaves, fresh	0.55	0.31	0.04	0.05	0.01	0
maize stover, fresh	136	40	9.2	9.21	2.5	0
oat straw	6.3	5.7	0.45	0.57	0.15	0
rape straw	12	11	1.1	1.3	0.36	0.01
rye straw	13	12	1.0	1.2	0.33	0

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tomato crop residues, fresh	6.5	1.1	0.53	0.39	0.10	0
triticale straw	8.6	7.9	0.60	0.76	0.20	0
wheat straw	1342	1221	109	140	41	10

Note that, because of lacking compositional data for some agri-residues (Table 10) the presented values underestimate the actual potentials (especially starch and sugar are essential according to Erreur ! Source du renvoi introuvable.).

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5 Conclusions

This deliverable presents a data framework and datasets for estimating volumes of agri-residues and their potential yield to diverse products. It explains and illustrates the role that the data framework and datasets have for estimating the potential benefits of utilizing agri-residues. This dataset stands as a basis and first step in our efforts to quantify the unexploited potential of these resources within a circular (bio-)economy, emphasizing the urgent need for sustainable agricultural and food production practices to mitigate environmental impacts. The system furthermore supports the prioritization of most promising valorisation pathways.

The datasets provide estimates of volumes of major primary and residue streams per country. In addition, through estimates of composition and parameters describing yield per nutrient of processing, quantitative potential to valuable products are provided.

The methodology enhances the understanding and decision-making capabilities for optimizing the exploitation of available resources. Furthermore, the ongoing exploration of pathways to transform agricultural residues into high-value products holds significant promise for future economic and environmental benefits. This deliverable will be taken along the Agriloop project, to complete the dataset and enrich it with experimental values as well as validation of the current results and underlying data.

A number of shortcomings/limitations were identified in the current data:

- Per crop fixed crop-to-residue ratios were assumed, although this may vary amongst crop production and harvest systems.
- Likewise in processing per material (crop) type fixed residue yields were assumed, whereas different applications will result in different product-to-residue ratios and residue material compositions.
- Compositional information of residue streams are partly incomplete.
- Environmental parameters are not yet included.
- Processes that are subject of technological work packages were not yet described.

These shortcomings will inevitably lead to inaccuracy of results. The gaps will be filled through literature study, based on expert estimates and results from Agriloop environmental sustainability and technologic research. According updates of the datasets will be addressed in next deliverables D1.5 and D1.6.

Finally, to assess the realistic sustainable potential, availability of the residues and components must be assessed. Many of the residue streams already have a function in the current system, for instance feed for livestock (especially for the secondary residues), for bedding or as fertilizer. In some situations valuable compounds may be extracted where the residue's function in the regular application is maintained, in other situations the (sustainability) value for alternative and regular applications must be compared.

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The datasets are currently provided for the EU27 countries; with the start of the Chinese consortium extension to China is foreseen and will be addressed in deliverables 1.5 and 1.6.

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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 and potential yields to protein, biopolymers and other biobased products	Calculation rules for the data	Scientific and popularized publications, conferences, various dissemination and capacity-building events. Will be updated in D1.5 and 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	IPR issues	Use of third-party	Restrictions on data sharing (Y/N)
1	WP1.2_WR_JB	WR	Jan Broeze	Require data transfer contract with chinese partners for closed data	no	Yes, compliance with GDPR (see closed data)

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

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