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Mapping of available biological feedstock streams: The case of agro-industrial waste and by-products in the Region of Central Macedonia - Greece

Patsios S.I.[1,2,*], Batsioula M.[2], Skoutida S.[2], Geroliolios D.[2], Melas L.[2], Karkanias C.[2], Karanasiou A.[1], Saliakelis P.[1], Malamakis A.[2], Banias G.F.[2]

[1] Chemical Process and Energy Resources Institute, Centre for Research and Technology-Hellas, Thermi, Thessaloniki, 57001, Greece
[2] Institute for Bioeconomy and Agri-Technology, Centre for Research and Technology-Hellas, Thermi, Thessaloniki, 57001, Greece

[*]corresponding author
e-mail: patsios@certh.gr

Abstract The European Union's Bioeconomy Strategy aims to the transition to a circular, sustainable bio-based economy. It should be highlighted that bio-based production systems face significant challenges concerning the sustainable availability of the biological materials that are used as feedstocks for bio-based products. The development of sustainable value chains of biological feedstocks is a challenging prerequisite for the implementation of the Bioeconomy Strategy and Green Deal priorities. An important step towards this goal is to develop a methodological approach for mapping the current European biological feedstocks by identifying their source, trade, and fate. In the material to follow, a general, comprehensive methodology for carrying out a Material Flow Analysis (MFA) of the main biological feedstocks that can be used by the bio-based industries is presented. The MFA methodology is implemented for the main agro-industrial waste and by-product streams in the Region of Central Macedonia (RCM) in Greece, identifying the most promising locally available biological feedstocks. Approximately 1.4 million tons (dry matter) residual biomass per year are harvested in the RCM mainly from cereals and industrial crops. The majority of this biological feedstock is valorized in conventional uses for bioenergy and for feed. Constrains regarding their use (e.g. legal, social, technical etc.) are also discussed. The outcomes of this study are expected to contribute to the development of the local circular bio-based economy and to act as a paradigm for other national (Greek) and European regions.
Keywords: Biological feedstocks, Agro-industrial waste and by-products, Material Flow Analysis, Circular economy, Bio-based products

1. Introduction

The European Union's Bioeconomy Strategy (European Commission, 2018) aims to the transition to a circular, sustainable bio-based economy with significant benefits for the economic growth, environmental protection and social development in Europe. The implementation of the EU Bioeconomy Strategy, as well as of other related initiatives, such as the European Green Deal (European Commission, 2019) and the Circular Economy Action Plan (European Commission, 2020), necessitate the sustainable use of renewable biological feedstocks in place of the fossil-based feedstocks, which are currently used. According to the European Commission's Knowledge Center for Bioeconomy, EU's average agricultural biomass production reaches almost 1 billion tons of dry matter per year; almost half of this biomass (i.e. approx. 46%) corresponds to residual biomass (Garcia Condado et al., 2018) that can be valorized through different technologies for the production of animal feed, bioenergy, biomaterials, biochemicals etc. However, bio-based production systems face significant challenges concerning the sustainable availability of the biological materials that are used as feedstocks for bio-based products. Biological feedstocks are characterized by high spatial distribution of available resources, seasonal production, variability on critical physicochemical properties, short storing time etc. Therefore, the development of sustainable value chains of biological feedstocks is a challenging prerequisite for the transition to a circular, sustainable bio-based economy.

An important step towards this goal is to develop a methodological approach for mapping the current European biological feedstocks by identifying their source, their trade, and their fate. Material Flow Analysis (MFA) is a method to quantify flows and stocks of materials or substances in a system, which can be an industrial plant, a sector, or a region. MFA can be used to track the sources, uses, and destinations of materials or substances, and to identify potential improvements in resource efficiency, waste reduction, or circular economy (Jayasundara and Rathnayake, 2023). A general comprehensive methodology for carrying out a MFA of the main biological feedstocks that can be used by bio-based value chains is presented. This methodology, which can be employed both in regional and in European level, is implemented for the main agro-industrial waste and by-product streams in the Region of Central Macedonia (Greece), identifying the most promising locally available biological feedstocks. The main results are presented and

discussed, pointing out opportunities and constrains regarding their valorization potential.

2. Materials and Methods

2.1. Material Flow Analysis methodology

Concerning the MFA development, the outcomes of different methodologies [6] have been consolidated and integrated into a novel methodological approach, presented in Figure 1. It primarily serves to the estimation of biological feedstock flows, based on data and databases concerning primary sector activities (i.e. agricultural, forestry, fishery etc.). The methodology can be adapted to different geographical scale to support the characterization of biomass flow balance and to analyze changes in biomass demand and consumption. To this end, the proposed MFA model is developed using input data regarding different processes and flows, such as raw materials, final uses, industrial by-products, imports, and exports, which are then categorized into three main parts: (i) feedstock origin, (ii) industrial processing, and (ii) final feedstock use. The main development steps comprise: (i) Goal and scope definition, (ii) Estimation of biological feedstock production potential, (iii) Assessment of biological feedstock fate and uses, (iv) Validation and filling of data gaps, and (v) Representation of the results.

2.2. The Region of Central Macedonia

The proposed methodological approach has been implemented for the Region of Central Macedonia (RCM) in Greece, concerning the main agro-industrial waste and by-product streams. The RCM is characterized by significant activity in the processing of primary's sector products (mainly food and beverages). These industries constitute 14% of the total number of relevant companies in Greece, whereas they provide almost 30% of employment in industrial sector in the Region. The RCM has almost 10 Industrial Areas, where many medium and large size companies are located, processing agricultural products, and producing products with high exporting potential (Table Olives, Honey, Wine, Dairy products like Feta cheese, Greek yogurt etc.). The agricultural sector has always been one of the major production sectors in the RCM, which produces approx. the 26% of the Greek primary agricultural sector in terms of Gross Value Added (GVA). Production of the primary sector, in which the Central Macedonia has a leading role in Greece, are Fruits (e.g., Peaches, Apples, Cherries, Olives), Cereals (e.g. rice, wheat, etc.) and Industrial/Fodder crops (cotton, corn, rapeseed etc.). Primary production and its processing into marketable products result in the generation of significant amounts of agricultural-related wastes and by-products. Each of the agricultural value chains produces different wastes and by-product streams, with specific physicochemical characteristics, both during the farming and/or agricultural processing. In particular, the boundaries of the analysis encompass the flows of biomass in the non-conventional bio-based value chains, extended from the agricultural phase to the processing phase of bio-based materials, without considering potential losses during distribution and final consumption. Agricultural wastes include residues that are left on the fields after harvesting (e.g., stalks, straw, etc.), as well as after processing into a valuable resource (e.g., husks, seeds, etc.), while agro-industrial waste includes losses generated by the fruit and food processing industries (e.g., kernels, fruit pulp, etc.).

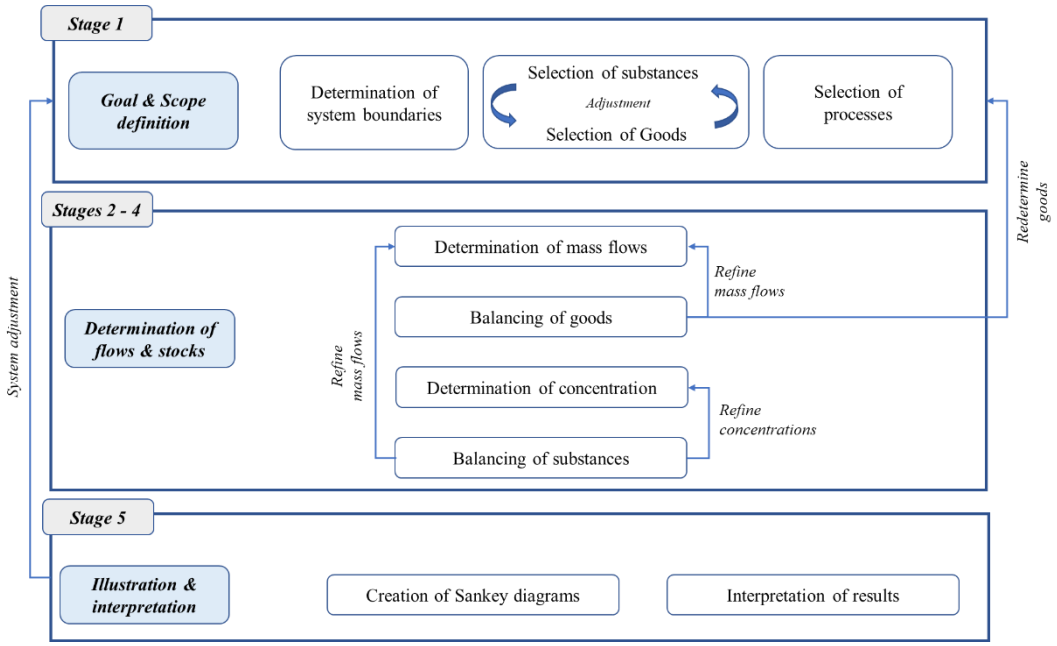

Figure 1. Schematic representation of MFA methodology development.

3. Results and Discussions

The main agricultural waste and byproduct streams in the RCM are summarized in Table 1. The main biological feedstocks are pruning that originate from tree cultivation during the autumn or winter, and straws/stems from cereal and industrial crops, during their harvesting.

Table 1. Summary of the main agricultural biological feedstocks in the RCM

Biological feedstock	Main Features (Origin, seasonality, composition etc.)
Pruning from tree crops	Composed from cellulose, hemicellulose, and lignin, the specific composition depends on the raw material. Moderate humidity and high seasonality; pruning is produced within 1-2 months each year.
By-products from cereal crops	Seasonal production in summer. High fiber, low protein content, and low humidity. Physicochemical composition significantly depends on the crop. High spatial distribution, whereas a portion should preferably be left in the field for replenishing carbon and nutrient content of the soil.
By-products from fodder/Industrial crops	The same characteristics to cereal by-products. The spatial destruction is lower, and given the well-established value chain, their collection and valorization are easier.

The quantities of the biological feedstocks produced in the RCM per year are summarized in Table 2. The quantities are presented as overall or theoretical quantities, which refer to the estimation of all the biological feedstock that is produced, and as available quantities that refer to the quantities that can be actually valorized after taking into consideration a number of limited factors (i.e. soil sustainability issues, nutrients and organic matter retain, technical constrains etc.).

Table 2. Estimation of the theoretical and available quantities of biological feedstocks produced in the RCM per year

Crop	Theoretical Quantity (tn D.M.)	Available Quantity (tn D.M.)
Cereals & Industrial Crops		
Soft wheat	149,557	55,336
Durum wheat	305,932	113,195
Barley	116,251	40,688
Oats	12,605	5,042
Rye	4,821	1,880
Maize	507,332	238,446
Rice	293,406	146,703
Tobacco	12,113	7,268
Cotton	687,920	316,443
Sunflower	146,534	73,267
Sugar beet	15,580	1,558
Canola	16,623	6,649
Potatoes	13,110	5,244
Tomatoes	25,648	12,824
Beans	1,380	414
Lentil	1,553	621
Chickpeas	4,233	1,693
SUM	**2,314,596**	**1,027,271**
Tree Crops		
Apples	10,266	8,213
Pears	6,431	5,145
Rays	22,988	18,390
Peaches/Nectarines	145,165	116,132
Cherries	65,833	52,666
Apricots	11,540	9,232
Almonds	15,525	12,420
Nuts	7,859	6,287
Chestnuts	18,654	14,923
Olives	130,101	104,081
Vines	39,125	31,300
SUM	**473,486**	**378,789**

Table 2 illustrates that the major part of the available biological feedstocks originates from the cereals and industrial crops (straws and stems) and accounts approx. 1 million tons of dry matter per year, whereas the tree crops provide approx. 0.4 million tons of biological wastes and by-products (mainly pruning) per year. Maize and cotton crops provide the highest quantities of available biological feedstocks, approx. 0.32 and 0.24 million tons D.M. per year, respectively. Concerning tree cultivations, peaches/nectarines pruning accounts for approx. 0.12 million tons of dry matter per year.

To estimate the potential uses of the biological feedstocks that are produced in the RCM, some typical utilization factors were employed. These factors were estimated from European reports and databases concerning the uses of biological feedstocks in Europe (Gurria et al., 2017; Gurria et al., 2022). It was assumed that the portion of available biomass that is used for bioenergy, feed and bio-based products is approx. 52.0%, 33.0%, and 0.5%, respectively. The rest (i.e. 14.5%) is considered that is used for non-specified uses. Based on these assumptions, the MFA of the biological feedstocks that are produced in the RCM is presented in the Figure 2. Results suggest that the quantities that are used for conventional uses (i.e. for bioenergy or feed purposes) are 1,000-fold those that are headed to the bio-based sector (i.e. bio-materials, bio-chemicals, etc.). Moreover, there is a portion that is currently used for purposes that are non-specified; further studies should be done to obtain insights on the uses of the harvested biological feedstocks in the RCM. It is also obvious that a significant portion of the total biological feedstocks are not harvested and are not valorized. It is important to assess the reasons that this biomass is not harvested and to specify the potential quantity that can be also valorized without compromising the long-term sustainability of the agricultural practice.

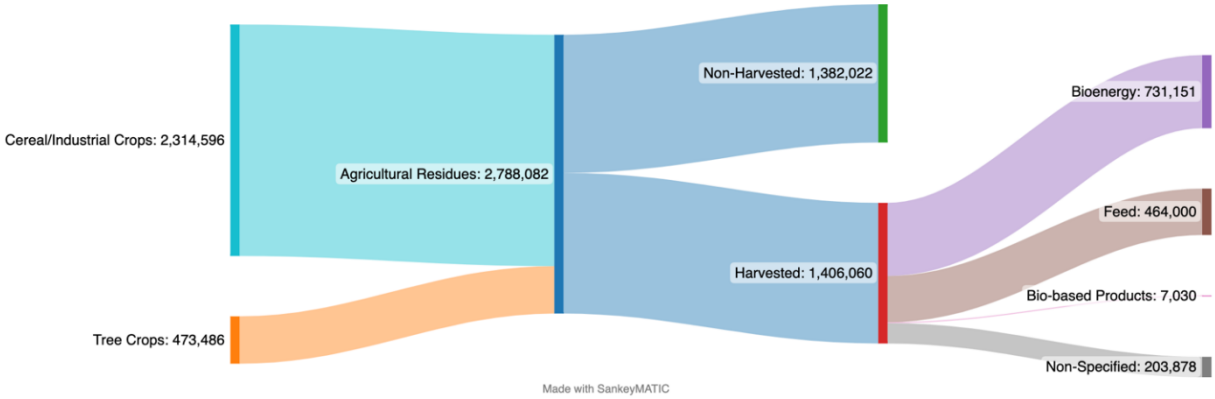

Figure 2. Sankey diagram of the agricultural residual biomass flows in the RCM (data in *tons dry matter/y*).

With respect to the main challenges and constrains regarding the valorization of these biological feedstock, it should be noted that currently, most agricultural by-products/waste streams are processed in non-environmentally friendly ways, i.e., burned in the fields (straw, pruning etc.) or temporarily stored in open ponds (e.g., olive and fruit pomace). Their seasonal production and variability hinder novel valorization schemes already proposed by scientists either for the recovery of bioactive compounds, production of composite material and certified bio-fertilizers. Agricultural by-products and wastes streams are also characterized by their large spatial distribution and, most of the time, lack of mature value chains with well-established logistics and supply lines. Moreover, these biomass streams are regarded by most stakeholders as a burden to be solved and not as a raw material with a specific value. The lack of certification schemes concerning the environmental and sustainability performance of these biological feedstock hinders their uptake as feeds from bio-based industry and thus the increase of their value for the benefit of farmers and the environment. Moreover, the certification scheme may solve the issues concerning the high variability of their properties, since if the origin and the production processes are known, it would be easier to provide an estimation/projection of their properties as well. Finally, consumer organizations will have a guarantee about the origin and sustainability of the secondary raw materials and may pay more for "green"/sustainable bio-products compared to their conventional counterparts.

4. Conclusions

The present study provides useful insights on the quantities of the biological feedstocks that are produced in the RCM and their potential uses. A MFA methodology has been developed and implemented to obtain quantitative data for the main agricultural corps in the RCM. The quantity of the available residual biomass is non-negligible, despite that only a tiny fraction is valorized to higher-value bio-based products. Constrains that hinder further development of higher-value valorization practices were also recognized. The outcomes of this study are expected to contribute to the development of the local circular bio-based economy and to act as a paradigm for other national and European regions.

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