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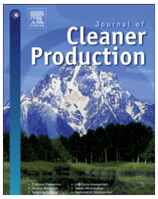

Assessment of agroforestry residue potentials for the bioeconomy in the European Union

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ABSTRACT

The biobased chemical industry is characterised by strong growth. Innovative products and materials such as biopolymers have been developed, and current European demand for biopolymers exceeds the domestic supply. Agroforestry residues can serve as main sources of the basic building blocks for chemicals and materials. This work assesses sustainably available agroforestry residues to feed a high added-value materials and product bioeconomy. To evaluate bioeconomic potential, a structured three-step approach is applied. Cultivation practices, sustainability issues, legislative restrictions, technical limitations and competitive applications are considered. All data regarding bioeconomic potential are processed on a regional level and mapped by ArcGIS. Our results identify wheat straw as the most promising source in the agricultural sector, followed by maize stover, barley straw and rape straw, which all contain a total concentration of lignocellulose of more than 80% of dry matter. In the forestry sector, residue bark from two coniferous species, spruce and pine, is the most promising source, with approximately 70% lignocellulose. Additionally, coniferous bark contains considerable amounts of tannin, which has attracted increasing interest for industrial utilisation. A sensitivity analysis concerning removal rates, residue-to-crop ratios, changes in farming technologies and competing applications is applied at the end of the study to consolidate our results.

1. Introduction

The transformation of traditional industrial processes to sustainable patterns is compulsory given limited resources and adverse environmental effects. In this context, the establishment of a biobased economy is a major responsibility. The aim of biobased economies is to substitute emission-intensive and non-renewable resources with renewable resources (McCormick and Kautto, 2013).

This article assesses the resource potential in the European Union for a biobased chemical industry from agroforestry residues. The chemical industry is one of the largest sectors in the EU-28, with revenues of over 500 billion EUR, a fuel and power consumption equivalent to 52.6 million tonnes of oil and greenhouse gas emissions of approximately 130 million tonnes CO_2 equivalent (CEFIC, 2017). Many innovative products and materials based on renewable input sources—so-called “biomaterials”—have already been developed within the concept of a biobased economy. By using biobased materials on a large scale, significant fractions of oil can be substituted by renewables. To do this, the supply of lignocellulose feedstock (LCF) needs to be secured in a sustainable manner. Lignin, cellulose, hemicellulose, and tannin are main constituents of the considered second generation feedstocks. Platform chemicals for the industry can be produced by mechanical, chemical, thermochemical or biological conversion of the biomass. The most promising sources are by-products from agricultural and forestry activities, which consist of large amounts of industrially interesting substances (Kamm and Kamm, 2004). A future-oriented bioeconomy, where basic building blocks from renewable resources replace oil-based materials and chemicals, can meet important environmental, social and economic requirements for sustainable development. Additionally, such a transformation supports the geostrategic goals of the European Union: by substituting oil with agroforestry products, the EU gains independence from oil-exporting countries and intensifies utilisation of domestic resources. However, misuse of industrial utilisation of biomass can also be associated with ecological and ethical concerns. For instance, arable land for growing biomass feedstock is limited, and thus industrial applications may compete with food production, and strain on environmental resources may have negative effects

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on humans, animals and plants. Therefore, an analysis of the European LCF potentials, taking into account sustainability issues and competitive application, is crucial.

Terminology in the current discussion of concepts for the assessment of biomass potential is inconsistent in the existing literature (Hennig et al., 2015). Despite this, some initiatives provide guidance for harmonisation of the calculation of potentials (Brosowski et al., 2016; Thrän and Pfeiffer, 2015; Vis and van den Berg, 2010). Brosowski et al. (2016) recently published a comprehensive review of publications on the biomass potential of wastes and residues in Germany. The review compiles the status quo for the theoretical and technical potential and proposes the reference unit "metric tonnes of dry matter". However, research focuses on the energy use of biomass residues, either for direct combustion or, with increasing interest, to feed advanced biofuel production (also known as "second-generation biofuels") (Kretschmer et al., 2012; Scarlat et al., 2010). Thrän and Pfeiffer (2015) and Vis and van den Berg (2010) suggest potential analysis in energy reference units (e.g. joule). In the light of a bioeconomy based on a material use of lignocellulose, the available feedstock needs to be assessed in mass. Therefore, Hennig et al. (2015) call for a reassessment of contemporary concepts of energy utilisation of biomass, which must be assessed when those already "tapped" raw materials are more beneficial in high-value applications.

The reviewed research on biomass potential concentrates on energy utilisation. Research analysing the potential of biobased industrial transformations that considers economic and ecological strains is rare, and comprehensive studies on the regional dispersal of sources and interdependencies with primary production processes are lacking (Scarlat et al., 2010). No research is available for the determination of the potential of agroforestry waste for high value-added applications addressing regional potentials, competitive applications (e.g. animal bedding, horticulture) and the content of focal substances (e.g. lignin, tannin, cellulose, hemicellulose), which are essential for the design of biopolymers as a precursor of high value-added industrial products. Consequently, no potential levels are described for biomass utilisation other than for energy use.

To fill this void, we herein apply a method for the assessment of potential agroforestry products as inputs for a European biobased industry. Based on this methodological work, the following application-orientated research questions are addressed:

- *Which agroforestry residue sources offer the largest potential as inputs for biomaterials, considering the feedstock quantity and biochemical composition?*
- *How large is the sustainable potential of selected agroforestry sources on a regional level in the EU-28?*

2. Materials and methods

To thoroughly address the research questions, a structured research process is implemented. The applied method sets out to quantify the bioeconomic potential for the use of high added-value bio-products, taking into account sustainable farming and forestry practices as well as competitive applications. Kretschmer et al. (2012) noted that existing literature on biomass is discordant in the classification of available potentials. Fig. 1 shows a transparent distinction between three levels of biomass potential we applied in this study, based on Vis and van den Berg (2010) and Thrän and Pfeiffer (2015).

Theoretical potential includes all parts of the total harvested biomass that have no direct use in food, feed or industrial production. The primary product (e.g. industrial roundwood or grains) and the theoretical potential sum to the total biomass. Due to factors such as sustainable harvesting practices (e.g. balancing humus quality, see Helwig et al., 2002; Münch, 2008) and legislation (e.g. restriction of the removal of treetops and small branches from forests), only a fraction of the theoretical potential is accessible for further utilisation. These facts are considered in the calculation of technical potential, which we define as the amount of residue that can be technically, legally and sustainably removed from the field or forest. Bioeconomic potential is the share of technical potential that is not necessarily used in competing applications. Additionally, refining residues of the primary product can add to the bioeconomic potential.

2.1. Identification of theoretical potential

In the first step, we identify relevant agroforestry sources of lignocellulose-based biomass. In the agricultural sector, we consider cereals, legumes, oil crops, sugar crops and fibre plants, in the forestry sector, we consider both, coniferous and broadleaf trees. Sources assessed in this study constitute an important share of agroforestry residues in general, however not all possible sources are considered. We assess the quantity of residues and their quality based on the main product, the residue-to-crop ratio and the concentration of focal substances (lignin, celluloses, hemicellulose and tannin) within the residues.

Crop production values serve as a proxy for the calculation of the theoretical potential of the lignocellulose feedstock (LCF). The crop production data are obtained from Eurostat (2016a) using the regional level NUTS 1 (Nomenclature des unités territoriales statistiques). The theoretical potential of residues is calculated with the residue-to-crop ratio (R:C ratio), which is derived by a literature study (see Supplementary Information Part 1). The R:C ratio has numerous influencing factors like the seed type, soil condition, weather events, and others and is therefore difficult to estimate. The harvesting index (HI; share of primary product in relation to total biomass above ground) is closely related to the residue-to-crop ratio and Equation (1) shows the connection of the HI to the R:C ratio. Research on the harvesting index addresses questions about the biophysical maximum of a plant, which is estimated to be about 0.65 for wheat grain (Foulkes et al., 2011). For wheat grain, observed values for the harvesting index are approximately 0.5, resulting in a residue-to-crop ratio of 1.0. In contrast to the HI, which has been constant since the early 1990s, crop yield has significantly increased in the last years, leading to higher straw yields (Foulkes et al., 2011). All other R:C ratios for investigated agricultural sources are in the Supplementary Information (see Supplementary Information Part 1).

$$R : C\ ratio = \frac{residue\left(\frac{t}{ha}\right)}{yield\left(\frac{t}{ha}\right)} = \frac{1}{HI} - 1 \tag{1}$$

To quantify the amount of focal substances, we additionally review the biochemical composition of the identified residues. The composition of reviewed agricultural harvesting residues is similar for most sources, with approximately 15–20% lignin, 30–45% cellulose, and 20–25% hemicellulose (Bakker et al., 2013; Kamm and Kamm, 2004). Table 2 shows the crop specific results of the reviewed studies. The presented values are derived from studies referring to multiple laboratory tests of different samples and must not be confused with data from samples from isolated industrial processes (Monteil-Rivera et al., 2013). Disparities among different studies are due to factors such as the measuring method, pretreatment of the material, and varying climatic conditions in different world regions (Buranov and Mazza, 2008). The literature