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Temporal and spatial mapping of theoretical biomass potential across the European Union

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Abstract

With the increasing challenge to shift our economic system from carbon to renewable energy carriers the demand for biogenic resources is growing. Biogenic municipal waste, agricultural by-products and industrial residues are under-utilised but are increasingly gaining in value. To date, there is no continuous database for these resources in the EU-27 countries. Existing datasets that estimate resource potentials in a single time step often lack validation. A reliable and continuous database is thus needed to support the growing bioeconomy.

Spatial and temporal high-resolution data of biogenic residues serve as an invaluable resource for identifying areas with significant theoretical biomass potential and allows an in-depth understanding of dynamic patterns over time. This study elucidates the theoretical biomass potentials of 13 distinct biomasses from municipal waste, agricultural by-products and industrial residues quantified annually from 2010–2020. The spatial scope of the research covers the EU-27 Member States incorporating all entities represented at various levels within the Nomenclature of Territorial Units for Statistics (NUTS) as delineated by Eurostat, where possible. The regionalised data are subsequently validated against national statistics. The findings demonstrate the feasibility of creating a time series of theoretical biomass potentials for the 13 selected waste types, by-products, and residues, and underscore the critical role of data validation when regionalising national or sub-national data to smaller NUTS entities. It could be shown that the values of small regions (NUTS 3) correlated well on average. When looking at individual regions in detail, regional characteristics such as the location of cultivation, waste management or reporting methods could lead to over- or underestimates of up to 100%. Therefore, data at the regional level provide only limited information. In the case of industrial residues regionalisation gave good results localising preference regions of high theoretical biomass potential but more data on industrial production are needed to estimate also residual quantities at sub-national and local levels.

Biomass potentials modelled in this study are published in an open access database, which is designed as an extensible tool, enabling the understanding of national and regional trends of theoretical biomass potentials in the European Union and of the reliability of the regionalised data.

The estimated theoretical potential dataset can be downloaded free of charge from: https://doi.org/10.48480/g53t-ks72 (Günther et al., 2023).

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1 Introduction

The need to shift the economy from fossil to renewable resources leads to a steadily rising demand for biogenic material. With the introduction of the Circular Economy Action Plan as one pillar of the European Green Deal the European Union (EU) demands to increase the rates of waste reuse and recycling as well as sustainable product design (EC, 2020). In order to achieve these ambitious goals, knowledge of available biogenic residues, by-products and wastes is essential, but data availability on the different resources varies greatly. Municipal waste (MSW) and its organic fraction is monitored by the EU statistic agency Eurostat on country level. Data on MSW streams indicate that landfill declined from over 60 % to 24 % over the last three decades. This is mainly achieved by increasing the rate of material recycling using composting and digestion of degradable wastes and incineration with each an increase of over 10 % (eurostat, 2022). However, more efforts are needed to fulfill the Waste Framework Directive (WFD), which explicitly demands for 2035 a 65 % recycling rate of MSW (European Parliament and of the Council, 2008). Countries such as Bulgaria, Croatia, Malta and Slovenia are still above 60 % landfill and face challenges in the upcoming years to fulfill EU targets. The fraction of MSW, which is composted or digestated increased slowly from 7 to 18 % over the same period in the EU. Some countries such as Austria, Italy or the Netherlands managed to increase this rate already well above 20 %, while many other countries are below the EU average. These data clearly show the differences in the implementation of waste policies across EU countries and a large share of theoretical biomass potential of bio-waste remains unused so far. For agricultural by-products and industrial residues such a monitoring system is currently not existing on a European level. In order to efficiently utilize biogenic residues, it is of outmost importance to monitor the local occurrence of generated waste and residual materials.

However, the review of Hamelin et al. (2019) on existing biomass potential studies in the EU reveals that the majority of these studies estimate forest and agricultural by-products only on a national level. High-resolution estimates on NUTS 3 level are limited to the studies by Bellot et al., (2021), Hamelin et al. (2019), or Scarlat et al., (2019) who published rasterised datasets of 1 km pixel size. These calculation models help to understand the spatial distribution and hence, the identification of areas with high biomass potential of single resources. Nevertheless, all of these studies estimate biomass potential for a single timestep only, while the implementation of political strategies and private investment need long-term planning and hence requires reliable time series of biomass potential development. This includes a solid data validation, which provides information on the accuracy and reliability of a monitoring instrument.

In this study a three-folded approach is used to model biomass potential. The theoretical biomass potential of 12 residues from agriculture, municipal waste and industry are modelled on a yearly basis for the period of 2010–2020 and mapped for Europe with a spatial resolution of NUTS 0 to NUTS 3, where possible. The NUTS classification is a standard geocode reference developed and regulated by the EU and is available from Eurostat with four different spatial levels. Level NUTS 0 entities

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represent countries, level 1 entities represent major socio-economic regions, level 2 entities represent basic regions and level 3 entities represent small regions. Regular revision of NUTS entities can lead to area and code changes, which have been taken into account. All estimations in this paper and the dataset of Günther et al. (2023) refer to the official geocode reference from 2016.

Whey is immediately available from Eurostat (EC, 2021) and therefore not modelled. The study, conducted in the scope of the Horizon 2020 BBI JU project "CAFIPLA" (GA. No.: 887115), considers the theoretical biomass potentials from agricultural by-products such as different straw types and sugar beet leaves, bio-waste from households, as well as industrial residues from sugar, beer and cheese production due to the suitability requirement for the designed pilot plant of the project. Data from Eurostat, European industrial associations, commercial registers as well as CORINE Land Cover raster are used for the model. Finally, the modelled biomass potentials are validated against available statistical data, derived from various national statistic agencies to assess the quality and reliability of the regionalised data.

The theoretical biomass potential is according to (Thrän and Pfeiffer, 2015) and Brosowski et al. (2020) considered as the maximum available biomass quantity under optimal management conditions. Since data on residues and by-products are often not available a common method of Residues-to-Product-Ratios (RPR) is used (Brosowski et al., 2020; Scarlat et al., 2019; Weiser et al., 2014). Although the method is widely used, the applied factors are not. Dependent on the authors or experts choice different RPRs are applied, leading to a wide range in biomass potential quantification over the different studies (Hamelin et al., 2019). Therefore, this study focuses only on a comparison of data reliability and time series and not to the comparison of the calculated biomass quantities.

2 Materials and Methods

Fig. 1 gives an overview of in- and output of the developed datasets. The first two rows show used input data sources, their spatial scope and how the data has been combined to regionalise the biomass potential. The time series was conducted from 2010–2020, where possible and therefore the areas of the official NUTS 2016 entities have been applied. Since the changes in NUTS areas during the applied period affected the consistency of the time series, several variables had to be recalculated starting from the 2016 area shapes going backwards. The last two rows show the resulting spatial output datasets. The approaches for the theoretical potential calculation have been adopted for the different residues as following:

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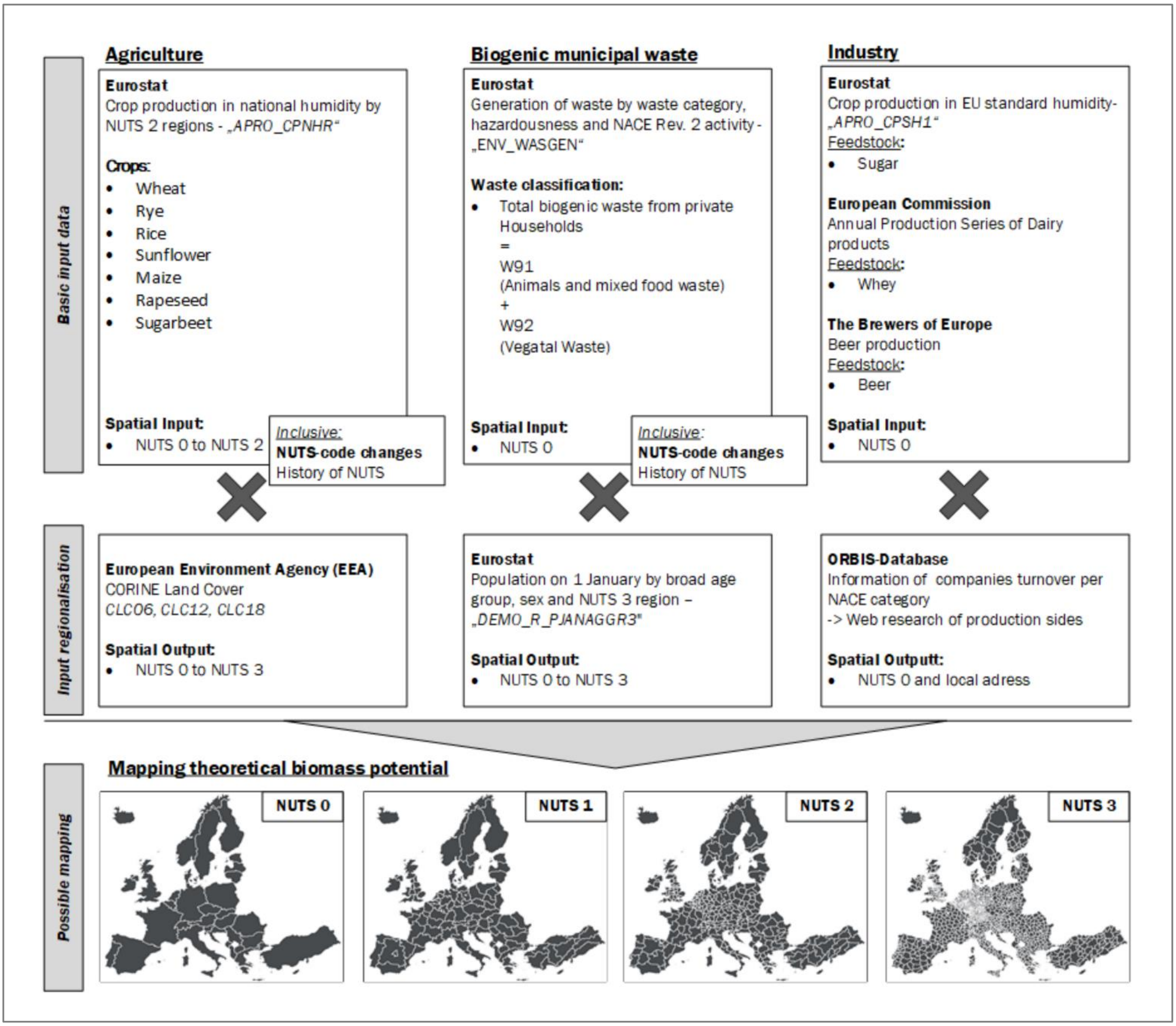

Fig. 1: Overview of input and output data of the study 2.1 Biogenic municipal waste

2.1.1 Theoretical potential

Regionalised biogenic waste data from households for each administrative unit were calculated by multiplying national-specific waste generation values per capita by the population value of the respective administrative area, using an approach similar to that used in other studies such as Bellot et al. (2021) and Hamelin et al. (2019). In contrast to Bellot et al. (2021) and

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Hamelin et al. (2019), however, a bio-waste allocation model is proposed in this study, which provides interpolated time series data over an 11-year period (2010–2020) while considering changes in the NUTS entities areas.

Specifically, the model is built on data derived from the statistical office of the European Union (Eurostat). More specifically, the sheets "env_wasgen" (eurostat, 2023c) containing and "demo_r_pjanaggr3" (eurostat, 2023d) were utilised. The sheet "env_wasgen" contains statistics for all EU-27 countries at NUTS 0 level for the European waste classification categories "*W091-Animals and mixed food waste*" and "*W092-Vegetal waste*" from different NACE activities. In this study, however, we solely focus on the biogenic waste generated from private households. The W091 and W092 data generated from private households are summed to calculate the total amounts of generated biogenic waste. The Eurostat sheet "demo_r_pjanaggr3" provides yearly population data for all EU-27 countries on all four NUTS levels and was also utilised to create the model.

Before the calculations were performed, several data gaps in the primary data tables were addressed using interpolation techniques. For example, European waste data are solely published every other year. The resulting gaps are closed by linear interpolation of two neighbouring data entries. Broader gaps of several years also occurred, but were not interpolated in order to avoid extensive data manipulation. Missing values in local population data (such as those at NUTS 3 level) are filled by calculating the differences between the incomplete population data and the total population values of the respective higher NUTS level (e.g., NUTS 2 level), and distributing the derived differences proportionally to the missing data fields.
The application of these interpolation techniques effectively addresses a significant number of data entry gaps, resulting in improved temporal availability of data on biogenic waste amounts from separate biogenic waste collection for the years 2010–2020 at all NUTS levels.

To examine regional differences, the Member States were grouped into four geographical regions: Eastern Europe (Bulgaria, Czech Republic, Hungary, Poland, Romania, and Slovakia), Northern Europe (Denmark, Estonia, Finland, Iceland, Lithuania, Latvia, and Sweden), Southern Europe (Croatia, Cyprus, Greece, Italy, Spain, Malta, Portugal, and Slovenia), and Western Europe (Austria, Belgium, France, Germany, Ireland, Luxembourg, and the Netherlands).

2.1.2 Data Validation

In order to assess the accuracy of the model, the modelled data are validated against regional waste statistics. For this purpose, waste statistics from nine EU-27 Member States at varying regional resolutions could be gathered. An overview of the compiled validation data are shown in Table I

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Table I: Overview of regional statistics on the quantities of biogenic waste generation from private households used to validate the model. In parenthesis: number of compiled data points of individual countries.

Country	NUTS 1	NUTS 2	NUTS 3
Austria	Yes (3)	Yes (9)	No
Germany	Yes (16)	Yes (36)	Yes (389)
Ireland	No	Yes (3)	Yes (8)
Italy	Yes (5)	Yes (21)	Yes (106)
Netherlands	Yes (4)	Yes (12)	No
Poland	Yes (6)	Yes (16)	No
Portugal	Yes (2)	Yes (7)	Yes (18)
Slovakia	No	Yes (4)	Yes (7)
Spain	Yes (7)	Yes (14)	No

The coefficient of determination (R^2) was used as a measure of goodness for the fit of the model, which was determined for the combined dataset on three regional levels (NUTS 1 to NUTS 3) as well as for individual countries. In this country-wise analysis, countries with fewer than four data points were excluded to ensure that the R^2 could be calculated accurately.

2.2 Agricultural by-products

2.2.1 Theoretical potential

Seven agricultural by-products from feedstocks (maize, rapeseed, rice, rye, sugar beet, sunflower and wheat) listed in Eurostat database are included in the calculation of theoretical biomass potential for the time series. The production data of the relevant feedstock is extracted from the Eurostat data table "APRO_CPNHR (eurostat, 2023b) on NUTS 0, NUTS 1 and NUTS 2 level. Unfortunately, continuous data-series of NUTS 1 and 2 regions was not always available in Eurostat due to spatial changes, missing data or non-adjusted data from Member States. Therefore, gaps are calculated with an approximation method using data from higher level or older spatial areas to regionalise the biomass potential and close data gaps on a spatial level, the agricultural area defined by CORINE Land Cover (European Environment Agency, 2019a, 2019b, 2019c) was used and combined with the production rate. Therefore, the share of CORINE agricultural area (A) for NUTS level of interest (i) according to the year (t) and feedstock (n) is set in relation to the area of the next higher available NUTS level (i-1) and is multiplied with the production amount (P) of the higher NUTS level (1). To enhance the dataset to a comprehensible time series from 2010–2020, CORINE Land Cover products are always connected to Eurostat data according to their reference timeline.

$$TP_{i,n,t} = \frac{A_{i,n,t}}{A_{i-1,n,t}} * P_{i-1,n,t} * RPR_n \qquad \exists (i,n,t) \in (I,N,T) \tag{1}$$

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Similarly, to the approach from Bellot et al. (2021) the production amount is multiplied using the residue-to-crop-ratio (RCR) from Scarlat et al. (2019) and Bundesministerium für Ernährung und Landwirtschaft (2017) for sugar beet leaves to calculate the theoretical biomass potential (TP) (1). In addition to arable land, Bellot et al. (2021) also consider heterogeneous agricultural land for downscaling to NUTS 3 level. We, on the other hand, only include the CORINE Land Cover classes 211 (non-irrigated cropland) and 213 (rice fields) in order to be more restrictive with regard to the possible NUTS-specific cultivated area.

2.2.2 Data Validation

The modelled NUTS 3 production data are validated against the German national statistics, which provide area (Regionalstatistik, 2022b) and area specific yields (Regionalstatistik, 2022a) for the year 2016 on NUTS 3 level. For each NUTS 3 region the estimated production from CORINE and Eurostat was compared to the production multiplied by the German area inside the NUTS 3 region and the corresponding yield. The resulting R^2 describes the accuracy of the model results. In addition, the calculated standard deviation (sd) gives an overview of the variation of the modelling.

2.3 Industrial residues

2.3.1 Theoretical Potential

Data availability and sources are, if existing, highly diverse in this category. Hence, no automated "fit for all" approach can be applied here. Input data for sugar production is retrieved from Eurostat data sheet APRO_CPSH1 (eurostat, 2023a) for the full time series. Beer production is published by the European association of brewers (The Brewers of Europe, 2020) for 2012 - 2018. Following the RPR approach, production volume data for sugar and beer processing is multiplied with the specific conversion factor for the different residues. In literature, a range of conversion factors can be found. Only factors with documented measurements and plausible numbers have been considered and shown in Table II . The number of different RPRs for the same residue is reflected in the calculated biomass potentials as minimum and maximum values. Data on whey is directly used from Eurostat (EC, 2021, 66) and available for 2010–2020.

All data are only available on NUTS 0. To achieve a regionalisation of the biomass potential, production sites are mapped using open data from industry associations, company websites and Orbis company register database. For almost none industrial food production sites individual production values can be found. Therefore, the biomass potential cannot be regionalised by volume but preference regions can still be visualised using the amount of production sites per NUTS entity. In EU-27 74 production sites of sugar are found and mapped. Dairies and breweries are slightly more difficult to map due to the amount of existing productions sites. Therefore, in a first step the Orbis database was used to filter the 50 companies with highest turnover rate in Europe. Orbis only provides the location of the headquarters. Hence, the company production locations of the 50

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identified companies are searched for using company websites and associations. Unlike sugar and beer factories, dairy locations are seldom reported from companies and production site numbers are much higher resulting in no regionalisation of whey.

Table II: RPR for industrial residues

Residue	RPR min	RPR max	Source	Resulting RPR min	Resulting RPR max
Spent grains	0.2	0.23	(Gupta et al., 2010)	0.2	0.2
Spent grains	0.2	0.2	(Mussatto et al., 2006)		
Spent yeast	0.02	0.04	(The Brewers of Europe, 2022)	0.085	0.11
Spent yeast	0.02	0.04	(Avramia and Amariei, 2021)		
Spent yeast	0.15	0.18	(Jaeger et al., 2020)		
Molasses	0.04	0.06	(MECAS, 2016)	0.04	0.06
Beet pulp	0.4	0.4	(Gaida, 2013)	0.45	0.45
Beet pulp	0.5	0.5	(Legrand, 2015)		

2.3.2 Validation

Due to the missing link between production sites and volumes no regionalisation could be carried out. Therefore, a validation is also not needed.

3 Results

3.1 Biogenic municipal waste

3.1.1 Theoretical Potential

Data on biogenic waste generation from private households, as reported by Eurostat, show a positive trend in total amount generated in the decade under study (2010–2020). The EU-27 Member States generated a total of 37.2 million tons of biogenic waste in 2020, a 68% increase from 2010. Highly populated countries such as Germany, France, Italy, the Netherlands, and Poland generated the highest amounts.

Western European countries collect the largest amounts of biogenic municipal waste due to high collection rates and population size. This group has seen ongoing growth in separate waste collection, with France and Austria reporting a more than doubled quantity of biogenic waste per inhabitant and year in the decade under study. With 128 kg per inhabitant and year, Austria reported the second-highest figure among EU 27 Member States. The rising population numbers in this group also contribute

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to the observed increase. Interestingly, Luxembourg reported only a fraction of its biogenic waste collection in 2020 (~4 400 t) compared to 2010 (~67 300 t).

Collection figures have significantly increased in both Northern and Southern Europe, and Eastern Europe experienced a particularly pronounced increase, raising from 0.46 million tons in 2010 to 3.03 million tons in 2020, representing a 564% increase. This is mainly due to the substantial growth in collection volumes in Poland, the most populous country of the Eastern European EU 27 Member States, which recorded the highest increase in the total amount collected, increasing its value by a factor of 20 in the decade under study.

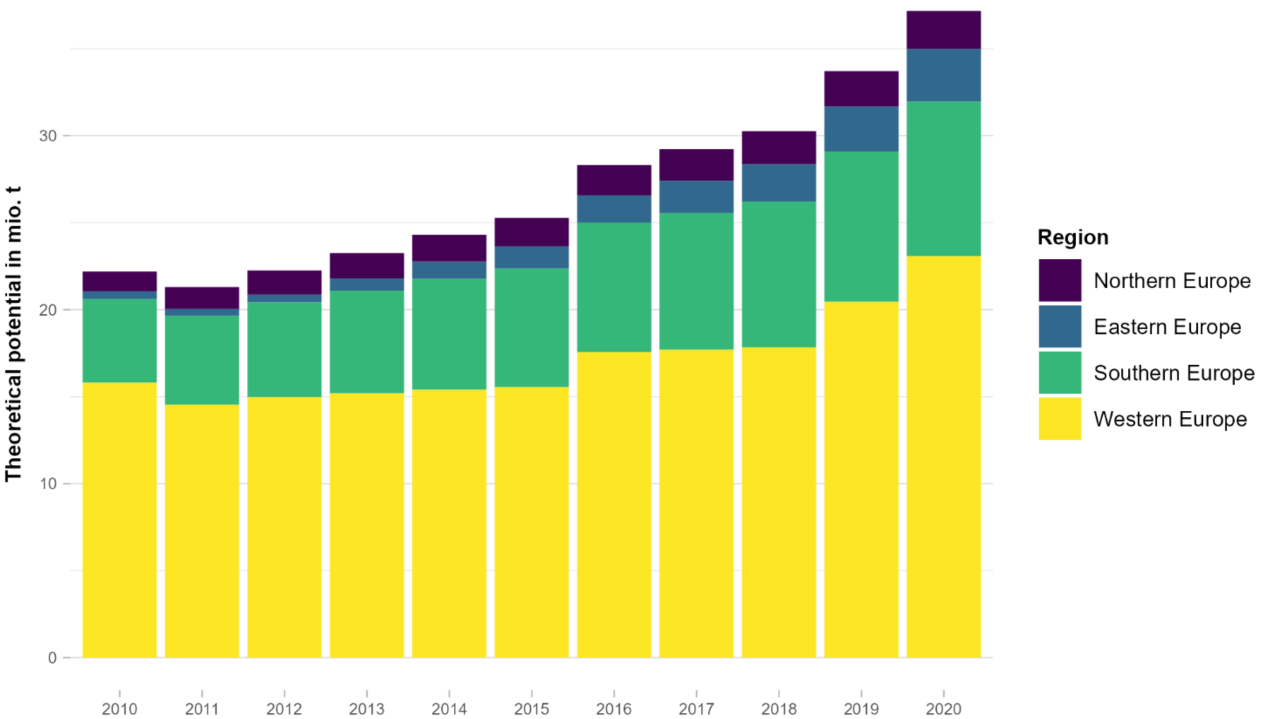

Fig. 2: Theoretical potential of biogenic waste from households in mio. t [FM] yr^{-1} for the time series from 2010–2020. Sum of country values on NUTS 0 level, grouped by regional affiliation

Although Eastern Europe has seen positive trends in biogenic waste collection volumes, they still show the lowest figure in average quantity of biogenic waste collected per person and year. However, there is significant room for improvement in Southern Europe, too. The average amount generated by private households collected per person in 2020 was 34.5 kg in Eastern Europe and 38.8 kg in Southern Europe, while Northern Europe and Western Europe (excluding Luxembourg) collected on average 52.4 kg and 104.5 kg of bio-waste per person and year, respectively

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3.1.2 Data Validation

At the NUTS 1 level, the R^2 for the combined dataset is 0.91 ($average_{valid\text{-}data}$ = 657 106 t; $sd_{residuals}$ = 204 032 t), indicating a strong fit between the model´s predictions and the statistical data. For individual countries, however, a scattering of R^2 values can be observed. The R^2 values range from 0.64 (Italy) to 0.93 (Germany), with an average of 0.78. This suggests that the model is capable of accurately predicting waste production for larger regions.

At the NUTS 2 level, the R^2 for the combined dataset is 0.82 ($average_{valid\text{-}data}$ = 167 512 t; $sd_{residuals}$ = 78 135 t). For individual countries, the R^2 values range from 0.42 (Spain) to 0.80 (Italy), with an average of 0.63, which also indicates a good accuracy of waste production estimates for medium-sized regions.

At the NUTS 3 level, the R^2 for the combined dataset is 0.77 ($average_{valid\text{-}data}$ = 32 092 t; $sd_{residuals}$ = 17 470 t). Here, the R^2 values vary considerably from 0.02 (Slovakia) to 0.93 (Germany), the average is 0.62. It can be noticed that the accuracy decreases with increasing spatial resolution, while the range of the determined R^2 values becomes larger.

Table III: Statistical evaluation of the data validation for the modelled data on bio-waste on NUTS 1, NUTS 2 and NUTS 3 level. Values marked with * are based on five or less data points

Country	NUTS 1	NUTS 2	NUTS 3
Austria	0.90*	0.62	-
Germany	0.93	0.73	0.52
Ireland	-	0.98*	0.96
Italy	0.64*	0.80	0.82
Netherlands	0.77*	0.62	-
Poland	0.76	0.74	-
Portugal	1.00*	0.63	0.77
Slovakia	-	0.45*	0.02
Spain	0.68	0.42	-
Combined	**0.91**	**0.82**	**0.77**

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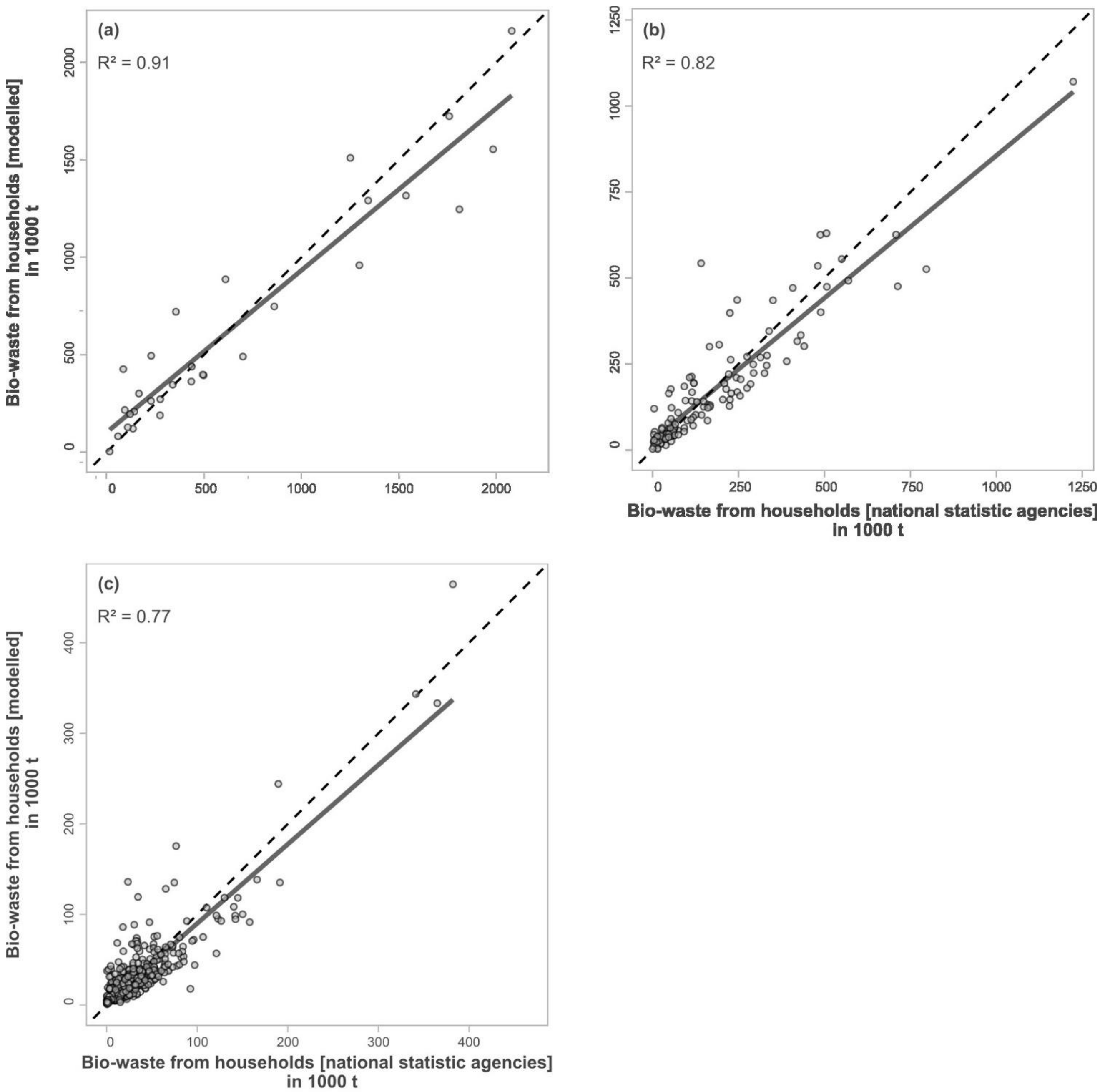

235 **Fig. 3: Correlation of modelled biogenic waste data and statistical data from statistical agencies in nine European countries at three different NUTS levels. (a) NUTS 1 level; (b) NUTS 2 level; and (c) NUTS 3 level. Solid line: linear regression line; dashed line: 1:1 relation.**

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3.2 Agricultural by-products

3.2.1 Theoretical Potential

By integrating the NUTS code changes between 2010 and 2020, a complete time series of biomass potential could be presented, as shown in Fig. 4. The highest theoretical biomass potential of 337 million tons in Europe (2014) resulted from the high production volume of sugar beet combined with high wheat production. Over time, the potential varied between 276 million (2010) and 337 million tons (2014). The maximum range of 61 million tons of theoretical biomass potential occurred within four years from 2010 to 2014. This shows the time dependence of biomass availability.

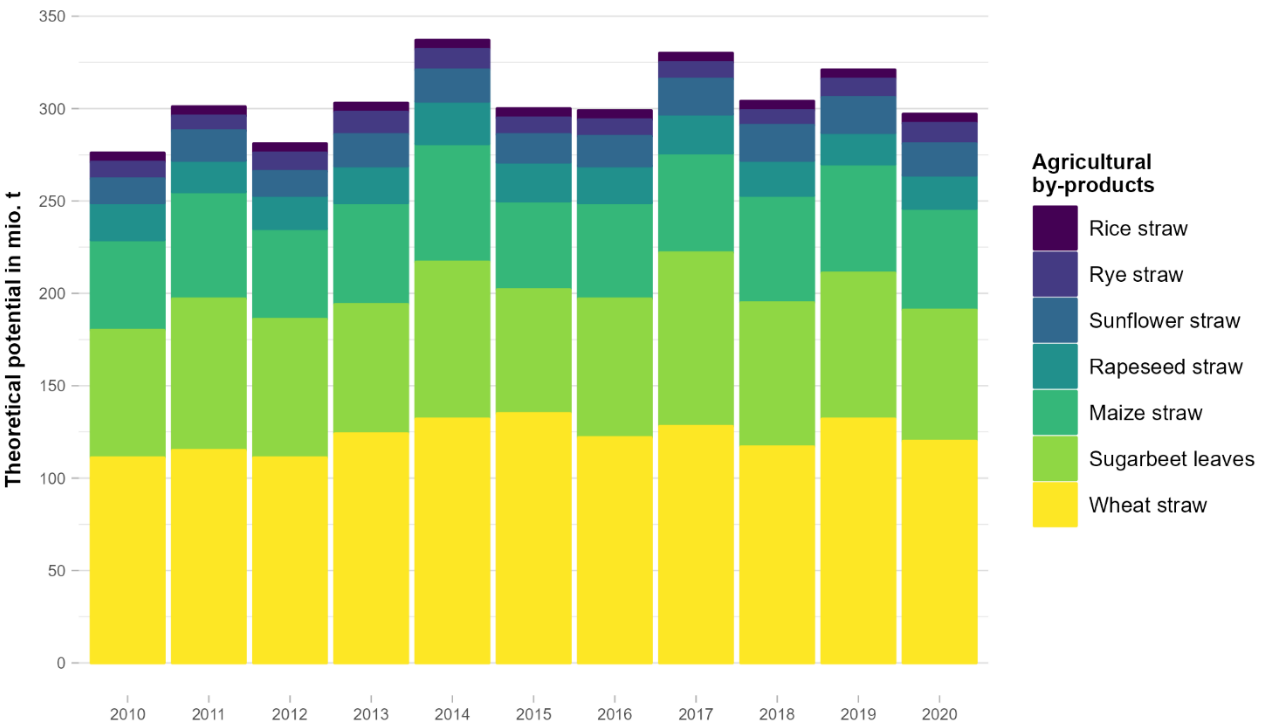

Fig. 4: Theoretical potential of agricultural by-products in mio. t [FM] yr^{-1} for the time series from 2010–2020. Sum of all EU-27 Countries on NUTS 0 level, grouped by biomass type

3.2.2 Data Validation

Data validation was possible for four crops (wheat, rye, rapeseed and sugar beet) in Germany and was carried out by comparing the production amount from national statistics with our modelled production. As shown in the scatter plot of Fig. 5 and the corresponding R^2 values in Table IV, the agricultural crops wheat, rye and rapeseed had R^2 values between 0.61 and 0.95. These R^2 values indicate that the method of downscaling the production to regional levels using of CORINE Land Cover data

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was feasible. The corresponding sd in Table 3 shows that within certain NUTS regions the values between modelled and statistically reported production can differ significantly. The downscaling of sugar beet production by the CORINE Land Cover datasets leads to R^2 values of 0.30 (NUTS 2) and 0.20 (NUTS 3) and less valid results for the correlation between the modelled data and the data from official German statistics. For sugar beet, the sd with respect to the average value is higher and shows that the local production value can deviate considerably.

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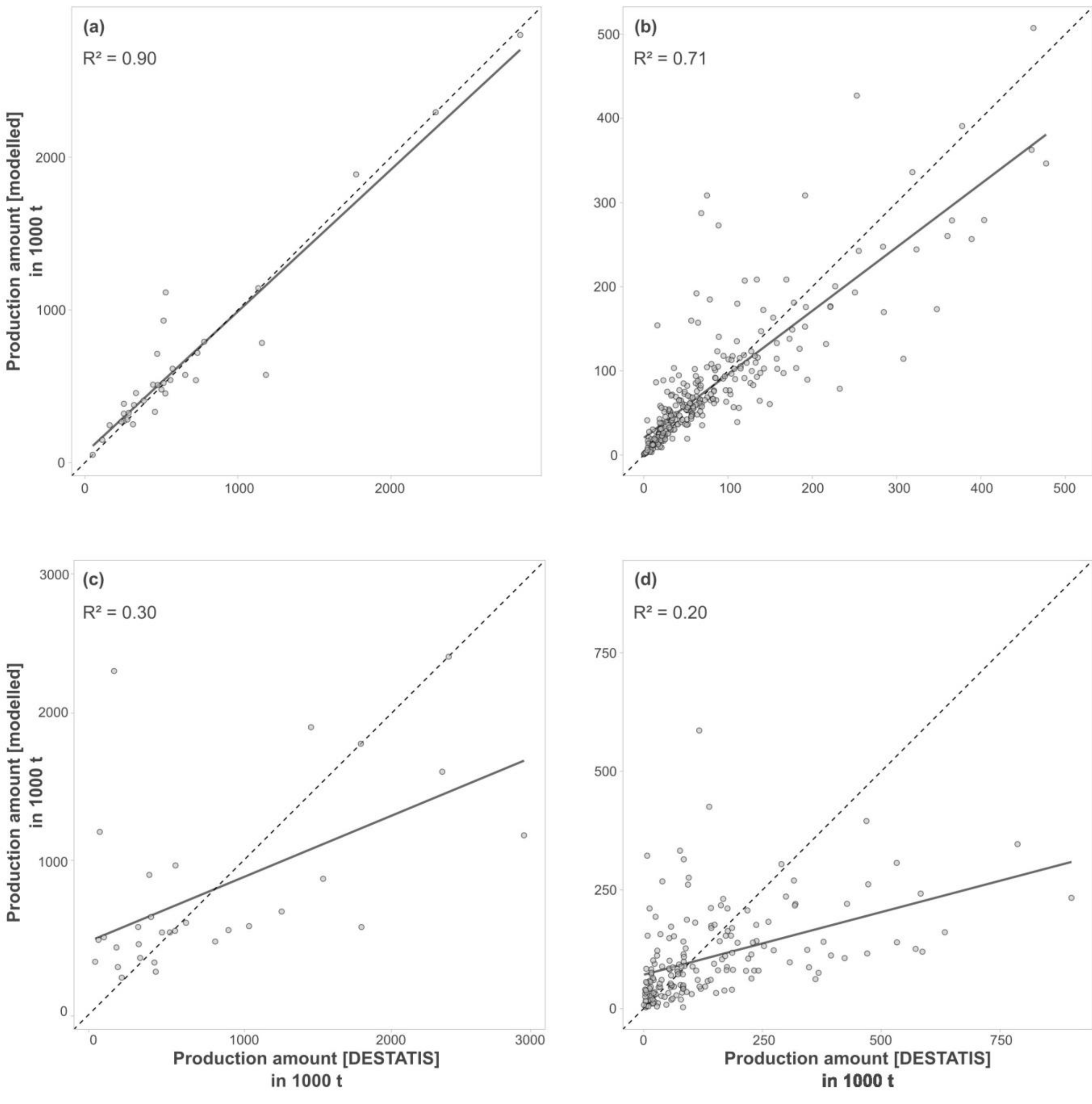

260 **Fig. 5: Correlation of modelled agricultural production amounts with official German statistics (Regionalstatistik, 2022a, 2022b). (a) wheat for NUTS 2 level; (b) wheat for NUTS 3 level; (c) sugar beet for NUTS 2 level; (d) sugar beet for NUTS 3 level. Solid line: linear regression line; dashed line: 1:1 relation**

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Table IV: Statistical evaluation of data validation for the agricultural sector at NUTS 2 and NUTS 3 level in Germany.

	NUTS 2			NUTS 3		
	R^2	$sd_{residuals}$ [t]	$average_{valid\_data}$ [t]	R^2	$sd_{residuals}$ [t]	$average_{valid\_data}$ [t]
Wheat	0.90	191 049	650 698	0.71	46 560	78 176
Rye	0.95	36 572	97 001	0.61	15 037	17 483
Rapeseed	0.87	61 108	128 290	0.80	9 709	17 748
Sugar beet	0.30	647 959	78 150	0.20	140 784	140 011

3.3 Industrial residues

3.3.1 Theoretical Potential

Fig. 6: Theoretical potential of industrial residues in EU-27 in Fig. 6 shows the theoretical potential of the five industrial biomass residues. For datasets with a data range from minimum to maximum, only the minimum value is visualised. The bar plots clearly show the comparably high theoretical biomass potential of whey and beet pulp. The amount of whey increased steadily from 37 to 44 mio. t [FM] yr^{-1} over the 11-year time period with an exceptional high of 50 mio. t [FM] yr^{-1} in 2019. The largest producer of whey in the EU is Germany with 14 mio. t [FM] yr^{-1} followed by the Netherlands with 9 mio. t [FM] yr^{-1}, Poland with 7 mio. t [FM] $yr^{-1}$and Italy and Ireland with 4 mio. t [FM] yr^{-1}. Nearly all countries show an increasing trend in whey production, especially Poland and the Netherlands. As explained the mapping of hot spot regions is not possible here.

The potential of beet pulp shows more variation from one year to the other with a minimum of 43 mio. t [FM] yr^{-1} in 2015 and a maximum of 60 mio. t [FM] yr^{-1} in 2017. Eurostat data reveal the three main sugar producers in Europe are France and Germany with nearly 30 % production share and Poland with more than 10 %. With the reform of the Common Agricultural Policy in 2013 the existing quota system on sugar was eliminated in 2017. The data show that this did not lead to a significant long-term change in biomass potential of residues from sugar production. Moreover, the production area decreased in Germany and Poland already in 2015 and 2016. In 2017 the area increased again in Germany to the former level and in Poland even slightly more than before. A significant increase in residues from sugar production cannot be detected after 2017. Reasons might be stronger influence of changing weather conditions combined with production area and the capacity of existing sugar factories. According to beet pulp also molasses (minimum) is varying. The numbers are less significant because the amount of residue accrue during production is much less. Overlaying the NUTS 0 beet pulp potential with the number of production sites underlines the high sugar industry residue potential of Germany, France and Poland from the Eurostat data. Comparing the potential map with amounts of factories per NUTS 0, 1, 2 and 3 shows the surplus of the method (Fig. 7). For countries with

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only one factory like Sweden or Finland a direct potential amount can be derived from the data. In other countries such as France only one region of sugar production is occurring and indicates the location of biomass potential.

Compared to the other three industrial residues spent grains and spent yeast biomass potentials are rather low but very stable over the smaller time period of 2012 - 2018. The potential of spent grains (minimum) ranges between 6.7 tsd and 7.1 tsd t [FM] yr^{-1} and for spent yeast (minimum) between 2.8 and 3 tsd. t [FM] yr^{-1}. According to the brewers of Europe (2019) Germany is the biggest producer of beer with nearly 30 % of EU production. Followed by Poland, Spain and Netherlands with about 10 % each. The production site mapping of the 50 biggest companies show accordingly a high density in Germany and the Netherlands although very spread. Spain, Poland, Denmark, Ireland and Sweden show regional hot spot areas. The production in the countries is smaller but the concentration of residues may be higher. The count of breweries shows the highest concentration of breweries in NUTS entities are in Arr. Halle-Vilvoorde with five followed by Bas-Rhin, France and Munich, Germany with three factories each.

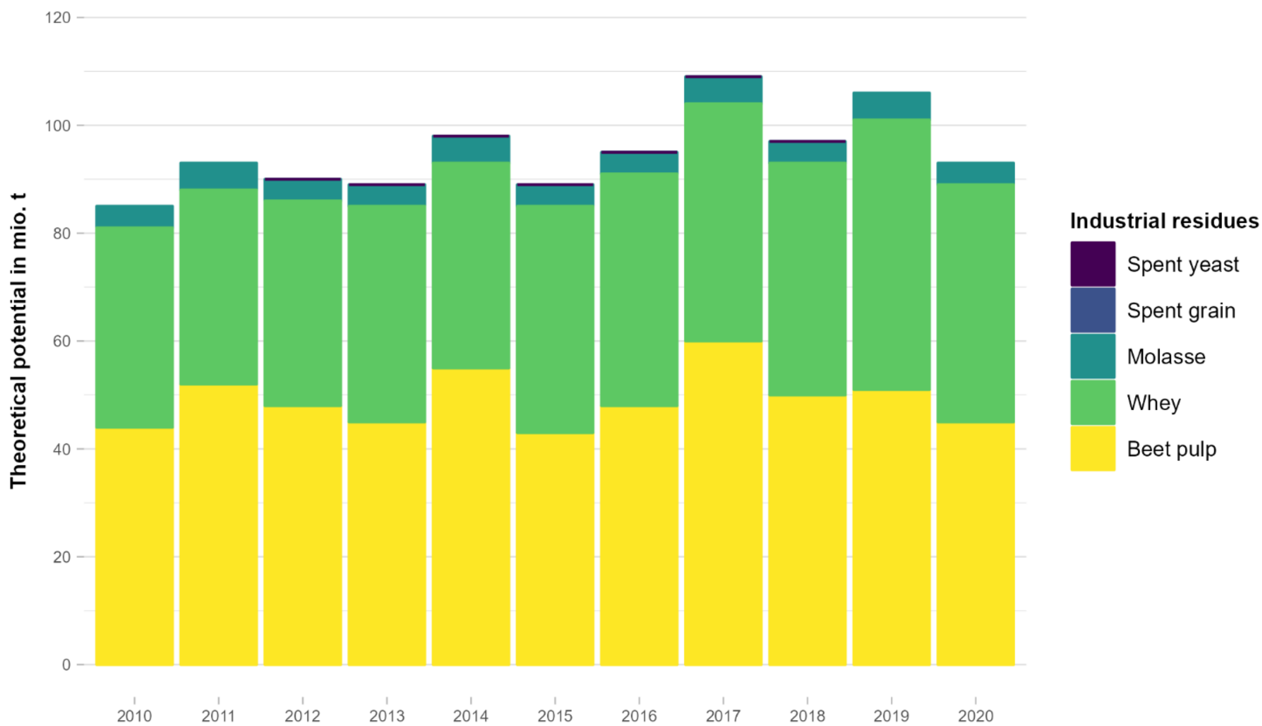

Fig. 6: Theoretical potential of industrial residues in EU-27 in 2010–2020. Sum of all EU-27 Countries on NUTS 0 level, grouped by residue type

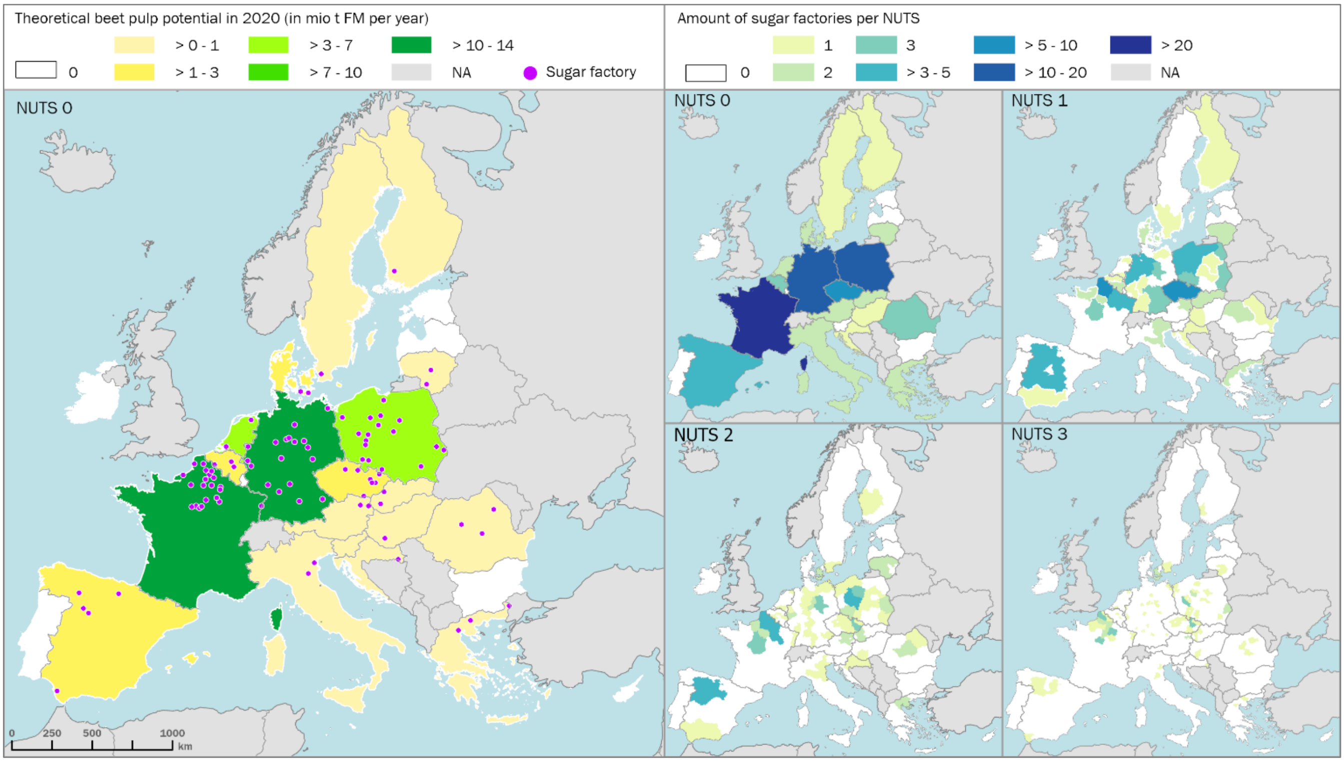

Fig. 7: Theoretical biomass potential of beet pulp and location of sugar factories

3.4. Cross-sectoral

3.4.1 Theoretical Potential

The estimated biomass potentials of all three categories show dynamics over the analysed time period. Looking at biogenic municipal waste the total biomass potential grew from its lowest amount of 21 mio. t [FM] in 2011 to 36 mio. t [FM] in 2020 with big steps in the past 4 years. This is a difference of 71 % in only nine years. Agricultural by-products vary more in between each year. Having the highest year in 2014 with 337 mio. t [FM] and the lowest 2010 with 276 mio. t [FM], means a decrease of 18 %. The year 2014 was followed by 2015 and 2016 with a theoretical biomass potential of only 300 mio. t [FM] and 298 mio t [FM] which is a decline of nearly 40 mio. t [FM]. More surprising are the dynamics in the industrial residues. Decreasing in 2014 to 2015 by 12 % in one year and increasing in 2016 to 2017 by 17 % in the other year. Fig. 8 shows the overall estimated biomass potential for all 13 wastes, by-products and residues per square kilometre, which gives another picture of the biomass density in one country. The three maps are chosen as 2010 is the start year of the time series and also the lowest year for biomass availability with 384 mio. t [FM]. 2017 is the year in contrast has with 469 mio. t [FM] the highest available biomass amount and2020 is included as the last year of the time series with 427 mio. t [FM].

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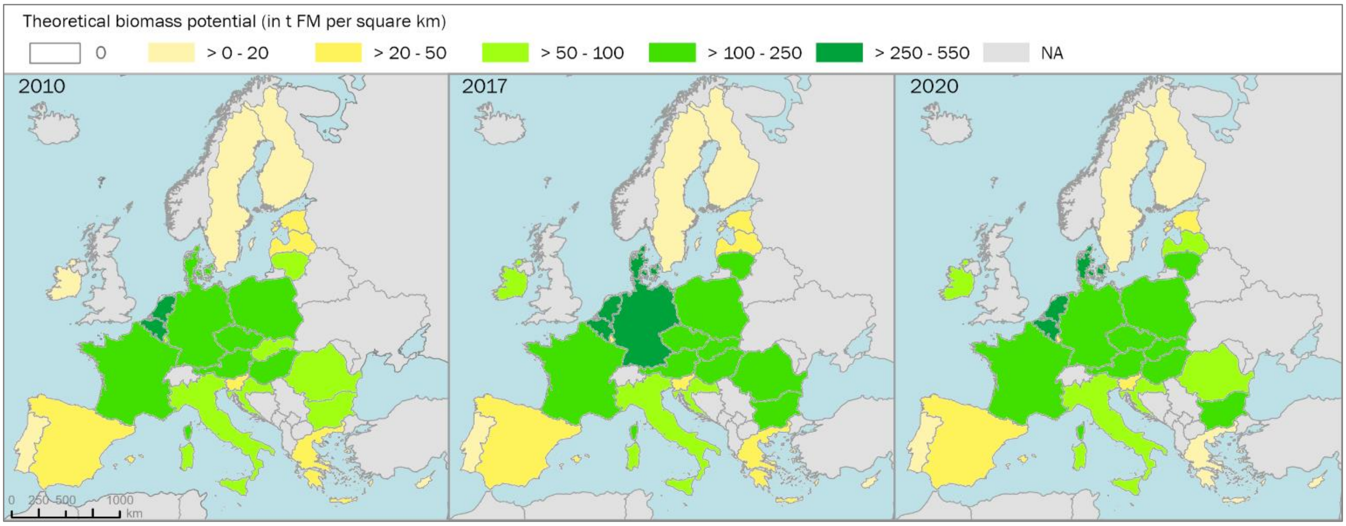

Fig. 8: Theoretical biomass potential from the presented biomasses in 2010, 2017 and 2020. Cross-sectoral sum in relation to country specific area

With increasing data volume and continuous tempo-spatial expansion, databases need to be based on automatisation tools, such as in this study. The open data results can be used instantly to calculate other products or visualise high potential biomass areas and time series as demonstrated in the DBFZ webapp (https://datalab.dbfz.de/resdb). All results on NUTS 0 to NUTS 3 from this study are visualised here with further analytics and an open API.

4. Discussion

For biogenic municipal waste, the regionalisation approach based on national average waste generation rates and population data resulted in estimates of the amount of separately collected biogenic waste from private households for the NUTS regions of the EU. In contrast to comparable studies, such as Bellot et al. (2021) and Hamelin et al. (2019), a validation of the regionalised data was performed to assess the accuracy of the modelled estimates. For this purpose, regional statistical data from several EU Member States were compiled. When correlating the modelled and the statistical data, R^2 values ranging between 0.77 on the NUTS 3 level and 0.91 on the NUTS 1 level were found. This suggests an overall high accuracy and reliable estimation of the generated amounts of biogenic waste at all three levels of regionalisation. However, weak or no correlations between the modelled and statistical data were observed for certain countries, e.g. Spain and Slovakia. This may imply that significant deviations exist between national averages and actual values of individual regions in these countries, leading to higher errors in the estimation. This is particularly challenging for countries with a low number of statistical entities, such as Slovakia, which consists of only seven NUTS 3 regions. In such cases, marked deviations occurred in the validation of the data, which could reflect differences in population behaviour or policy implementation status across regions within a country Additionally, differences in the enforcement and implementation of waste management policies and regulations may

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also contribute to the observed deviations. Therefore, results on NUTS 3 level must be taken with caution, especially in countries, where nation-wide implementation of separate collection systems is of immature status and hence prone to heterogeneity across their regions.

The estimation of agricultural by-products was validated by comparing modelled results of crop production with regional statistical data from Germany on NUTS 2 and NUTS 3. The validation demonstrated overall good accuracy in the estimated straw residues declining with higher regionalisation. With an R^2 of 0.8 for rapeseed and 0.7 for weed straw, the most common crop residues in Europe, show still very good results on NUTS 3 with the used regionalisation method. Nevertheless, the standard variation reveals that regionally high deviation can occur. The accuracy of modelled sugar beet leaves shows very little correlation on NUTS 2 and 3. One explanation for this is that sugar beet requires specific soil conditions, which are not available everywhere. Therefore, the area under sugar beet is limited to selected areas within a higher NUTS level, so that an area-wide distribution of sugar beet using the CORINE Land Cover class 211 (non-irrigated arable land) makes the downscaling to a lower NUTS level less accurate. This shows that the regionalisation method based on the share of agricultural area is not applicable for smaller and very regional crops.

For industrial residues only a partial regionalisation of biomass potential was feasible due to mostly confidential production data (Patricio et al., 2020; Song et al., 2017). The gap of input data for biomass estimation is also reflected by the low amount of studies in this field. Some studies use socio-economic indicators, waste statistics and company register to estimates the general amount of biogenic residues (Patricio et al., 2020; Caldeira et al., 2019) but on an individual residue and wider scale studies are very limited. Moreover, company registers only provide data at headquarters level, which makes it difficult to break down the data to the actual production sites and assess their geographical distribution. Therefore, the spatial approximation approach used was merely a first step to regionalize industrial biomass potential, but further research and open data are needed to combine it with other proxy data in order to estimate the spatial availability of individual biomass potentials. Despite these limitations, the visualisation illustrates that regions with higher biomass potential can be identified in most cases.

With regard to the total biomass availability of the studied time period it was shown that trends are different depending on the geographical location. For example, the biomass potential is increasing in Europe by 86 mio. t [FM] between 2010 and 2017. Looking at the map its noticeable that this effect is driven by middle and eastern EU countries. The controlling effects of these curves are different in each sector. Some effects are long-term and slower as the change in the WFD or the elimination of sugar quotas while others, such as weather conditions, have an immediate effect every year and strongly vary over the NUTS 3 entities compared to the average NUTS 0, as also shown previously by Brosowski et al. (2020). With double digit changes in biomass potential from one year to the other it can be concluded that an estimation of available theoretical biomass potential based on a single reference year is not enough to understand the national and regional biomass availability. Additionally, in

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this study the area changes in NUTS 2 and 3 over time have been considered to ensure comparability between the analysed years and estimated amounts.

As discussed different methods, input data and reference years but also the definition of theoretical biomass potential make the comparison between studies rather difficult, especially at regional level the estimation error can be very high. This study showed for the analysed biomasses that validation on the regionalised data and long-term data plots are necessary to understand biomass availability. To achieve this, the data situation must be improved on the one hand and the survey methods on the other. This study was limited to 13 wastes, by-products and residues and should be expanded to other biomasses such as animal by-products and forest residues in a next step. Additionally, with recent remote sensing novelties, high resolution crop-land area products such as from (d'Andrimont et al., 2022) or (Blickensdörfer et al., 2022) become available now and need to be considered for regionalisation of agricultural by-products. The biggest challenge lies in the data collection of industrial residues and must be improved through regulatory requirements.

5 Data availability

- Dataset: https://doi.org/10.48480/g53t-ks72 (Günther et al., 2023).
- Webapp: https://datalab.dbfz.de/resdb (under development)

6 Conclusion

This study provides valuable insights into the regional distribution and temporal trends of theoretical biomass potential of 13 different biogenic wastes, by-products and residues in the EU-27 between 2010–2020. The study revealed the strengths and weaknesses of currently available primary data and biomass estimations. It was shown that data regionalisation works well in general. For biogenic household waste the combined accuracy reached R^2 values of 0.91 (NUTS 1), 0.82 (NUTS 2) and 0.77 (NUTS 3). For agricultural by-products average R^2 values of 0.76 (NUTS 2) and 0.58 (NUTS 3). However, it was also shown that the accuracy of the data can vary highly in NUTS 3 entities or in general by crops with a small overall cultivation area. Data of industrial residues lack availability and quality which made regionalisation difficult on a European scale. The approximation approach using production sites is a good first step but only possible if the industry products are directly correlated to the residues. With more complex industries such as dairy products this approach is not feasible.

Relevant for time series and hence trend analysis are consistent input data. With the correction of NUTS area changes and gap filling of missing data these time series are provided as an open source dataset (Günther et al., 2023). Variation in biomass availability are connected to the different NUTS level and can be visualised. This helps to understand regional and local trends as highlighted for 2017, which was the year with the highest amount of biomass over the time period, but biomass increases can be seen mainly in central and eastern Europe. Providing an open access dataset and visualisation tool (website) for temporal and spatial differentiation of theoretical biomass potential for the studied residues is a step forward to a reliable continuous monitoring system. The structure of the database supports the inclusion of further biomasses and the need in in the growing EU bioeconomy is clearly given.

Author contribution

SG was responsible for conceptualisation, project administration and draft preparation of the paper. SG, TK and SS conducted the data curation, methodology, analysis, visualised data and wrote the final paper. TK and SS carried out the validation. FNT and DT have been responsible for the supervision and paper review.

Competing interests

"The authors declare that they have no conflict of interest."

Disclaimer

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