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ORIGINAL ARTICLE

Estimation and bio-valorisation of food industry by-products in Northern Europe

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Abstract

The lack of quantitative data regarding the geographical availability of secondary bioresources hinders the exploration of regional valorisation opportunities within the context of circular bioeconomy. The study aimed to identify the main by-products of the food processing and manufacturing industry in eight Northern European countries, including Denmark, Estonia, Finland, Iceland, Latvia, Lithuania, Norway, and Sweden, and propose potential bio-valorisation solutions for these by-products to derive value-added products. By analysing available Food and Agriculture Organization (FAO) statistics for the period between 2015 and 2020 and reviewing the scientific literature, by-product volumes were estimated and respective bio-valorisation methods were summarised in two separate databases. The first database lists the processed food products, their by-products and estimated volumes, while the second details the bio-valorisation methods applicable to these by-products. Estimated by-product volumes provide an understanding of their availability in the Northern European region. Our findings revealed that fresh whey is the predominant by-product in the region, with Denmark generating the highest average volume of 2318.3 kt/year. Similarly, sugar beet pulp, also highest in Denmark, averaged 1421.3 kt/year. Among the bio-valorisation methods studied, whey and brewer's spent grain were the most used substrates, with xylanases, ethanol, and acetic acid being the primary value-added products. This research offers valuable data-driven insights to support the circular bioeconomy in Northern Europe while demonstrating an approach to estimating food industry by-product volumes using commonly reported statistical data.

Keywords Food processing · By-product · Waste quantification · Circular bioeconomy · Value-added product · Biotechnology

1 Introduction

Globally, food loss and food waste are identified as resource flows, the generation of which must be reduced or prevented to reach the United Nations Sustainable Development Goal 12.3 of reducing food loss generation at post-harvest, processing and manufacturing and distribution and halving food waste at the retail and final consumption stages by 2030 [1]. Meanwhile, targeted actions to quantify by-products of food processing and manufacturing are not common. Even though by-products are an inevitable side flow formed during food processing and manufacturing, there is a lack of easily accessible information on their formation, quantities, and handling operations. Moreover, the quantification of by-products generated during food processing and manufacturing is excluded from the mandatory reporting of food waste quantities in the EU [2]. If a by-product is not managed as waste, it should not be classified as such. However, excluding by-products from quantification and reporting prevents generation of data and information on how such a resource is used and whether the selected path is the most desirable option in terms of optimal use of the resource. One of the objectives of the EU Circular Economy Action Plan is to add value to secondary raw materials, including waste and by-products, by creating a well-functioning EU market [3]. Accordingly, the EU Bioeconomy Strategy states that circular bioeconomy aims to add value to bio-waste and

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residues [4]. Cascading is one of the strategies associated with a circular bioeconomy where residues or secondary materials, including by-products, are recycled as many times as possible [5]. Stegmann et al. [6] summarised product value within the context of circular bioeconomy: pharmaceuticals and fine chemicals are categorised as the highest value-added products, followed by valorisation into food and feed, bioplastics and polymers, bulk chemicals and materials and finally energy, heat and fuels as the lowest value-added products. However, to achieve a circular bioeconomy, an important precondition is to understand what type and what quantities of such by-products are available. Information on the type and quantity of by-products is limited. Existing studies that have estimated food loss and waste at the processing and manufacturing stage address the importance of uniform and harmonised measurements, including common definitions, across different countries, as well as inclusion of less researched resource flows, such as by-products [7–12]. For instance, Hanssen et al. outlined the importance of reporting more detailed data than the EU minimum reporting requirements [8]. Hartikainen et al. stressed that there is a need for distinct estimates based on country of origin and type of food [7]. Chiaraluce et al. discussed the necessity for a regional database containing quantitative data and information on agri-food by-products and waste, as well as their valorisation solutions [13]. Such a database could serve as a key enabler for circular economy development.

Caldeira et al. [12, 14] used the mass flow analysis (input–output flows) method to estimate food waste and by-product quantities in the EU per product groups (meat, fish, dairy, eggs, cereals, fruits, vegetables, potatoes, sugar beets, and oil crops) in various food supply stages, including food processing and manufacturing. A combination of statistical data and coefficients was used to estimate food waste and by-product quantities. In their study, by-products were considered resource flows that are removed from the food supply chain for use as animal feed or for valorisation. As the quantities of food waste and by-products were aggregated together, it was not possible to clearly distinguish between specific types of by-products. A follow-up study by de Laurentiis and Caldeira [14] estimated food waste, including by-products, per product groups and along the whole food supply chain in various EU Member States. Sugar beet, cereals, fruits, vegetables, potatoes, oilseeds, meat, fish, eggs, and dairy products were covered in that study. The authors addressed the complexity of quantifying food loss and by-products at the processing and manufacturing stage due to the different steps and transformation processes involved in the production of the final product [14].

Some studies have described by-products and food waste generated at the level of a single company, their uses, and potential valorisation methods [15, 16]. A study by Ong et al. [17] focused on food waste generation in five Asian countries. They discussed the generation of the main types of food waste and valorisation pathways, and briefly described possible future valorisation strategies in each of the countries. Various review studies focused on one specific by-product or a group of by-products and respective value-added products that can be obtained [18, 19]. Caldeira et al. [20] reviewed scientific research of various food waste valorisation pathways, addressing challenges such as the low technology readiness of the studied valorisation options, feedstock availability and logistics, as well as the scarcity of studies quantifying the potential amounts of food waste that is available for valorisation.

While the EU Bioeconomy Strategy [4] incentivises the use of secondary bio-based resources in the production of value-added products, there is a lack of uniform information on what these secondary resources are and of quantitative data on their volumes. Moreover, targeted actions of food processing by-products, a type of secondary bio-based product, are neither clearly outlined in the UN Sustainable Development Agenda [1], nor defined under a uniform reporting procedure, such as the one for food loss and waste [2]. Thus, leading to a resource flow that is potentially under-reported and under-used in sustainably managed bio-resource flows.

The aim of this study is to quantify by-products associated with the main processed food products (in terms of production quantity) in eight Northern European countries and identify their possible bio-valorisation pathways. These countries include Denmark, Estonia, Finland, Iceland, Latvia, Lithuania, Norway, and Sweden. We also found reported bio-valorisation pathways where each of the identified by-products was used for obtaining value-added products. By covering these countries, we present the main feedstock streams from the food industry of the region and thus inform biotechnology and bio-based industry on the region's potential for bio-valorisation development.

As a result, we have developed two related databases: one mapping by-products and their volumes and another detailing their potential bio-valorisation pathways. This work, tailored for a wide audience, not only sheds light on potentially overlooked secondary bio-resources but also paves the way for sustainable bioeconomy strategies in Northern Europe.

This paper first presents the definitions, data, and methods used for the analysis, as well as defines the boundaries of the studied system (Materials and Methods section). The Results section presents the estimated by-product volumes and coefficients for their calculation, as well as the value-added products obtainable from the by-products and microorganisms used in the valorisation process. The paper concludes with critical reflections on the data availability and quality of reported valorisation studies and sets the direction for further research (Conclusions and further outlook section).

2 Methodology

2.1 Definitions and scope of the study

The current study is aimed at the food processing and manufacturing (also defined as the food industry) stage of the food supply chain (FSC) (see Fig. 1). All FSC stages before and after the food processing and manufacturing stage are excluded from this study. Thus, residues generated at pre-harvest, harvest, and post-harvest stages (e.g., straw, stalks, leaves, stones, peels) are outside the scope of this study.

For this study, a *by-product* (also referred to as a *side-stream*, *side-flow,* or *residue*) is defined as a product that is formed during the food processing and manufacturing process, generation of which is unavoidable; a by-product is not the target processed edible food product [21–23]. In this study, by-products are classified as a separate category that does not fall under the overall definition of food loss or food waste.

P*rimary processed product* (PPP) is a processed food product that is produced primarily for human consumption during the production and manufacturing stage using the feedstocks (crop or livestock) from the primary production (e.g., farming, fisheries). For this study, the term *secondary processed product* (SPP) was introduced, defined as a product produced using PPP as its main ingredient. For instance, wheat flour is an example of PPP, while bread is an SPP, because wheat flour is produced from wheat grains, while bread is produced from wheat flour. Tertiary processed product (TPP) is a processed product produced using SPP as its main ingredient.

We looked at the process as a whole and did not distinguish at which sub-stage a by-product is generated. Production and manufacturing process efficiency and its impact on by-product generation were not considered either. Water content, such as water loss (due to evaporation) or water addition during processing and production, was not estimated separately in this study.

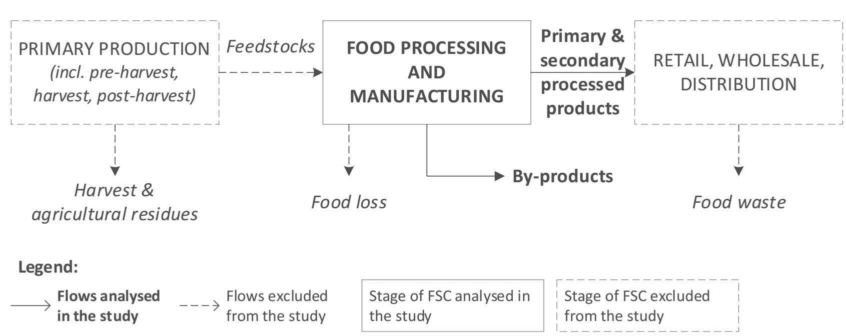
Food loss and wastewater were excluded from the estimations. According to the FAO definition [21], food loss is defined as an unintended decrease in the quantity and quality of edible food before it reaches the final consumption stage. Thus, food that is lost due to spoilage, spillage, technical faults, or mistakes made during the production and manufacturing stage is not included in the estimates of this study.

2.2 Food production data

To identify the main processed food products, we first collected statistical data on production quantities of processed crop and livestock products for the eight Northern European countries: Denmark, Estonia, Finland, Iceland, Latvia, Lithuania, Norway, and Sweden. The FAOSTAT database "Food Balances: Supply Utilization Accounts" [24] was used as the source of statistical data. The data were compiled for the years from 2015 to 2020. At the time of writing this article, the year 2020 was the latest year for which production data were available in the FAOSTAT database. From this database, we selected *production data of processed crop products* and *production data of processed livestock products*. The database contained the total production quantity of the commodity during a calendar year, referred to as Item [25]. We assumed that if a product was produced then by-products were also generated at the point of production. Thus, import and export data were not considered in this study, because the aim was to estimate the volume of by-products generated at the point of production. As we do not have more detailed data (i.e., company level), estimations were made at a country level. The total number of unique processed products downloaded from the database amounts to 174 items. Downloaded data were cleaned to acquire the necessary dataset for the analysis (see Fig. 2).

We excluded products derived from slaughtered animals such as meat and animal fats because animal-based by-products are heavily regulated [26] and multiple solutions have been identified and applied for their use efficiently [27, 28]. We also identified processed food products for which the exact feedstocks were not known, or processed products were made from multiple feedstocks, the proportion of which was not known. We excluded these products from further analysis because it was not possible to identify the exact type and share of by-product generated.

Fig. 1 Scope of the study



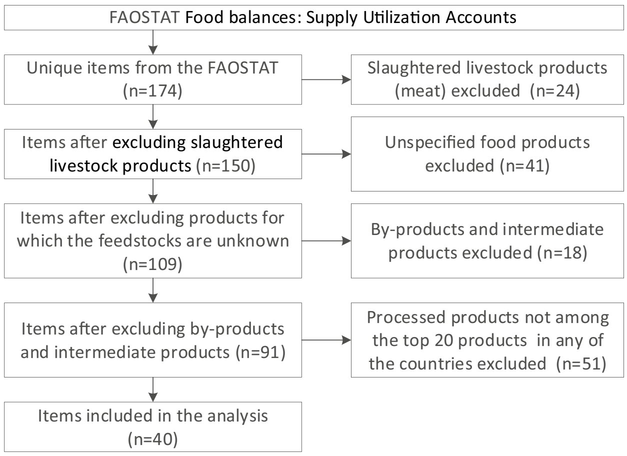


Fig. 2 Data cleaning procedure

We used data from the FAOSTAT Supply Utilization Accounts' section "Definitions and standards" to extract descriptions (definitions) of each item, as well as the FAOSTAT Commodity List (FCL) codes. Descriptions were used to identify processed products (primary and secondary) and their by-products as production data from FAOSTAT also include some products that are by-products (e.g., fresh whey, barley bran, or wheat germ). FCL codes were used to identify processed products (first, second, and third level) and by-products that are summarised in the FAOSTAT commodity trees [29]. Thus, items were classified into primary processed products (PPPs), secondary processed products (SPPs), tertiary processed products (TPPs), by-products (BPs), and intermediate products (IPs), e.g., barley malt. Processed products in the first level were classified as PPP. Second and third-level processed products were classified as SPPs and TPPs, respectively. All items that refer to by-products were classified as by-products regardless of the level. After the exclusion of meat products, products of unknown or multiple feedstocks, as well as by-products and intermediate products, the dataset included 91 items.

We subsequently calculated the annual average production volumes (measured in t/year) for each country from 2015 to 2020. From these calculations, we identified the top 20 processed products (both PPPs and SPPs) for each country. By excluding processed products that were not present among the top 20 products in any of the countries, the final number of unique items analysed in our study is 40. Products such as skim milk, beer of barley, cheese from whole cow milk, wheat flour, buttermilk, rye flour, fresh cream, butter from whole cow milk, as well as skim milk and whey powder are among the top 20 produced products in all the analysed countries.

Table 1 lists the 40 items included in our study, indicating each item's product category (livestock—L, crop—C), class (PPP or SPP), annual average production volume between 2015 and 2020 in each country, and by-products. In some studies, by-products are indicated as indirect by-products. An indirect by-product is a by-product that is not formed during the processing and production of a given product but is formed during the production of another food product (e.g., PPP) that is also used as an ingredient in the production of a given product (SPP). An example could be bran and germ of wheat as indirect by-products of pasta production. Wheat flour is used as an ingredient in pasta production, and germ and bran of wheat are direct by-products formed in wheat flour production. In this study, we assumed that PPPs are the final target products that are then distributed as food or feed. We assumed that in FAOSTAT production data, PPP production quantities do not include quantities that are used as ingredients in the production of SPPs.

The highest annual average production volumes of more than 100 kt/year were observed for these five products: beer of barley (285 kt/year), wheat and meslin flour (280 kt/year), raw cane or beet sugar (157 kt/year), refined sugar (138 kt/year), as well as cheese from whole cow milk (106 kt/year). Of these products, Sweden accounted for the largest production volumes of wheat and meslin flour, while Denmark accounted for the largest production volumes of the other four products. At a national level, beer of barley is the most produced product in Denmark, Estonia, Finland, and Iceland, while wheat and meslin flour—in Latvia, Lithuania, Norway, and Sweden. Moreover, all these products were produced in each of the analysed countries during the analysed period (Table 1).

Based on the annual average production values of the top 20 products, the five least produced products in the region during the analysed period were eggs (2703 t/year), wine (2640 t/year), tomato juice (2354 t/year), cocoa powder (1056 t/year), as well as cocoa butter, fat and oil (936 t/year). At a country level, eggs were among the top 20 most produced products only in Estonia and Latvia. Wine was among the top 20 products only in Estonia, tomato juice—in Latvia, and cocoa powder and cocoa butter, fat and oil—in Iceland.

The production data show that the production of some products was more distinct in a particular country. For example, 94% of potato starch, 92% of orange juice, and 74% of potato flour produced in the Northern European region was produced in Denmark; 88% of all soya bean oil—in Norway; 65% of wheat starch—in Lithuania (See Table SM1.6 of supplementary material SM1).

According to the FAOSTAT production data, the following by-products were also used as animal feed: bran of cereals (barley, maize, oats, pulses, rice, rye, wheat), the germ of maize and wheat, maize and wheat gluten, cocoa husks and shells, as well as fresh whey. These products are also included in the FAOSTAT production quantity data [24]. However, we classified these products as by-products,

Table 1 List of 40 unique items included in the analysis based on their annual average production volumes from 2015 to 2020 in the Northern European countries (cells highlighted in green indicate the top 20 processed products in each respective country, more details in Table SM1.6 of supplementary material SM1)

Item*	Product category	Class	Annual average production volume (tonnes)								By-products	Reference for by-product
			DK	EE	FI	IS	LV	LT	NO	SE		
Skim milk of cows (AF)	L	PPP	1,106,212	120,817	976,895	69,924	234,547	599,445	553,720	1,267,310	-	
Beer of barley, malted	C	SPP	602,617	134,374	381,000	23,900	77,412	283,566	303,200	470,333	Brewer's spent grain (residual spent grain), brewery spent yeast, hot trub (spent hops)	[15]
Wheat and meslin flour	C	PPP	207,159	66,816	238,000	13,578	180,933	529,074	403,833	597,796	Bran of wheat[3] (AF), germ of wheat[3] (AF)	[29]
Raw cane or beet sugar (AF)	C	PPP	397,959	NA	69,775	0	NA	141,875	0	333,422	Molasses[3], sugar beet pulp, wet Sugar beet pulp, dry[3]	[29, 30]
Refined sugar (AF)	C	SPP	371,721	892	125,010	NA	228	132,074	731	332,295	Molasses[3] (indirect), sugar beet pulp, wet (indirect) Sugar beet pulp, dry[3] (indirect)	[29, 30]
Buttermilk, curdled and acidified milk (AF)	L	PPP	79,063	51,283	368,134	25,102	62,210	181,568	151,643	66,122	-	
Cheese from whole cow milk	L	PPP	441,583	44,843	85,765	13,118	45,540	55,092	75,683	84,520	Fresh whey[3] (AF)	[29]
Rapeseed or canola oil, crude	C	PPP	237,333	54,633	54,750	82	56,650	81,909	5133	126,617	Rapeseed cake	[29]
Flour, meal, powder, flakes, granules and pellets of potatoes	C	PPP	243,732	NA	21,123	NA	128	NA	5864	58,607	Potato peels	[15, 31]
Starch of potatoes (AF)	C	PPP	176,744	NA	NA	NA	1780	10,500	NA	NA	Potato pulp (dry/wet)	[32, 33]
Starch of wheat (AF)	C	SPP	NA	NA	NA	8724	488	179,550	82,950	5504	Wheat gluten[3] (AF), bran of wheat[3] (indirect), germ of wheat[3] (indirect)	[29]
Yoghurt[1]	L	PPP	24,650	20,220	NA	NA	23,730	60,065	NA	142,350	-	
Cream, fresh	L	PPP	66,433	10,984	53,630	3173	34,014	61,749	36,499	100,622	-	
Flour of rye	C	PPP	73,833	18,657	111,902	363	37,559	18,471	15,507	72,552	Bran of rye[3] (AF)	[29]
Coffee, decaffeinated or roasted	C	PPP	13,339	NA	49,966	841	NA	NA	27,570	84,845	Coffee silverskin	[34]
Butter of cow milk	L	PPP	63,150	4965	62,125	2483	4753	14,656	15,717	49,092	-	
Skim milk and whey powder (AF)	L	SPP	45,717	8694	67,981	1366	4872	22,355	17,985	43,718	-	
Whole milk powder (AF)	L	PPP	70,783	177	16,329	252	5116	36,617	2354	33,210	-	
Flour of maize (AF)	C	PPP	15,499	7842	15,732	12,105	NA	NA	NA	48,405	Bran of maize[3] (AF), germ of maize[3] (AF),	[29]
Whey, dry (AF)	L	SPP	49,250	8984	26,514	3444	11,825	23,095	20,550	718	-	
Uncooked pasta, not stuffed or otherwise prepared[2]	C	SPP	NA	NA	20,743	NA	22,758	10,006	NA	NA	Bran of wheat[3] (indirect), germ of wheat[3] (indirect)	[29]
Whey, condensed (AF)	L	SPP	0	21,987	0	NA	13,909	12,615	NA	45,094	-	
Oats, rolled	C	PPP	16,417	869	29,711	NA	26,655	5971	19,185	5942	Bran of oats (AF), oat hulls (husks)[3]	[29, 35]
Pot barley (AF)	C	PPP	3871	2036	13,720	NA	26,014	39,655	734	12,842	Barley hulls (husks)[3], bran of barley[3] (AF)	[29]

Table 1 (continued)

Item*	Product category	Class	Annual average production volume (tonnes)								By-products	Reference for by-product
			DK	EE	FI	IS	LV	LT	NO	SE		
Soya bean oil	C	PPP	556	NA	5500	0	550	170	78,983	4361	Soybean cake[3]	[29]
Cheese from skimmed cow milk	L	SPP	NA	NA	NA	323	3564	31,913	NA	NA	Fresh whey[3] (AF)	[29]
Orange juice	C	PPP	16,021	NA	NA	NA	1320	NA	NA	NA	Orange fruit pulp[3] (also known as citrus pulp)	[36]
Skim milk, condensed	L	SPP	NA	NA	NA	NA	NA	NA	NA	8396	-	
Starch of maize (AF)	C	SPP	NA	NA	NA	3045	NA	11,917	NA	NA	Maize gluten[3] (AF), bran of maize[3] (indirect), germ of maize[3] (indirect)	[29]
Whole milk, evaporated (AF)	L	PPP	16,281	1124	NA	0	410	4333	12,034	7874	-	
Prepared groundnuts	C	SPP	3752	NA	NA	NA	NA	NA	6758	NA	Groundnut shells[3]	[29]
Processed cheese	L	SPP	4112	1740	14,219	NA	626	4282	NA	4690	-	
Buttermilk, dry (AF)	L	SPP	1050	40	18,000	435	1719	5058	1796	655	-	
Eggs, liquid	L	PPP	3930	1012	4157	NA	4292	1367	1156	3004	Eggshells, eggshell membrane	[37]
Wine	C	PPP	NA	6547	NA	0	2435	4219	0	NA	Marc of grapes	[38]
Whole milk, condensed	L	PPP	0	1112	0	NA	2396	10,702	824	2795	-	
Tomato juice	C	PPP	3841	NA	755	NA	4444	1164	NA	1569	Tomato pulp[3]	[29]
Rice, broken (AF)	C	SPP	2173	NA	NA	116	NA	NA	NA	NA	Rice hulls[3] (indirect), bran of rice[3] (indirect)	[29]
Cocoa powder and cake	C	SPP	1349	340	2036	173	512	297	1659	2079	Cocoa husks and shells[3] (indirect)	[29]
Cocoa butter, fat and oil	C	SPP	1196	301	1805	153	454	263	1471	1843	Cocoa husks and shells[3] (indirect)	[29]

*Item titles named as in FAOSTAT production data; AF—processed product or by-product is also used as animal feed (according to the FAOSTAT data); C—processed crop product; L—processed livestock product, PPP—primary processed product; SPP—secondary processed product; NA—data not available in the FAOSTAT database

[1]Assumption that this is not Greek, *skyr* yoghurt, or quark

[2]Assumption that pasta is made wholly of wheat flour

[3]Data from the FAOSTAT commodity trees

because they are not the primary target products of food processing and manufacturing (Fig. 2).

As can be seen in Table 1, for multiple products, mainly dairy products, no by-products are listed. In the case of butter and cream, buttermilk or skimmed milk are formed as secondary products, but we did not classify those as by-products because they can further be used as food or in food processing and manufacturing. We assumed that for condensed, evaporated, or dried dairy products there are no by-products, but water is partly or fully removed, based on the processing technique (evaporation, drying, condensation etc.) used to produce the final product. Water loss was not estimated in this study. There are multiple fermented dairy products, like *skyr* yoghurt, Greek yoghurt, and quark, the production of which is associated with the generation of acid whey [39]. We assumed that yoghurt is not any of those types of fermented products because we do not precisely know the production share of such products in each country.

2.3 Quantification of by-products

To estimate the by-product quantities at both the country and regional levels, we compiled information on by-products formed during food processing and manufacturing (Table 1). Additionally, we analysed the proportion or weight of by-products relative to the PPP or SPP from which they originate. Secondary data sources such as scientific literature and reports were used to collect such information. In the literature, data on by-product quantities are expressed in various formats. Studies provide by-product proportion or quantity (weight basis) with respect to the raw material used, or output target product (PPP or SPP). Some studies provide average values, while others provide a range from minimum to maximum (see Table SM1.7 of supplementary material SM1). Also, by-products are not defined uniformly across different studies. Therefore, in the supplementary material, we provide definitions of the by-products analysed in this study (see Table SM1.1 of supplementary material SM1).

One of the information sources used for the collection of conversion factors was the FAOSTAT publication "Technical Conversion Factors for Agricultural Commodities" [29]. The technical conversion factor is a unitless coefficient used to convert from one commodity to another. The publication lists the sequence of products from the primary (unprocessed) product, indicating which products and by-products are formed, and contains information on the share of primary products that can be converted to processed products and by-products, including average, minimum, and maximum values. Figure 3 shows that a by-product (*Level 1 By-product*) is formed in the production of PPP. For example, wheat bran is a by-product of wheat flour production. In turn, wheat flour can then be used to produce SPP, e.g., wheat starch. In this process, wheat gluten is formed as a by-product (*Level 2 By-product*). In the case of wheat starch production, wheat bran can be considered an indirect by-product, as it is generated during the production of wheat flour. A by-product can also be used in the production of another processed product. For example, wheat bran is used in breakfast cereals, residues from virgin oil extraction are used to extract more oil, or whey is processed into nutritional products (whey powder, lactose, proteins, vitamin B_{12}).

In the calculation of by-products, understanding input product characteristics is crucial (see Fig. 3), as that directly affects the results of by-product volumes. For example, in this study, we assume that maize used in the production of maize products only includes maize (or corn) grains. Maize cob and husks, inevitable parts of maize, are thus not taken into consideration in this study. We assume that these by-products are formed in the primary production (*Level 0 By-product*), not the processing and manufacturing stage.

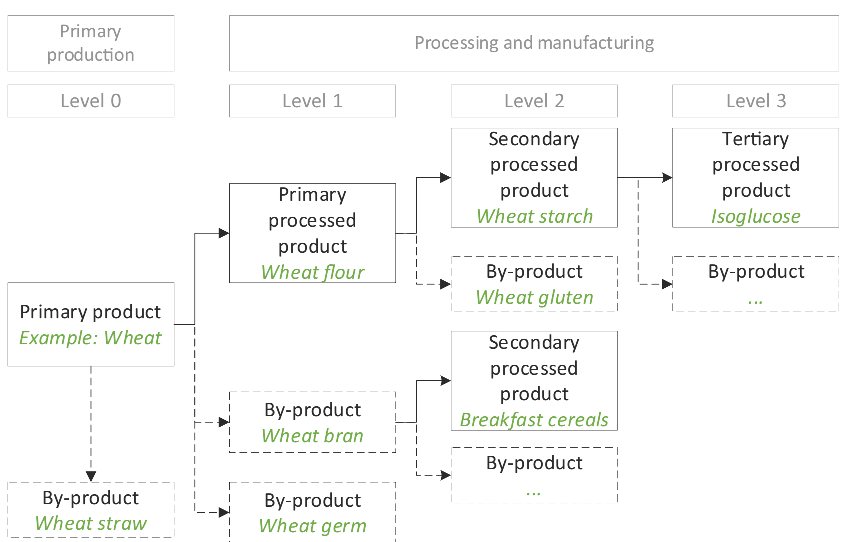


Fig. 3 Product and by-product sequence. Examples of products and by-products in a sequence are provided in Italics. Own elaboration based on the FAOSTAT [29]

We used the conversion factors to determine a by-product coefficient illustrating the amount of by-product generated per tonne of the target output product—either PPP or SPP (see Eq. 1). By knowing the by-product coefficients, we assessed how much food processing and manufacturing by-products can potentially become available in a region for conversion into value-added products and/or energy. For the by-products listed in Table 1, we estimated minimum, average, and maximum by-product coefficients ($c_{BP,i}$). If a conversion factor representing the average value was available, we first estimated the average by-product coefficient (see Eq. 1).

$$c_{BP,avg,i} = \frac{BP_{avg,i}}{PP_{avg,i}}, \tag{1}$$

where $c_{BP,avg,i}$—average by-product coefficient; i—item, i.e., processed crop or livestock product (Table 1); $BP_{avg,i}$—average share or weight of by-product with respect to the primary product for the respective item (i); $PP_{avg,i}$—average share or weight of the processed product with respect to primary product for the respective item (i).

Minimum and maximum by-product coefficient values were estimated based on data availability. If the average conversion factor value was known, then Eqs. (2) and (3) were used. While, if the average conversion factor value was not known, then Eqs. (4) and (5) were used.

$$c_{BP,min,i} = \frac{BP_{min,i}}{PP_{avg,i}} \tag{2}$$

$$c_{BP,max,i} = \frac{BP_{max,i}}{PP_{avg,i}} \tag{3}$$

$$c_{BP,min,i} = \frac{BP_{min,i}}{PP_{max,i}} \tag{4}$$

$$c_{BP,max,i} = \frac{BP_{max,i}}{PP_{min,i}}, \tag{5}$$

where BP_{min}—minimum share or weight of by-product with respect to the primary product for the respective item (i); BP_{max}—maximum share or weight of by-product with respect to the primary product for the respective item (i); PP_{min}—minimum share or weight of the processed product with respect to primary product for the respective item (i); PP_{max}—maximum share or weight of the processed product with respect to primary product for the respective item (i).

In the estimation of indirect by-products, the following approach was used:

$$c_{BP,avg,i} = \frac{BP_{avg,i}}{PPP_{avg,i} \bullet SPP_{avg,i}}, \tag{6}$$

where $PPP_{avg,i}$—average share or weigh of primary processed product with respect to primary product for the respective item (i); $SPP_{avg,i}$—average share or weight of the secondary processed product with respect to the primary processed product (i).

Minimum and maximum indirect by-product coefficient values were estimated based on data availability. If the average value was known, then Eqs. (7) and (8) were used. While, if the average value was not known, then Eqs. (9) and (10) were used.

$$c_{BP,min,i} = \frac{BP_{min,i}}{PPP_{avg,i} \bullet SPP_{avg,i}} \tag{7}$$

$$c_{BP,max,i} = \frac{BP_{max,i}}{PPP_{avg,i} \bullet SPP_{avg,i}} \tag{8}$$

$$c_{BP,min,i} = \frac{BP_{min,i}}{PPP_{max,i} \bullet SPP_{max,i}} \tag{9}$$

$$c_{BP,max,i} = \frac{BP_{max,i}}{PPP_{min,i} \bullet SPP_{min,i}}, \tag{10}$$

where $SPP_{min,i}$—minimum share or weight of processed product with respect to primary product for the respective item (i), $SPP_{max,i}$—maximum share or weight of processed product with respect to primary product for the respective item (i).

The annual by-product volumes (expressed in tonnes per year) were estimated (see Eq. 11) for each country using the production data (Table 1) and the expressed by-product coefficients.

$$BP_{i,j} = PP_{i,j} \bullet c_{BP,i}, \tag{11}$$

where $BP_{i,j}$—the volume of the by-product of the corresponding item in the respective country, t/year; $PP_{i,j}$—production volume of the corresponding item in the respective country, t/year; $c_{BP,i}$—average, minimum or maximum by-product coefficient; i—item, i.e., primary processed crop or livestock product; j—respective country.

The derived by-product coefficient values are presented in the Results section. Also, all coefficients, i.e., raw data extracted from the FAOSTAT database and other literature sources used to determine the by-product coefficient values are available in the table SM1.7 of supplementary material SM1. All by-products were estimated on fresh weight (wet basis).

2.4 Valorisation of by-products

After identifying the top 20 processed crop and livestock products produced in each of the Northern European countries, i.e., a list of 40 unique items (Table 1), we conducted a literature review on biological valorisation methods of the identified by-products. We used information only from original research articles and excluded review articles. For this study, we defined biological valorisation (bio-valorisation) as any valorisation, which uses living organisms (microorganisms, macroscopic fungi) or enzymes that are produced by these organisms. Valorisation methods, which require the use of multiple types of by-products, were included only if all these by-products were derived from the studied crop and livestock products. Methods, that require the use of one type of by-product and a different type of waste (non-food waste, for example, manure), were excluded.

We focused our research on bio-valorisation as biotechnology is a rapidly growing research field with new biological transformation methods being developed constantly, while, e.g. chemistry is a more established field. Bio-valorisation methods are often developed to replace chemical methods because they tend to create less harm to environment. Chemical transformation methods often require high temperatures and the use of toxic reagents while in biotechnology this is mostly avoided.

In total, 62 original research articles fit the criteria (see References_Table SM2.1 of supplementary material SM2). The selected articles were very different. Some focused on improving the bio-valorisation process (including genetically modifying microorganisms) to increase the amount of product that can be gained from it, while others tried to test whether a certain strain of bacteria is able to produce any valuable compounds from a food industry by-product. What all included articles have in common is that they used microorganisms to obtain value-added products from food industry by-products.

From the selected articles, we gathered information, such as the function of the by-product in value-added product production, the concentration or amount of by-product used, methods used for by-product pre-treatment, the technology used for valorisation, the organisms used, organism biomass concentration, specific growth rate, the scale of the process, setup type, oxygen availability to the organisms and its saturation, system pH and pH control method, the temperature of the process environment, supplementary carbon and nitrogen sources and their concentrations, the concentration of carbon source that was consumed, the value-added products that were produced and their concentrations, type of value-added products, and downstream processing methods. See Table SM2.1 of supplementary material SM2 for more detail. By-product function in the valorisation process was classified into four categories: carbon source, nitrogen source, carbon and nitrogen source, and *other*. These categories were based on the most common uses of by-products in valorisation processes. If the by-product function in the valorisation process was not explicitly stated, then it was determined based on other components used in the process. For example, if no other carbon source was listed in the composition of the fermentation medium then it was inferred that the by-product was used as the carbon source.

Pre-treatment methods were considered any processes that the by-product was involved in before its conversion to a value-added product. Uncommon, very specific methods and ones used in only one paper were grouped under the category *other*. Mechanical reduction of particle size of the by-product was not included as a pre-treatment method.

Biological valorisation technologies were divided into six categories: submerged fed-batch fermentation, submerged batch fermentation, solid-state fermentation, submerged continuous fermentation, enzymatic hydrolysis, and *other*. The scale of the process was expressed in terms of working volume. This parameter was grouped into four categories: less than 1 L, 1 L to 10 L, 10 L to 50 L, and more than 50 L. Higher volumes were not included because most of the reviewed articles were written about lab-scale processes with small working volumes. In the cases where solid-state fermentation was used and the amount of substrate used was expressed in grams (as opposed to g/L), we assumed 1000 g of solid substrate used would correspond to 1 L of working volume.

The setup types used for the valorisation process were classified into two categories: flask and bioreactor. If the setup type was not mentioned in the text, then it was determined based on the culture conditions. For example, if stirring speed or aeration rate was mentioned in the Materials and Methods section, then the bioreactor setup was selected. Conversely, if incubation on a shaker or agitation speed was mentioned, then the flask setup was chosen. The flask category included not only Erlenmeyer flasks, but also glass jars, Roux bottles, and Petri dishes. The bioreactor category included not only the stirred-tank bioreactors that are commonly used for submerged fermentation but also tray bioreactors and packed-bed bioreactors that are used in solid-state fermentation.

The value of biomass concentration at the beginning and end of the process was expressed in the units that were used in the reviewed articles (e.g., CFU/mL, OD, spores/g of the substrate). If biomass concentration was not mentioned in the text, in some cases, its approximate value could be determined based on graphs in the article. Such values were marked as approximate using the "~" sign.

Oxygen availability in the process environment was described using three categories: anaerobic, aerobic, and microaerobic. The default category was aerobic, and all processes were assumed to belong to that category unless stated otherwise. Oxygen saturation was expressed in percent. Information about the parameter was only available for the processes performed in bioreactors where the oxygen saturation is controlled.

The pH control in the process environment was classified into three categories: continuous control, pH buffer, and *none*. Continuous control of pH can only be achieved in a bioreactor. In flasks, the only options to control the pH are by adding a buffer to the medium at the beginning of the process or not to control the pH at all. We also recorded the reported pH value of the process environment throughout the process (if continuous pH control was employed) or at the beginning of the process if no pH control or a buffer was used.

We defined supplementary carbon or nitrogen sources if the by-product had a different function in the valorisation. In some cases, supplementary carbon or nitrogen sources were also used in addition to the by-product even if it was meant to function as a carbon or nitrogen source. We defined downstream processing methods as any method that was used after the value-added product production phase to obtain a crude or purified value-added product.

We classified all the value-added products that were reported in the reviewed articles into eight categories: acids, alcohols, antioxidants, enzymes, polymers, proteins, sugars, and *other*. The acid category contains products, such as acetic acid, lactic acid, and succinic acid. The alcohol category contains ethanol, xylitol, and 2,3-butanediol. If an acid is known as an antioxidant, then it was placed in the antioxidant category, rather than the acid one. The antioxidant category contains carotenoids, red pigment, bacteriochlorophyll, and polyphenols. If a product was an enzyme, it was placed in the enzyme category and not the protein one. The enzyme category contains products, such as CMCase, avicelase, and xylanase. Poly-acids (polyhydroxyalkanoates) were placed in the polymer category. The sugar category contains products, such as galacto-oligosaccharides, xanthan gum, and alginate. Amino acids, fatty acids, and other products not mentioned previously, such as phosphates, lipids, and biosurfactants, were put into the category *other*.

To assess if by-product composition has an impact on the types of obtainable value-added products, we divided the by-products into groups based on their composition: carbohydrate-rich, fibre-rich, protein-rich, lipid-rich, and high in inorganic compounds. We defined a by-product as being rich in a component if it contained more than 30% (or 30 g/100 g dry weight) of the specific component.

3 Results

3.1 By-product coefficients

Table 2 lists all by-products that arise during production of the processed products analysed in this study (listed in Table 1). Each by-product is characterised by minimum, average, and/or maximum by-product coefficient value illustrating the amount of by-product generated per tonne of the respective target output product. The table should read as, for example, [brewer's spent grain] from [beer of barley, malted] is generated on an average amount of 0.12 t/t. An empty cell in Table 2 indicates that the respective by-product coefficient was not estimated in the study due to insufficient quantitative data.

3.2 By-product estimates and value-added products

The by-product coefficient estimates show that the production of various items such as raw cane or beet sugar, cheese, rapeseed and soya bean oil, potato flour, and starch results in a higher proportion of by-product compared to the target product (see Table 2). In terms of food production volume, beer of barley and wheat and meslin flour are the most abundant food products in the region (see Table 1). However, when considering the volume of by-products, the production of cheese from whole cow milk, raw cane or beet sugar, potato starch, and rapeseed oil generates a higher volume of by-products compared to the production volume of beer of barley and wheat and meslin flour. This is due to the by-product to processed food product ratio.

Figures 4, 5, 6, 7, 8, 9, 10, 11 and 12 show the distribution of by-product volumes resulting from the production of PPP and SPP. In the figures, the bars represent the average values of the by-product volumes, and the error bars represent the possible range between the minimum and maximum values of the by-product volume based on the estimated minimum and maximum by-product coefficient values. A missing bar or error bars indicates that no average or minimum, or maximum by-product coefficient value was determined (see Table 2), and thus no by-product volume was quantified. Graphs are presented in descending order of by-product volumes.

3.2.1 Dairy

The highest average annual by-product volume was estimated for fresh whey, a by-product of cheese from whole cow milk production. Average volume of whey in the analysed Northern European region amounted to 4442.3 kt/year. Denmark covered 52% of cheese production in the whole region in the respective period, thus, accounting for the highest generation of fresh whey, on average 2318.3 kt/year (Fig. 4). The lowest volume of fresh whey was estimated in Iceland, an average of 68.9 kt/year.

Whey (including whey permeate) was among the most used by-products in the analysed valorisation research.

Table 2 By-product coefficients for the analysed 40 items (see Table 1 for products and Table SM1.7 of supplementary material SM1 for all calculations)

By-product	Item (product in the production of which the by-product arises)	Type of by-product	Item group	By-product coefficient value			Northern European country with the highest by-product volume
				Min	Ave	Max	
Brewer's spent grain	Beer of barley, malted	Direct	Brewery and winery		0.12		Denmark
Brewery spent yeast	Beer of barley, malted	Direct	Brewery and winery		0.02		Denmark
Marc of grapes	Wine	Direct	Brewery and winery	0.14	0.29	0.43	Estonia
Bran of maize	Flour of maize	Direct	Cereals		0.13	0.24	Sweden
Germ of maize	Flour of maize	Direct	Cereals		0.07	0.1	Sweden
Bran of rye	Flour of rye	Direct	Cereals	0.18	0.21	0.35	Finland
Bran of oats	Oats, rolled	Direct	Cereals	0.28	0.38	0.57	Finland
Oat hulls	Oats, rolled	Direct	Cereals	0.53	0.57	0.6	Finland
Barley hulls	Pot barley	Direct	Cereals			0.12	Lithuania
Bran of barley	Pot barley	Direct	Cereals		0.26	0.42	Lithuania
Maize gluten	Starch of maize	Direct	Cereals		0.13		Lithuania
Bran of maize	Starch of maize	Indirect	Cereals		0.18		Lithuania
Germ of maize	Starch of maize	Indirect	Cereals		0.10		Lithuania
Wheat gluten	Starch of wheat	Direct	Cereals			0.04	Lithuania
Bran of wheat	Starch of wheat	Indirect	Cereals	0.13			Lithuania
Germ of wheat	Starch of wheat	Indirect	Cereals	0.03			Lithuania
Bran of wheat	Uncooked pasta, not stuffed, or otherwise prepared	Indirect	Cereals		0.23		Latvia
Germ of wheat	Uncooked pasta, not stuffed, or otherwise prepared	Indirect	Cereals		0.03		Latvia
Bran of wheat	Wheat and meslin flour	Direct	Cereals	0.13	0.23	0.33	Sweden
Germ of wheat	Wheat and meslin flour	Direct	Cereals	0.03	0.03	0.04	Sweden
Fruit pulp for feed	Orange juice	Direct	Fruit and vegetables		1.00		Denmark
Molasses	Raw cane or beet sugar (centrifugal only)	Direct	Fruit and vegetables		0.29		Denmark
Sugar beet pulp, wet	Raw cane or beet sugar (centrifugal only)	Direct ↑	Fruit and vegetables		3.57		Denmark
Tomato pulp	Tomato juice	Direct	Fruit and vegetables			0.25	Latvia
Rapeseed cake	Rapeseed or canola oil, crude	Direct ↑	Oils and fats	1.18	1.58	1.58	Denmark
Soybean cake	Soya bean oil	Direct ↑	Oils and fats		4.39		Norway
Groundnut shells	Prepared groundnuts	Indirect	Pulses, nuts, and oilseeds	0.83			Norway
Potato peels	Flour, meal, powder, flakes, granules, and pellets of potatoes	Direct ↑	Roots and tubers	0.68		2.22	Denmark
Potato pulp, dry	Starch of potatoes	Direct	Roots and tubers	0.19		0.34	Denmark
Potato pulp, wet	Starch of potatoes	Direct ↑	Roots and tubers	1.91		3.38	Denmark
Cocoa husks and shells	Cocoa butter, fat, and oil	Indirect	Stimulants		0.53		Sweden
Cocoa husks and shells	Cocoa powder and cake	Indirect	Stimulants		0.47		Sweden
Coffee silverskin	Coffee, decaffeinated, or roasted	Direct	Stimulants		0.05		Sweden
Whey, fresh	Cheese from whole cow milk	Direct ↑	Dairy	2.00		8.50	Denmark
Eggshells	Eggs, liquid	Direct	Eggs		0.14		Latvia

↑—An upward arrow indicates that in the production of a particular product, the amount of the by-product is greater than the amount of the target product (PPP or SPP).

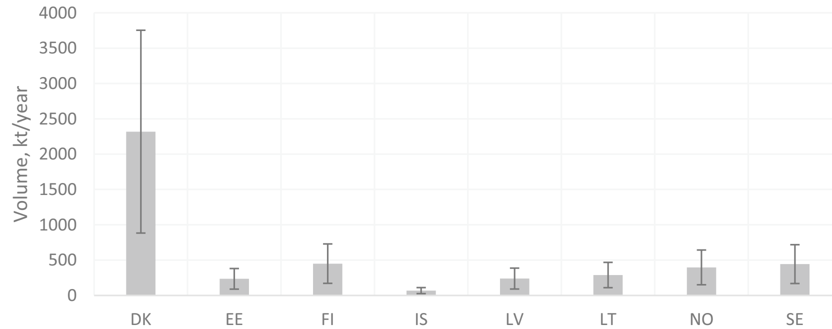


Fig. 4 Annual average volume (2015–2020) of fresh whey—the by-product of cheese (from fresh cow milk) production

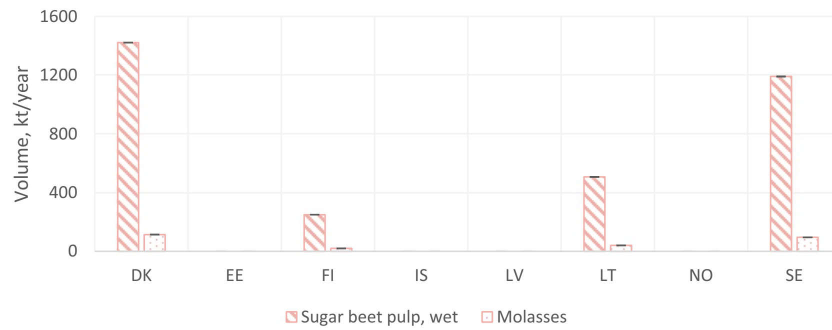


Fig. 5 The annual average volume (2015–2020) of sugar beet pulp (wet basis) and molasses—the by-products of sugar production (Estonia, Iceland, Latvia, Norway—no production data)

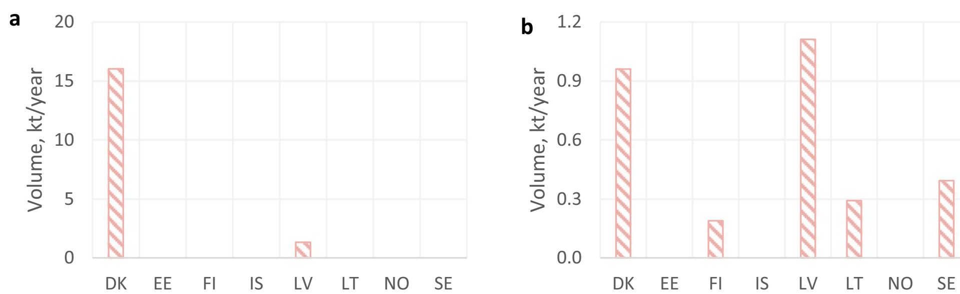


Fig. 6 The annual average volume (2015–2020) of **a** fruit pulp—the by-product of orange juice production (Estonia, Finland, Iceland, Lithuania, Norway, Sweden—no production data) and **b** tomato pulp—the by-product of tomato juice production (Estonia, Iceland, Norway—no production data)

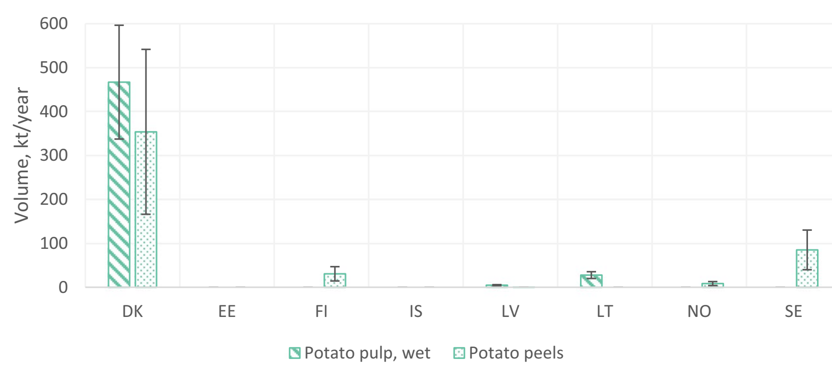


Fig. 7 The annual average volume (2015–2020) of potato pulp (wet basis) and potato peels—the by-products of processed potato products, i.e., potato starch (Estonia, Finland, Iceland, Norway, Sweden—no production data) and flour (Estonia, Iceland, Lithuania—no production data)

Whey was used as a carbon source in most cases, but it was also used as both a carbon and nitrogen source or had other uses in a few cases. Except for solid-state fermentation, every reviewed technology category was used in at least one study on whey valorisation. Among the obtained products in the analysed research on whey valorisation into value-added products are an alcohol (ethanol), acids (galactonic, acetic, tartaric), an antioxidant (red pigment), enzymes (lipase, flavanone 3-hydroxylase, chalcone 3-hydroxylase), a polymer (polyhydroxyalkanoates), sugars (galacto-oligosaccharides,

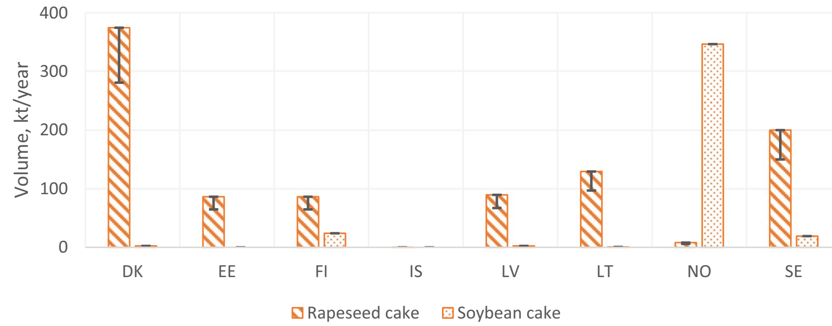


Fig. 8 The annual average volume (2015–2020) of rapeseed cake and soybean cake—the by-products of rapeseed and soya bean oil production

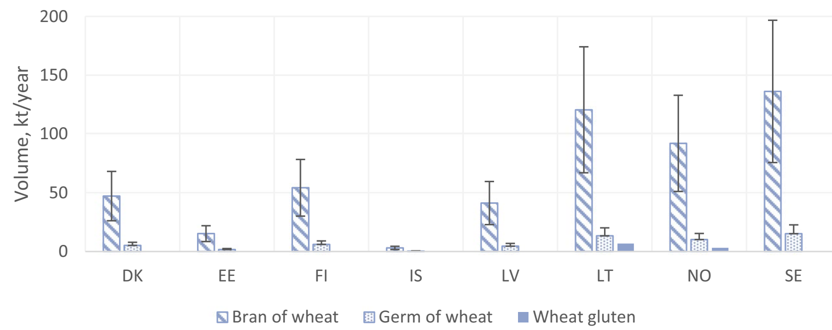


Fig. 9 The annual average volume (2015–2020) of bran of wheat, germ of wheat, and wheat gluten—the direct by-products of wheat and meslin flour production (wheat gluten represents the maximum values, not the average values)

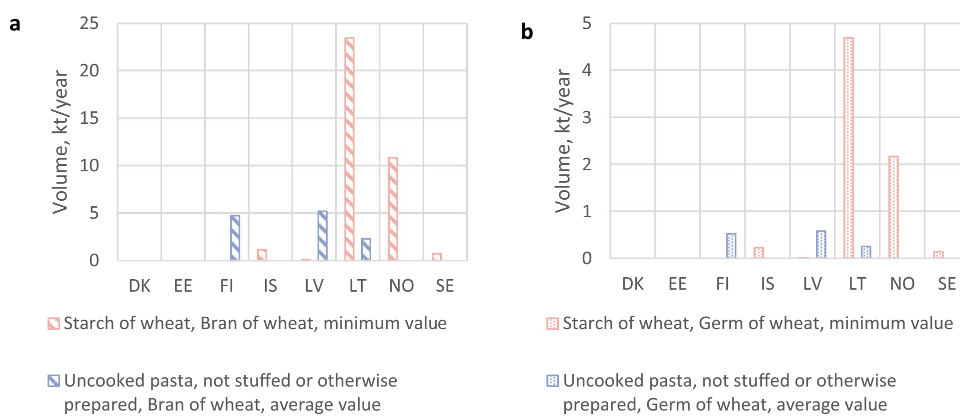


Fig. 10 The annual average volume (2015–2020) of **a** bran of wheat, an indirect by-product of starch and pasta production; **b** germ of wheat, an indirect by-product of starch (Denmark, Estonia, Finland—no production) and pasta (Denmark, Estonia, Iceland, Norway, Sweden—no production) production

xanthan gum), and *other* products not classified in the above categories, such as lipids and surfactin (for details see Table SM2.1 in the Supplementary material SM2).

3.2.2 Fruits and vegetables

In the fruit and vegetable item group, pulp and molasses are the main by-products. The highest average annual volumes of sugar beet pulp (wet basis) were estimated for Denmark and Sweden (1421.3 kt/year and 1190.7 kt/year, respectively). The generation of molasses was significantly lower than sugar beet pulp (Fig. 5).

In by-product valorisation studies, sugar beet pulp, molasses, and pectin were used as a carbon source. Most often the technology used for the valorisation of these by-products was submerged batch fermentation, though submerged fed-batch fermentation, solid-state fermentation, and enzymatic hydrolysis were also used. Studies reported solutions to valorise sugar production by-products into acids (acetic, succinic, ferulic, lactic), alcohols (ethanol, 2,3-butanediol), enzymes (xylanase, exo-polygalacturonase, laccase) and other products (L-lysine, hydrogen, 5-aminolevulinic acid, acetoin).

Orange fruit pulp was generated in Denmark and Latvia where orange juice production was reported (Fig. 6a). Tomato pulp was the least generated by-product in the item group, with production data available for Denmark, Finland, Latvia, Lithuania, and Sweden (Fig. 6b).

In valorisation studies, fruit pomace (grape, lemon, orange, tomato) was mostly used as both a nitrogen and

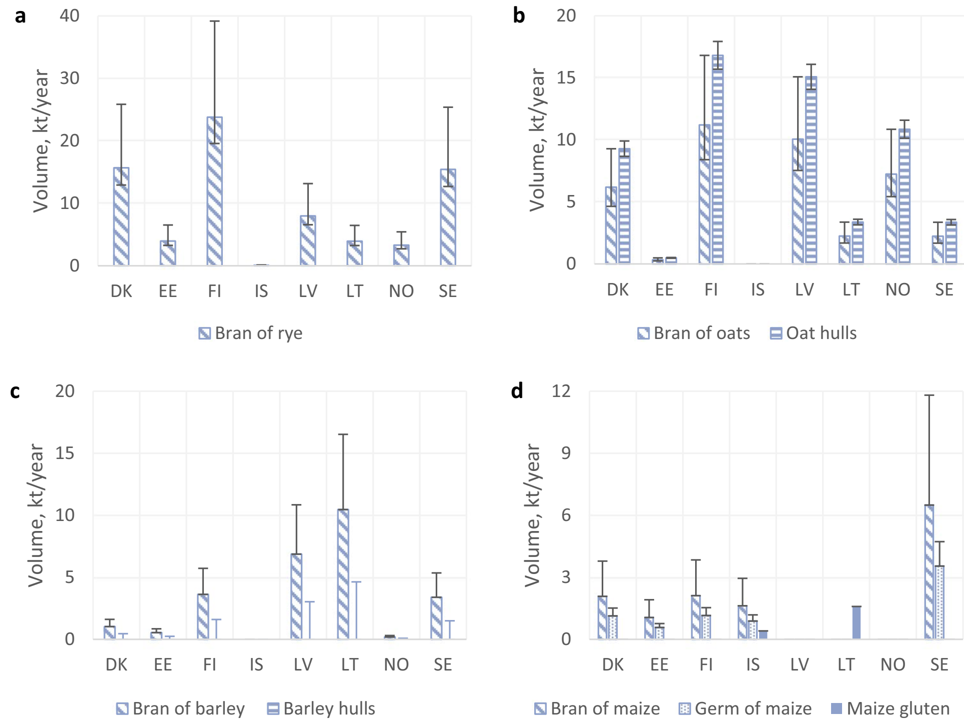


Fig. 11 The annual average volume (2015–2020) of **a** bran of rye—the by-product of rye flour production; **b** bran of oats (average value) and oat hulls (maximum value) —the by-products of oat product production (Iceland—no production data); **c** bran of barley and barley hulls—the by-products of barley product production (Iceland—no production data); **d** bran of maize, germ of maize, and maize gluten—the by-products of maize flour (Latvia, Lithuania, Norway—no production) and maize starch (Denmark, Estonia, Finland, Latvia, Norway, Sweden—no production) production

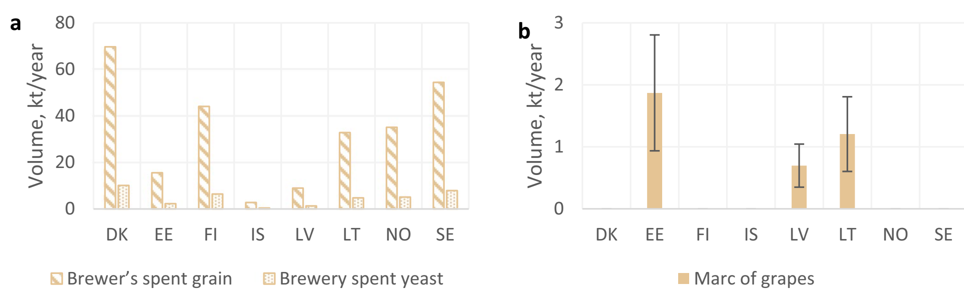


Fig. 12 The annual average volume of **a** brewer's spent grain and brewery spent yeast—the by-products of beer production and **b** marc of grapes—the by-product of wineries (Denmark, Finland, Iceland, Norway, Sweden—no production)

carbon source, or as a carbon source or a nitrogen source. In all cases, the valorisation technology used for these by-products was submerged batch fermentation in flasks with a working volume of under 1 L. Obtained value-added products belonged to the acid (acetic acid), alcohol (ethanol), enzyme (xylanase), and protein (single-cell protein) categories.

3.2.3 Roots and tubers

Potato pulp represents the by-product of potato starch production (produced only in Denmark, Latvia, and Lithuania), while potato peels—the by-product of potato flour production, produced in all countries except Estonia, Iceland, and Lithuania. As Denmark had the highest production of potato flour and potato starch in the region, i.e., 74% and 94% respectively, it also accounted for the highest volume of these by-products (Fig. 7). Potato pulp (wet basis) amounted to 467.0 kt/year and potato peel to 353.9 kt/year in Denmark. The smallest volume of potato pulp and peels was estimated for Latvia, 4.7 kt/year and 186.0 t/year, respectively. While the total production quantity of potato starch was smaller than the quantity of potato flour, it had higher volume of by-products than potato flour.

Four research articles on the valorisation of potato peels were analysed. In three out of the four studies, this by-product was used as a carbon and nitrogen source in submerged batch fermentation. In the remaining study, it was used as a carbon source in solid-state fermentation. The value-added products produced from potato peels included enzymes (laccase, manganese peroxidase), a sugar (alginate), and a product in the *other* category (lipids).

3.2.4 Oils and fats

Rapeseed cake was formed in all the analysed countries, with the highest volume in Denmark, 374.7 kt/year (Fig. 8). While the smallest volume was estimated in Iceland, on average 129.0 t/year. Soybean cake was formed in all countries, except Estonia. The highest soybean cake volume of 346.6 kt/year was observed in Norway, as 88% of all soya bean oil in the region was produced there. The smallest volume was estimated in Lithuania, 746.0 t/year.

Different oil crop (rapeseed, soybean) cake and meal uses in valorisation processes fell under all the defined by-product use categories (carbon source, nitrogen source, both or other), but they were mostly used as a carbon source or as both a carbon and nitrogen source. All valorisation technologies, except continuous fermentation, were used for oil crop cakes or meals at least once. These by-products were converted into antioxidants (carotenoids, bacteriochlorophyll), enzymes (xylanase, lipase, pectinase, avicelase), a protein (single cell protein), a sugar (carbohydrates), and *other* products (e.g., uridine and acetoin). One study was also devoted to the simultaneous valorisation of wheat bran and rapeseed meal. Here, the bran served as a carbon source and the rapeseed meal as a nitrogen source. Submerged batch fermentation of these two by-products yielded an enzyme (xylanase).

3.2.5 Cereals

Among cereal crops, wheat bran was the most abundant by-product in the whole Northern European region, with the highest volume of 136.2 kt/year in Sweden and the lowest volume of 3.1 kt/year in Iceland. Bran of wheat and germ of wheat are both direct by-products of wheat and meslin flour (PPP) production. In turn, wheat gluten is a direct by-product of wheat starch (SPP) which was produced in Iceland, Lithuania, Norway, and Sweden. The highest wheat gluten volume was estimated for Lithuania, while the lowest—for Latvia.

Wheat starch and pasta are SPPs that are produced from wheat flour (PPP). While the bran of wheat and germ of wheat are not direct output flows of wheat starch and pasta production, these by-products can be considered indirect by-products produced in the previous stages of food production. Bran of wheat (Fig. 10a) and germ of wheat (Fig. 10b) are also indirect by-products of SPPs, wheat starch, produced in all countries except Denmark, Estonia, Finland, and pasta, produced only in Finland, Latvia, and Lithuania.

Bran of rye is a direct by-product of rye flour production with the highest average volume of 23.8 kt/year in Finland and the lowest of 77.0 t/year in Iceland (Fig. 11a).

The highest volume of oat hulls and oat bran was estimated for Finland, 16.8 kt/year and 11.2 kt/year respectively. The lowest volume was estimated for Estonia, 492.0 t/year and 328.0 t/year respectively (Fig. 11b). Bran of barley and barley hulls are by-products of pot barley production. In Fig. 11c, the bran of barley represents the annual average value. The highest volume of barley bran (10.5 kt/year) was estimated for Lithuania, while the lowest value (194.0 t/year) was for Norway. The volume of barley hulls is represented with an error bar indicating the maximum available value (no average values were estimated due to the lack of by-product coefficients).

Bran and germ of maize are by-products of maize flour (PPP), produced in all countries, except Latvia and Norway. The highest volume of these by-products was estimated for Sweden, 6.5 kt/year of bran and 3.5 kt/year of germ (Fig. 11d). In turn, maize gluten is a by-product of maize starch (SPP) production, which was produced only in Lithuania and Iceland, amounting to 1.6 kt/year and 0.4 kt/year, respectively.

Bran of various cereals (barley, maize, oat, rice, rye, wheat) was used in valorisation as a carbon source or as both a carbon and nitrogen source. The use of wheat and rice brans was reported most often. Value-added products from bran were produced using all technologies, except continuous fermentation. In most cases, the process was performed in flasks with a working volume below 1 L. In a few studies, where rice bran valorisation was performed, the process was done in bioreactors with a working volume in the range of 1–10 L. The products obtained from different types of bran were alcohols (ethanol, isoamyl alcohol), acids (acetic, ferulic, lactic), an antioxidant (red pigment), enzymes (e.g., phytase and xylanase), a sugar (polysaccharides), and *other* products (e.g., isovaleric acid and lipids).

Hulls (husks) from barley, rice, or soybean were used in value-added product production as carbon sources or as carbon and nitrogen sources. All research studies, except for one, employed submerged batch fermentation. Most studies were conducted using the flask setup with a working volume under one litre. The products that were obtained from different types of hulls included an alcohol (ethanol), enzymes (α-amylase, laccase, peroxidase), a sugar (microcrystalline cellulose), and *other* products (biosurfactants, lipids).

3.2.6 Brewery and winery

Brewer's spent grain was identified as the main by-product of beer production, with the highest volume of 69.8 kt/year in Denmark and the lowest of 2.8 kt/year in Iceland (Fig. 12a). Hot trub (spent hops), another beer production by-product, is formed from spent hops, if used in the brewing process. While not included in the graph, the highest average hot trub volume of 0.6 kt/year was estimated for Denmark. Also, comparatively smaller amounts of grape marc, a by-product of wine production, were generated in the region (Fig. 12b).

Brewer's spent grain was among the most studied by-products in the analysed valorisation research. Brewer's spent grain was used as a carbon source or as both a nitrogen and carbon source in submerged batch or solid-state fermentation. This by-product was valorised to produce different alcohols (ethanol, xylitol), antioxidants (polyphenols), enzymes (e.g., laccase and cellulase), and polymers (polyhydroxyalkanoates, polyhydroxybutyrate).

3.2.7 Other by-products

The highest volume of eggshell by-products was generated in Latvia, equalling to on average 0.59 kt/year. In turn, the smallest volume was estimated for Estonia, 0.14 kt/year. Eggshells were valorised together with brewery wastewater. Even though we did not quantify wastewater that is generated during food manufacturing processes, we included this valorisation case [40] in our study by assuming that food processing generates enough wastewater to be valorised. In that study, eggshells were used as a $CaCO_3$ source and immobilization support for cells, and brewery wastewater was a carbon and nitrogen source. One acid (fumaric) and one alcohol (ethanol) were produced in submerged batch fermentation of these by-products. One study reported the valorisation of eggshell membrane that was used in submerged batch fermentation as a carbon and nitrogen source. Protein hydrolysate was produced in that process.

Coffee (decaffeinated or roasted) was reported to be produced in Denmark (though not among the top 20), Sweden, Finland, Norway, and Iceland. The highest average volume of coffee silverskin, a direct by-product of coffee roasting, reaching 4.5 kt/year, was estimated for Sweden.

Groundnut shells are an indirect by-product of prepared groundnuts. Prepared groundnuts were only produced in Denmark and Norway and their minimum by-product, i.e., groundnut shells, volume amounted to 3.1 kt/year and 5.6 kt/year in Denmark and Norway, respectively.

Cocoa husks and shells are indirect by-products of cocoa powder and cake, as well as cocoa butter production. While produced in all the analysed countries, they ranked among the top 20 products only in Iceland. However, Iceland had the lowest average volume estimates among the analysed countries. Cocoa husks and shells produced from cocoa powder and cake amounted to 81.6 t/year, while those from cocoa butter, fat, and oil production amounted to 81.5 t/year. The highest volume estimates were made for Sweden, amounting to 980.4 t/year and 980.2 t/year, respectively.

Apart from eggshell by-products, for the other by-products outlined in this section, no bio-valorisation methods were found through literature analysis.

3.3 By-product bio-valorisation into value-added products: characterisation

In this study, bio-valorisation methods were identified for all the analysed by-products, except the germ or gluten, brewery spent yeast, cocoa husks and shells, coffee silverskin, groundnut shells, hot trub, oat hulls, and potato pulp. All the compiled biological valorisation methods include the use of fermentation technologies or enzymatic reactions. Among the analysed research articles, bacteria were used in food industry by-product valorisation more often than fungal species (bacteria used in 34 articles (Fig. 13a), fungi (other) used in 27 articles (Fig. 13b), fungi (yeast) used in 22 articles (Fig. 13c)). *Saccharomyces cerevisiae* and *Escherichia coli* were the most used species. Both are popular model organisms with available genetic engineering protocols and known optimal growth conditions, which could explain why they were used most often. In fact, *E. coli* was genetically engineered in all the studies where it was used.

E. coli, Kluyveromyces marxianus, Bjerkandera adusta, Fomes fomentarius, and *Schizophyllum commune* were the microorganisms that were reported to produce the highest diversity of different products. *E. coli* could produce enzymes, alcohols, and *other* products, and *K. marxianus* produced alcohols and *other* products, while the latter three species could only produce enzymes. In fact, most of the fungi not classified as yeast could only produce enzymes, while the value-added products obtainable from most of the yeast species were alcohols and acids. The reason why many different products could be produced by *E. coli* lies in genetic engineering.

Figure 14 shows the different value-added product types producible using by-products belonging to different composition groups. Four out of five defined composition groups were represented in the analysed scientific articles on by-product valorisation (excluding lipid-rich by-products). Oat and rice by-products, i.e., bran and hulls, as well as whey, sugar beet by-products and maize cake, are examples of carbohydrate-rich products. Cereal (wheat, rye, maize) bran, potato peels, marc of grape, and tomato pulp are examples of fibre-rich products. Rapeseed and soybean cake and meal, maize and wheat gluten and eggshell membranes are examples of protein-rich products. In many cases, the composition data was incomplete (the sum of all components was not close to 100% or 100 g/100 g). As a result, some by-products (e.g., hot trub, orange fruit, and citrus pulp) were not categorised in any of the five composition groups. This could also mean that some by-products could belong to other groups, not just the ones identified in this study (see Table SM2.2 of supplementary material SM2 for more detail).

There is no observable relation between the by-product composition group and the types of obtainable value-added products. Conversely, differences in the range of value-added

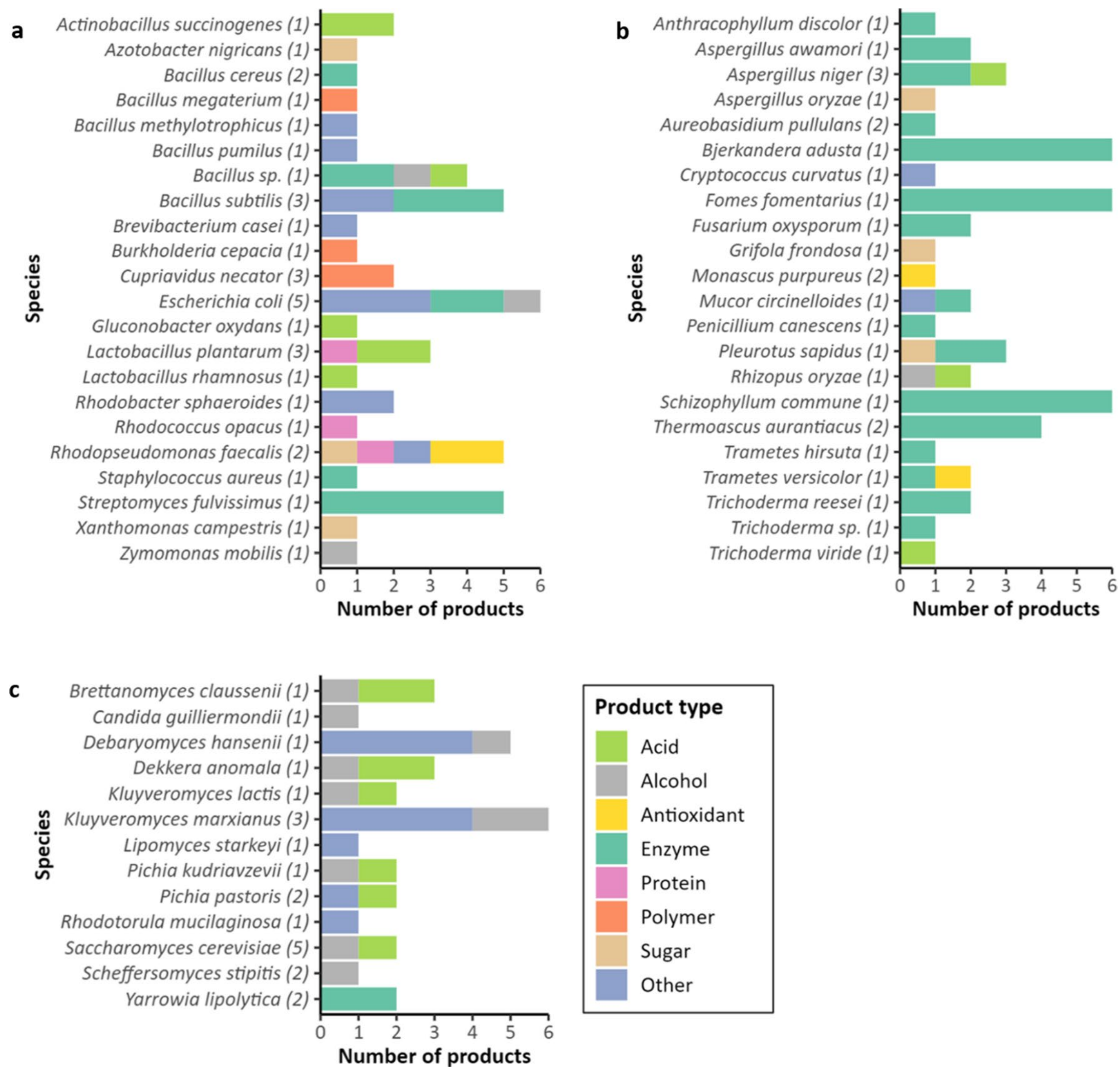


Fig. 13 Different value-added product types producible from food processing and manufacturing by-products by **a** bacterial species; **b** fungal (other than yeast) species; **c** fungal (yeast) species. The number in parentheses after each species represents the number of times this species was used in by-product valorisation research

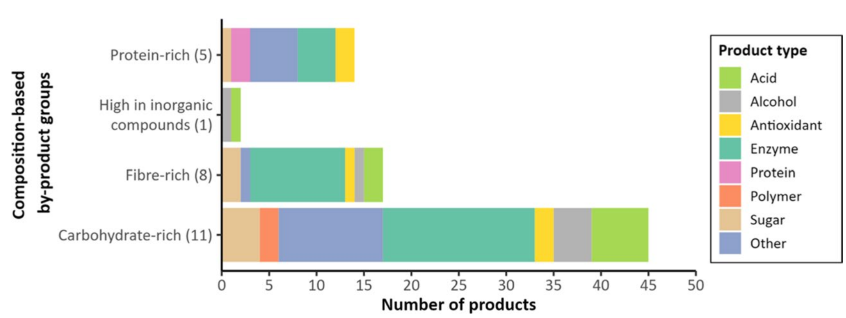


Fig. 14 Different product types produced from by-products belonging to different composition groups. Numbers in parentheses after the name of the composition group represent the number of studied by-products that belong to the group

products produced depending on the group of microorganisms can be observed in Fig. 13. Most fungi (other) produced enzymes, while most fungi (yeast) produced alcohols and acids. Therefore, knowledge about the by-product composition appears not to be useful for determining the type of value-added products that could potentially be produced. However, this data can be useful for ensuring that the microorganism selected for the process can utilise the selected by-product. All terrestrial plants, including crop-derived by-products, contain hemicellulose [41]. To fully utilise such by-products, it is necessary to use a microorganism species which can metabolise hemicellulose. For example, brewer's spent grain, a carbohydrate-rich substrate, can be used by fungal (other) species *Aureobasidium pullulans* to produce the enzyme xylanase [42]. The choice of microorganism depends not only on the composition of the substrate to be used but also on the desired value-added product. While the natural characteristics of a species can be changed using genetic engineering the approach is not always straightforward. Therefore, it is necessary to assess the feasibility of using genetic engineering to introduce new pathways for value-added product production or chemical compound utilisation.

In most cases, macroelements, microelements, vitamins, or additional substrates were also added to the fermentation medium. These additives might increase the cost and the impact on the environment of the process. Thus, it could be beneficial to research the composition of by-products to determine if they contain any of the macroelements, microelements, or vitamins necessary for value-added product production and their potential as a cheaper alternative to pure compounds. In most cases, the by-product used was also subjected to various pre-treatments to make it more available for microbial degradation or modification, which can also increase the cost of the valorisation. Hence, more research on developing sustainable and cheap pre-treatments is needed.

3.4 Types of value-added products obtained through valorisation

Among the analysed studies, xylanases emerged as the predominant value-added product, being produced in 22 out of 107 analysed by-product valorisation approaches (see Table SM2.1 of supplementary material). The second most common product was ethanol (produced in 16 valorisation approaches), followed by acetic acid (produced in nine approaches).

Xylanases are enzymes that break down xylan, a constituent of hemicellulose [43]. They can be used as a substitute for ClO_2 in the bleaching process of paper production, which would make this process more sustainable [44]. Xylanases can also be used to improve the quality of bread, decrease the viscosity of fruit juice, and increase feed digestibility [45]. As can be seen in Fig. 14, most by-products used in the analysed studies are carbohydrate-rich and judging by the microorganisms' ability to produce xylanases, many of the analysed carbohydrate-rich products contain hemicellulose. Hence, the organisms that can break down and use hemicellulose-containing by-products as a carbon source can produce xylanases.

While the units used to express the concentrations of value-added products varied in all the product groups, the enzyme group's products had by far the most variability in units. Thus, the results concerning enzyme production were the most difficult to interpret. The effectiveness of enzyme production was most often reported in units per gram (U/g) or units per millilitre (U/mL). Authors of most of the studies failed to define the enzyme unit (U) that they used. The international enzyme unit (IU) is defined as the amount of enzyme it takes to catalyse the transformation of 1 μmol of substrate per minute [46]. Although the IU was most likely used in most studies, the used unit should still be clearly defined in each study to avoid confusion. This uncertainty made it difficult to name a study where a product from the enzyme group was produced in the highest concentration, but Antoine et al. [47] probably reached the highest production level of xylanase. When xylanase concentration was expressed in U/g of the substrate, Antoine et al. [47] achieved 18,895 ± 778 U/g of substrate using soybean cake as the substrate. The highest result expressed in U/mL was achieved by Torkashvand et al. [48]. They produced 108.5 U/mL xylanase from tomato pomace.

Ethanol is an alcohol that can be produced by many microorganisms during carbohydrate fermentation [49]. In the analysed research articles, when ethanol was one of the value-added products, yeast species were commonly used as the producing organism. Acetic acid was produced mostly as an additional product in ethanol or other acid production by yeast and bacteria. The highest titre for ethanol was 19.5 g/L in a study by Ozmihci and Kargi [50], where they used whey as the carbon and nitrogen source in continuous fermentation. The highest titre of acetic acid (ca. 15 g/L) was obtained by Marzo et al. [51] using sugar beet pulp as a carbon source. They also produced 30 g/L of lactic acid during the same fermentation.

Overall, in the alcohol group, Erian et al. [52] achieved the highest titre for a product. They obtained 56.3 g/L ± 2.0 g/L of 2,3-butanediol using sugar beet molasses as a carbon source. In the acid group, lactic acid reached the highest titre of 123 g/L which was achieved by Li et al. using rice bran as a carbon source [53].

The highest titre for an antioxidant expressed in g/L was achieved by Saejung and Sanusan [54]. They produced ca. 2 g/L of bacteriochlorophyll using soybean meal as a carbon and nitrogen source. They simultaneously obtained another antioxidant, carotenoids, achieving a titre of 331.1 mg/L. In addition to the two antioxidants, carbohydrates, lipids, and single cell protein were also obtained.

Products in the protein group were produced from lemon pulp, orange pulp, eggshell membrane, and soybean meal. All studies, where single cell protein was produced, achieved a titre below 2 g/L [54, 55].

The highest titre for a product in the sugar group was achieved for galacto-oligosaccharides. Simovic et al. [56] produced 62 g/L of this product from whey. Some of the highest titres for products in the group *other* were for uridine, acetoin, and L-lysine. Fan et al. [57] produced uridine and acetoin simultaneously, achieving titres of 40.62 g/L and 60.48 g/L for these products, respectively. Soybean meal was used as a pH-neutralising agent in the study. He et al. [58] produced 45.89 g/L of L-lysine using sugar beet molasses as a carbon source.

The highest result in polymer production was achieved by Domingos et al. [59] and Llimós et al. [60]. Domingos et al. [59] produced 10.62 g/L polyhydroxyalkanoates using whey as a carbon source. Llimós et al. [60] produced 9.0 ± 0.44 mg/g of substrate of polyhydroxyalkanoates using brewer's spent grain as a carbon source.

In the analysed studies, often a pre-treated food by-product was used in valorisation, making it difficult to estimate the actual amount of untreated by-product used. For example, reporting the amount of deproteinised whey used in fermentation. Often the amount of by-product used in the fermentation medium was reported as sugar equivalents, which means that the amount of by-product was adjusted so that a certain sugar concentration in the fermentation medium would be reached. Thus, the specific amount of by-product in the medium was not known. Sometimes the volume of the by-product was mentioned, instead of the weight.

In 79% of all compiled valorisation studies, flasks were used as the setup for value-added product production, and in 85% of cases, the working volume for the process was under 1 L. No study reported the use of a working volume exceeding 50 L (see sheet *Summary_SM2.1.* of supplementary material SM2). This clarifies that all the valorisation methods described in the analysed literature have been tested at the lab scale. Although it may be interesting to compare the different by-product valorisation methods based on the amount of product that could be produced, this information might lead to misleading conclusions as most studies were conducted using small working volumes. Yet, more studies are needed to assess whether scaling up these valorisation methods is possible and economically viable, particularly for the Northern European region given the obtained by-product estimates.

To some extent, the information availability of different value-added products from by-products is influenced by by-product composition and the frequency of that by-product's use in research. For example, carbohydrate-rich by-products, from which the highest number of value-added products could be produced, were the most abundant and the most-researched by-products in the analysed research articles (brewer's spent grain, whey and whey permeate). Thus, further research is needed to form a robust knowledge of how by-product composition affects obtainable value-added products.

4 Conclusions and further outlook

The circular bioeconomy promotes the cascade principle, giving priority to the production of value-added products. Several recent studies, including Caldeira et al., provide an overview of various transformation pathways, linking secondary substrates (food waste) to value-added products and their applications [20]. However, in reviewing the databases available to obtain up-to-date information on biorefinery feedstocks, processes, and products, Mukamwi et al. concluded that their usability is largely limited by the lack of detail of the information provided and the infrequency with which a database is updated and maintained [61].

In this study, we established a uniform method for estimating food industry by-product volumes in Northern European countries, drawing on FAO food production statistics and by-product information in the literature. The unique aspect of the study is the quantitative estimation of specific food processing by-products based on geographical area and the relation of these by-products to potential value-added products. Thus, providing new knowledge on the possible development of a circular bioeconomy in a regional context. This assumption is supported by Haller et al. study, which points out that resource quantification allows the identification of potentially underutilised resource flows whose transformation into value-added products could contribute to circular regional development [62].

However, it should be noted that the estimated by-product volumes refer to the overall situation in each of the analysed countries. A case study would be needed to assess the practical implementation of bio-valorisation in a specific region. Due to the lack of country-specific data in available literature, we quantified and applied uniform by-product coefficients across all countries. Nevertheless, this study offers a structured overview of by-product availability. Leveraging statistical data commonly reported to the FAO shows promise for potential assessment of by-product volumes in other countries too. Furthermore, a comprehensive examination of bio-valorisation methods within this study revealed diverse strategies to derive value-added products, fitting within the framework of the circular bioeconomy.

Although the valorisation of by-products into value-added products is in line with the EU's bioeconomy strategy, various environmental, technical, economic, and social aspects are still insufficiently or not explicitly explored [20]. The utilisation of by-products into value-added product production could reduce waste [63], but environmental impact assessment of biorefineries is still a matter for study. Circular economy models require the exchange of information on the availability of secondary resources [64]. Cooperation among different stakeholders is essential to ensure continuity of by-product availability. Moreover, in the event of disruption in distribution networks it is crucial to ensure process continuity by access to alternative sources of the respective by-product. Considering that food by-products are easily perishable resources, they must be treated soon after they are generated or be stored at suitable conditions to prevent spoilage before they reach the valorisation stage. Thus, proximity between the source where the by-product is generated to where it is transformed into the value-added product is important too. This could lead to potential uncertainty and increased costs and environmental impacts associated with storage and transportation before conversion into value-added products can take place. In addition, most studies on bio-valorisation using by-products are at an early stage of research and need to be scaled up. It is unclear whether the microbial processes will produce good results when scaled up. More research is needed to understand whether the reported microbial processes can be used for large-scale by-product valorisation. The implementation of valorisation should also be based on the needs and affordability of potential users, as well as possible future trends.

This study presented a comprehensive overview of by-product coefficient estimates and value-added products using bio-valorisation. Highlighting specific findings, whey and sugar beet pulp emerged as the predominant by-products in Northern Europe by fresh weight. Denmark with its advanced food industry, recorded the highest by-product volumes, indicating its prime position for setting up scaled-up by-product valorisation facilities. In terms of bio-valorisation research, whey and brewer's spent grain, both carbohydrate-rich resources, were frequently utilised as substrates in the analysed bio-valorisation studies. This often led to the production of xylanases, ethanol, and acetic acid as the value-added products. However, refining by-product estimations and evaluating their suitability for producing value-added products remains an area needing further research. Aligning by-product availability with a region's potential for circular bioeconomy growth is crucial. Thus, further research is needed to provide data driven insights into by-product availability. In conclusion, while the circular bioeconomy and bio-valorisation pose various challenges, the intertwined environmental, technical, economic, and social aspects need to be further explored to ensure an efficient and equitable transition to a circular bio-economy and achieve sustainable development goals.

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Data availability The authors confirm that the data supporting the findings of this study are available within the article and its supplementary materials.

Declarations

Competing interests The authors declare no competing interests.

References

1. UN (2015) Transforming our World: The 2030 Agenda for Sustainable Development. https://sdgs.un.org/publications/transforming-our-world-2030-agenda-sustainable-development-17981. Accessed 8 June 2022
2. EC (2019) Commission Delegated Decision (EU) 2019/1597 of 3 May 2019 supplementing Directive 2008/98/EC of the European Parliament and of the Council as regards a common methodology and minimum quality requirements for the uniform measurement of levels of food waste. OJ L 248, p 77–85. http://data.europa.eu/eli/dec_del/2019/1597/oj
3. EC (2020) A new Circular Economy Action Plan for a cleaner and more competitive. https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=COM:2020:98:FIN
4. EC (2018) A sustainable bioeconomy for Europe – Strengthening the connection between economy, society and the environment – Updated bioeconomy strategy. Publications Office. https://data.europa.eu/doi/10.2777/792130
5. EEA (2018) The circular economy and the bioeconomy – Partners in sustainability. Publications Office. https://data.europa.eu/doi/10.2800/02937
6. Stegmann P, Londo M, Junginger M (2020) The circular bioeconomy: its elements and role in European bioeconomy clusters Resources. Conserv Recycl: X 6:100029. https://doi.org/10.1016/J.RCRX.2019.100029
7. Hartikainen H, Mogensen L, Svanes E, Franke U (2018) Food waste quantification in primary production—the Nordic countries

as a case study. Waste Manage 71:502–511. https://doi.org/10.1016/j.wasman.2017.10.026

8. Hanssen OJ, Östergren K, Hartikainen H, Andersson T, Werge M, Prestrud K (2021) Monitoring food waste and loss in the Nordic region—definitions, methods and measures for prevention. Nordic Council of Ministers. https://doi.org/10.6027/temanord2021-504
9. Joensuu K, Hartikainen H, Karppinen S, Jaakkonen AK, Kuoppa-aho M (2021) Developing the collection of statistical food waste data on the primary production of fruit and vegetables. Environ Sci Pollut Res 28:24618–24627. https://doi.org/10.1007/S11356-020-09908-5/TABLES/5
10. Hartikainen H, Svanes E, Franke U, Mogensen L, Andersson S, Bond R, Burman C, Einarsson E, Eklöf P, Joensuu K, Olsson ME, Räikkönen R, Sinkko T, Stubhaug E, Rosell A, Sundin S (2017) Food losses and waste in primary production Case studies on carrots, onions, peas, cereals and farmed fish https://doi.org/10.6027/TN2016-557
11. Caldeira C, De Laurentiis V, Ghose A, Corrado S, Sala S (2021) Grown and thrown: exploring approaches to estimate food waste in EU countries. Resour Conserv Recycl 168:105426. https://doi.org/10.1016/j.resconrec.2021.105426
12. Caldeira C, De Laurentiis V, Corrado S, van Holsteijn F, Sala S (2019) Quantification of food waste per product group along the food supply chain in the European Union: a mass flow analysis. Resour Conserv Recycl 149:479–488. https://doi.org/10.1016/J.RESCONREC.2019.06.011
13. Chiaraluce G, Bentivoglio D, Finco A, Chiaraluce G, Bentivoglio D, Finco A (2023) The circular economy model in the agri-food sector: a new strategy for the regional development. AIMS Agric Food 8(3):851–872. https://doi.org/10.3934/AGRFOOD.2023045
14. De Laurentiis V, Caldeira C, Sala S (2021) Building a balancing system for food waste accounting at National Level. Publications Office of the European Union. https://doi.org/10.2760/316306
15. Garcia-Garcia G, Stone J, Rahimifard S (2019) Opportunities for waste valorisation in the food industry—a case study with four UK food manufacturers. J Clean Prod 211:1339–1356. https://doi.org/10.1016/j.jclepro.2018.11.269
16. Valta K, Damala P, Angeli E, Antonopoulou G, Malamis D, Haralambous KJ (2017) Current treatment technologies of cheese whey and wastewater by Greek cheese manufacturing units and potential valorisation opportunities. Waste Biomass Valorization 8(5):1649–1663. https://doi.org/10.1007/S12649-017-9862-8
17. Ong KL, Kaur G, Pensupa N, Uisan K, Lin CSK (2018) Trends in food waste valorization for the production of chemicals, materials and fuels: case study South and Southeast Asia. Bioresour Technol 248:100–112. https://doi.org/10.1016/J.BIORTECH.2017.06.076
18. Pathak PD, Mandavgane SA, Puranik NM, Jambhulkar SJ, Kulkarni BD (2017) Valorization of potato peel: a biorefinery approach 38:218–230. https://doi.org/10.1080/07388551.2017.1331337
19. Usmani Z, Sharma M, Diwan D, Tripathi M, Whale E, Jayakody LN, Moreau B, Thakur VK, Tuohy M, Gupta VK (2022) Valorization of sugar beet pulp to value-added products: a review. Bioresour Technol 346:126580. https://doi.org/10.1016/J.BIORTECH.2021.126580
20. Caldeira C, Vlysidis A, Fiore G, De Laurentiis V, Vignali G, Sala S (2020) Sustainability of food waste biorefinery: a review on valorisation pathways, techno-economic constraints, and environmental assessment. Bioresour Technol 312 https://doi.org/10.1016/j.biortech.2020.123575
21. FAO (2011) Global food losses and waste—extent, causes and prevention. https://www.fao.org/sustainable-food-value-chains/library/details/en/c/266053/
22. EC (2008) Directive 2008/98/EC of the European Parliament and the Council of 19 November 2008 on waste and repealing certain Directives. Off J European Union L312:3–30
23. Östergren K, Gustavsson J, Bos-Brouwers H, Timmermans T, Hansen J, Møller H, Anderson G, O'Connor C, Soethoudt H, Quested T, Easteal S, Politano A, Bellettato C, Canali M, Falasconi L, Gaiani S, Vittuari M, Schneider F, Moates G, Waldron K, Redlingshöfer B (2014) FUSIONS definitional framework for food waste
24. FAOSTAT. Supply Utilization Accounts (2010) https://www.fao.org/faostat/en/#data/SCL. Accessed 22 Feb 2023
25. FAO. Concepts and definitions of supply utilization accounts (SUAs). https://www.fao.org/economic/the-statistics-division-ess/methodology/methodology-systems/concepts-and-definitions-of-supply-utilization-accountssuas/en/. Accessed 22 Feb 2023
26. EC (2009) Regulation 1069/2009 of the European Parliament and of the Council of 21 October 2009 laying down health rules as regards animal by-products and derived products not intended for human consumption and repealing Regulation (EC) 1774/2002. Off J European Union 1–33
27. Marti DL, Johnson R, Mathews KH (2011) Where's the (not) meat? Byproducts From beef and pork production
28. Pinto J, Boavida-Dias R, Matos HA, Azevedo J (2022) Analysis of the food loss and waste valorisation of animal by-products from the retail sector. Sustainability 14:2830. https://doi.org/10.3390/SU14052830
29. FAO: technical conversion factors for agricultural commodities
30. Heuzé V, Thiollet H, Tran G, Sauvant D, Bastianelli D, Lebas F. Sugar beet pulp, pressed or wet. https://www.feedipedia.org/node/710. Accessed 31 Aug 2023
31. Torres MD, Domínguez H (2020) Valorisation of potato wastes. Int J Food Sci Technol 55:2296–2304. https://doi.org/10.1111/IJFS.14228
32. Kot AM, Pobiega K, Piwowarek K, Kieliszek M, Błażejak S, Gniewosz M, Lipińska E (2020) Biotechnological methods of management and utilization of potato industry waste—a review. Potato Res 63:431–447. https://doi.org/10.1007/S11540-019-09449-6/TABLES/2
33. Fritsch C, Staebler A, Happel A, Márquez MAC, Aguiló-Aguayo I, Abadias M, Gallur M, Cigognini IM, Montanari A, López MJ, Suárez-Estrella F, Brunton N, Luengo E, Sisti L, Ferri M, Belotti G (2017) Processing, valorization and application of bio-waste derived compounds from potato, tomato, olive and cereals: a review. Sustain 9:1492. https://doi.org/10.3390/SU9081492
34. Narita Y, Inouye K (2014) Review on utilization and composition of coffee silverskin. Food Res Int 61:16–22. https://doi.org/10.1016/j.foodres.2014.01.023
35. Decker EA, Rose DJ, Stewart D (2014) Processing of oats and the impact of processing operations on nutrition and health benefits. Br J Nutr 112:S58–S64. https://doi.org/10.1017/S000711451400227X
36. Cypriano DZ, Lopes Da Silva L, Tasic L (2018) High value-added products from the orange juice industry waste. Waste Manag 79:71–78. https://doi.org/10.1016/j.wasman.2018.07.028
37. Norwegian Food Safety Authority: the Norwegian Food Composition Database 2022. https://www.matportalen.no/verktoy/the_norwegian_food_composition_table/. Accessed 13 July 2023
38. Muhlack RA, Potumarthi R, Jeffery DW (2018) Sustainable wineries through waste valorisation: a review of grape marc utilisation for value-added products. Waste Manage 72:99–118. https://doi.org/10.1016/j.wasman.2017.11.011
39. Bolwig S, Brekke A, Strange L, Strøm-Andersen N (2019) Valorisation of whey: a tale of two Nordic dairies. In: From waste to value: valorisation pathways for organic waste streams in circular

bioeconomies, pp 162–186. https://doi.org/10.4324/9780429460289
40. Das RK, Brar SK, Verma M (2015) Valorization of egg shell biowaste and brewery wastewater for the enhanced production of fumaric acid. Waste Biomass Valorization 6:535–546. https://doi.org/10.1007/S12649-015-9377-0/FIGURES/4
41. Scheller HV, Ulvskov P (2010) Hemicelluloses. 61:263–289. https://doi.org/10.1146/ANNUREV-ARPLANT-042809-112315
42. Yegin S, Buyukkileci AO, Sargin S, Goksungur Y (2016) Exploitation of agricultural wastes and by-products for production of Aureobasidium pullulans Y-2311–1 xylanase: screening, bioprocess optimization and scale up. Waste and Biomass Valorization 8(3):999–1010. https://doi.org/10.1007/S12649-016-9646-6
43. Bajpai P (2022) Molecular cloning and expression of xylanase gene. In: Microbial xylanolytic enzymes. Academic Press, p 109–116
44. Sharma D, Chaudhary R, Kaur J, Arya SK (2020) Greener approach for pulp and paper industry by Xylanase and Laccase. Biocatal Agric Biotechnol 25:101604. https://doi.org/10.1016/J.BCAB.2020.101604
45. Bhardwaj N, Kumar B, Verma P (2019) A detailed overview of xylanases: an emerging biomolecule for current and future prospective. Bioresources and Bioprocessing 6(1):1–36. https://doi.org/10.1186/S40643-019-0276-2
46. Bauer C, Cercignani G, Paolini M (1996) Defining "enzyme unit" correctly. The Lancet 348:271. https://doi.org/10.1016/S0140-6736(05)65584-5
47. Antoine AA, Jacqueline D, Thonart P (2010) Xylanase production by penicillium canescens on soya oil cake in solid-state fermentation. Appl Biochem Biotechnol 160:50–62. https://doi.org/10.1007/S12010-008-8496-5/FIGURES/2
48. Torkashvand N, Soltan Dalal MM, Mousivand M, Hashemi M (2020) Canola meal and tomato pomace as novel substrates for production of thermostable Bacillus subtilis T4b xylanase with unique properties. Biomass Conversion and Biorefinery 2020:1–13. https://doi.org/10.1007/S13399-020-01031-2
49. Yang ST, Liu X, Zhang Y (2007) Metabolic engineering—applications, methods, and challenges. In: bioprocessing for value-added products from renewable resources: new technologies and applications. Elsevier. pp. 73–118
50. Ozmihci S, Kargi F (2008) Ethanol production from cheese whey powder solution in a packed column bioreactor at different hydraulic residence times. Biochem Eng J 42:180–185. https://doi.org/10.1016/J.BEJ.2008.06.017
51. Marzo C, Díaz AB, Caro I, Blandino A (2021) Valorisation of fungal hydrolysates of exhausted sugar beet pulp for lactic acid production. J Sci Food Agric 101:4108–4117. https://doi.org/10.1002/JSFA.11046
52. Erian AM, Gibisch M, Pflügl S (2018) Engineered E. coli W enables efficient 2,3-butanediol production from glucose and sugar beet molasses using defined minimal medium as economic basis 06 Biological Sciences 0605 Microbiology. Microb Cell Fact. 17:1–17. https://doi.org/10.1186/S12934-018-1038-0/TABLES/6
53. Li Z, Lu JK, Yang ZX, Han L, Tan T (2012) Utilization of white rice bran for production of l-lactic acid. Biomass Bioenergy 39:53–58. https://doi.org/10.1016/j.biombioe.2011.12.039
54. Saejung C, Sanusan W (2021) Valorization of lignocellulosic wastes and nutrient recovery by anoxygenic photosynthetic bacteria. Waste Biomass Valorization 12:4835–4844. https://doi.org/10.1007/S12649-021-01351-Y/TABLES/4
55. Mahan KM, Le RK, Wells T, Anderson S, Yuan JS, Stoklosa RJ, Bhalla A, Hodge DB, Ragauskas AJ (2018) Production of single cell protein from agro-waste using Rhodococcus opacus. J Ind Microbiol Biotechnol 45:795–801. https://doi.org/10.1007/s10295-018-2043-3
56. Simović M, Milivojević A, Ćorović M, Banjanac K, Bezbradica D (2019) Whey valorization using transgalactosylation activity of immobilized β-galactosidase. Int J Food Sci Technol 54:3074–3082. https://doi.org/10.1111/IJFS.14222
57. Fan X, Wu H, Jia Z, Li G, Li Q, Chen N, Xie X (2018) Metabolic engineering of Bacillus subtilis for the co-production of uridine and acetoin. Appl Microbiol Biotechnol 102:8753–8762. https://doi.org/10.1007/S00253-018-9316-7/TABLES/4
58. He X, Qi Y, Chen K, Li Y, Ouyang P (2016) Enhancing l-lysine production of beet molasses by engineered Escherichia coli using an in situ pretreatment method. Appl Biochem Biotechnol 179:986–996. https://doi.org/10.1007/S12010-016-2045-4/FIGURES/3
59. Domingos JMB, Puccio S, Martinez GA, Amaral N, Reis MAM, Bandini S, Fava F, Bertin L (2018) Cheese whey integrated valorisation: production, concentration and exploitation of carboxylic acids for the production of polyhydroxyalkanoates by a fed-batch culture. Chem Eng J 336:47–53. https://doi.org/10.1016/J.CEJ.2017.11.024
60. Llimós J, Martínez-Avila O, Marti E, Corchado-Lopo C, Llenas L, Gea T, Ponsá S (2020) Brewer's spent grain biotransformation to produce lignocellulolytic enzymes and polyhydroxyalkanoates in a two-stage valorization scheme. Biomass Conversion and Biorefinery 2020:1–12. https://doi.org/10.1007/S13399-020-00918-4
61. Mukamwi M, Somorin T, Soloha R, Dace E (2023) Databases for biomass and waste biorefinery—a mini-review and SWOT analysis. Bioengineered 14. https://doi.org/10.1080/21655979.2023.2286722
62. Haller H, Fagerholm AS, Carlsson P, Skoglund W, van den Brink P, Danielski I, Brink K, Mirata M, Englund O (2022) Towards a resilient and resource-efficient local food system based on industrial symbiosis in Härnösand: a Swedish case study. Sustainability 14:2197. https://doi.org/10.3390/SU14042197
63. Reguengo LM, Salgaço MK, Sivieri K, Maróstica Júnior MR (2022) Agro-industrial by-products: valuable sources of bioactive compounds. Food Res Int 152:11087, 1. https://doi.org/10.1016/J.FOODRES.2021.110871
64. Järvenpää AM, Salminen V, Kantola J (2021) Industrial symbiosis, circular economy and industry 4.0—a case study in Finland. Manag Prod Eng Rev 12:111–121. https://doi.org/10.24425/MPER.2021.139999