The socio-economic impacts of wastewater sludge valorization: The case of biofertilizers in Italy

Date of document – March/2021 (M34)

D8.8: Report on case study "The Bioeconomy Pilot from the Vanguard Initiative"

Authors: Gianmaria Tassinari (UCSC); Stefano Boccaletti (UCSC); Claudio Soregaroli (UCSC)

Monitoring the Bioeconomy

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 773297.

Technical References

Project Acronym	BIOMONITOR
Project Title	**Monitoring the Bioeconomy**
Project Coordinator	Justus Wesseler Wageningen University justus.wesseler@wur.nl
Project Duration	June 2018 – May 2022 (48 months)

Deliverable No.	D8.2
Dissemination level [1]	PU
Work Package	WP 8 – Case studies
Task	T 8.2 – Case study analysis
Lead beneficiary	P6 (TUM)
Contributing beneficiary(ies)	P2 (UCSC)
Due date of deliverable	31 March 2021
Actual submission date	31 March 2021

[1] PU = Public
PP = Restricted to other programme participants (including the Commission Services)
RE = Restricted to a group specified by the consortium (including the Commission Services)
CO = Confidential, only for members of the consortium (including the Commission Services)

Document history

V	Date	Beneficiary	Author
V1	10.03.2021	Intern	UCSC
V2	22.03.2021	Intern	UCSC
V3	31.03.2021	All	UCSC

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 773297.

Summary

Preserving natural resources and ensuring global food security are among the greatest challenges facing contemporary agriculture. The valorization of waste into by-products applying circularity principles is a central theme for the bioeconomy and a way to foster sustainable economic development. In this context, municipal wastewater has high potential for nutrient valorization and sustainable supply chain development. To assess the feasibility and potential benefits of agricultural use of sludge-based fertilizers, it is important to monitor the sustainability impacts of these fertilizers on the overall economy. The objective of this case study is to evaluate the economic and social impacts of a wastewater valorization biotechnology. To this end, we model an empirical case study with a hybrid input-output (IO) analysis, combining data on new processes and sectors with an existing supply-use table (Exiobase). In particular, we quantify direct and indirect impacts for replacing a synthetic fertilizer with fertilizers derived from wastewater. The results show that the development of a biorefinery for the valorization of nutrients from sewage sludge has great relevance in creating added value and employment for the rural society of the local area.

In the context of the BioMonitor project, the case study represents an application of the input-output methodology aimed at measuring the spillover effects of sludge treatment in a bioeconomic supply chain. Using the socio-economic indicators defined by WP1, the case study applies IO analysis to monitor the cascading effects generated by bio-based products and their contribution to a circular economy. In addition, the driving forces indicated by WP1 were explored in the context of the case study. Feedback is reported in validating the relevance of indicators and drivers are also reported as essential information for monitoring the bioeconomy.

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1 Introduction

Preserving natural resources and at the same time ensuring global food security are among the greatest global challenges facing society today. The valorization of waste into by-products applying circularity principles is a central and essential issue to foster sustainable economic development (European Commission, 2019). In this context, municipal wastewater has high potential for nutrient valorization and sustainable production chain development. An example of this is the use of sewage sludge as a source of nutrients for agricultural crops.

A recent technological innovation in the treatment of sewage sludge allows nutrients in it, such as phosphorus, to be recovered as a fertilizer, potentially replacing synthetic fertilizers with biological and renewable sources (Herzel et al., 2016). In the particular case of rock-based phosphorus fertilizers, there are a few mining sites (Morocco, China, Brazil, and the US, none in Europe) that serve essentially all farmers worldwide (Edixhoven et al., 2014). The operation to recover phosphorus from sewage sludge has the potential to slow the depletion of these stocks, limit the energy consumed to produce synthetic fertilizer, and create new economic and social value.

The innovative use of non-food biomass is at the heart of the debate led by the Vanguard Initiative (VI) for the development and new growth of the European industry. The Vanguard Initiative is a European network that aims to contribute to the industrial renewal in Europe by supporting regional clusters and ecosystems (Vanguard Initiative asbl, 2021). The VI Bio-Economy pilot project promotes new bio-based value chains by highlighting seven pilot and demonstration cases. Thanks to the regional innovation ecosystem supported by the Vanguard Initiative's Italian demo case coordinator, it was possible to learn about and contact the companies involved in the supply chain for the nutrient valorization of sludge in the Lomellina region, Italy.

1.1 Research question

To assess the feasibility and potential sustainability benefits of a circular bioeconomic value chain, it is important to study its impact on the economy. The goal of this study is to measure the cascading socio-economic implications in the national context of nutrient valorization from organic residues for agricultural use.

RQ1: "How does nutrient valorization from organic residues affect the local economy?"
RQ2: "How does the socio-economic sustainability of fossil-based fertilizers change with sludge as a replacement for nutrient inputs?"

To this end, we investigate the on-site (direct) and supply chain (indirect) impacts of biofertilizer use on the Italian economy, applying a hybrid input-output (IO) analysis. This analysis is based on the inclusion of data from new processes and sectors in existing supply-use tables (SUTs), an important statistical tool highlighted by the BioMonitor project that advances monitoring and measuring of the economic, social, and environmental activities of a nation. In particular, coupling the strengths of SUTs with conventional impact analysis provides completeness by eliminating systems truncation

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and considering the entire supply chain of the investigated bio-based industry (Malik et al., 2015; Rodríguez-Alloza et al., 2015).

Answering these research questions allows the elaboration of important feedback and recommendations for the users of BioMonitor indicators and data collection methods, which are designed for monitoring the total potential implications of the bioeconomy for value chains, products, and industries.

1.2 Justification of research approach

To capture the socio-economic impact of nutrient valorization from waste, we applied a hybrid IO approach to quantify the effects of introducing new products and industries into an economy, extending a SUT with process data collected from a case study. The case study under analysis is a supply chain, including wastewater treatment plants (WWTP$_S$) and a biorefinery, producing biofertilizers and biosolids from municipal sewage sludge. The case was detected thanks to one of the coordinators of a demo case in the Vanguard Initiative Bioeconomy pilot project. The bio-based supply chain is located in the territory of Lomellina, in Lombardy (Italy). This area has a strong agricultural reputation, especially for the production of rice, but the low intensity of livestock farming reduces the availability of manure. The data collected from the biorefinery includes (i) monetary inputs to cover the operating and capital costs associated with the transformation of sewage sludge into biofertilizers; and (ii) physical satellite accounts data for indicators, such as employment.

The input-output analysis is a powerful tool for analyzing complex supply chain networks. According to the BioMonitor project, SUTs/IO tables are valuable analytical tools for assessing the spillover effects of the bioeconomy; they represent the interdependencies that exist among different but interconnected products and industries. The applied augmentation approach has been widely used in the literature for several bio-based productions (Murray et al., 2008; Malik et al., 2015, 2016; Wilkson et al., 2018; Chen et al., 2019, 2020; Wang et al., 2020). For this study, we chose the Exiobase database (Stadler et al., 2018). In its most recent version (v3.8 release in November 2020), the database provides SUTs ranging from 1995 to 2022 for 43 different countries (Nathani & Hellmüller, 2019). The monetary form of Exiobase contains data for 163 industries and 200 products. In addition, this database contains factor inputs and several satellite accounts (emissions, resources, and materials types) for each industry (Nathani & Hellmüller, 2019).

This study contributes to the BioMonitor research on monitoring the methodologies for impact analysis using circular bioeconomy models. We illustrate the strengths and caveats in coupling SUT/IO tables with conventional process analysis for sustainability impact monitoring. Second, we test and validate the use of indicators outlined by BioMonitor in the hybrid input-output analysis approach. Third, we provide empirical evidence on the importance of bioeconomy drivers in monitoring activities, as emphasized by WP1. Further developments are needed to better understand the socio-economic impact of nutrient valorization from waste since most of the existing literature has focused only on the environmental impacts of such production. The implications are relevant not only to policymakers but also for producers who must respond to increasing requests of information for environmental responsibilities.

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2 Methodology

2.1 Input-output analysis

Input-output analysis is an economic tool developed by Wassily Leontief in the 1930s (Leontief, 1936). The basic idea of IO analysis is to represent the economy as a circular system structured as sets of industries and products. Industries are groups of firms or other organizations (e.g., government) that produce and consume products such as goods and services (e.g., agricultural products and retail services). This structure is an opportunity to understand the interdependencies between industries according to the monetary transactions that occur between the groups at a particular time (year). Leontief (1986) formulated a set of linear equations representing the complex interdependencies occurring within an economy as:

$$x = Ax + y \tag{1}$$

$$x = (I - A)^{-1}y \tag{2}$$

where: x is a column vector of the total output of an economy; y, a column vector of final demand; I is the identity matrix; A, the input-output matrix of technical coefficients that depicts the direct requirements needed to produce a unit of output.

The Leontief quantity model is driven by the demand for products (Lenzen & Rueda-Cantuche, 2012). Assuming proportional relations between inputs and outputs, there will be a direct effect on the total output given a final demand variation (Δy) and additional indirect effects captured by the so-called Leontief inverse matrix, $L = (I - A)^{-1}$.

2.2 SUT database

Input-output analysis depends on IO tables. IO tables derive from SUTs (Figure 1a), which are matrices industry-by-product that record how products are brought into an economy (**V**, supply matrix) and how those products are used as intermediate and internal consumption (**U**, use matrix) and as final demand (**y**). Final demand consists of households consumption, government consumption, investment (including change in stocks), and exports. Imports are considered as a commodity. Finally, value added (**v**)—including taxes, subsidies, and factor inputs (e.g., labor and capital)—balances supply total outputs and use total inputs. In addition, SUT/IO tables can be coupled with noneconomic, physical data (**Q**) on social and environmental indicators, such as employment, energy, or greenhouse gas emissions (Malik 2018).

The SUT used in this research is derived from the Multi-Regional Input-Output (MRIO) database Exiobase (Stadler et al., 2018). Exiobase focuses on the European regions and provides data at the aggregate level of 163 industries and 200 products, making it the most disaggregated among the most frequently used MRIO databases (Tarne et al., 2018). As a tool for measuring the impacts of economic activities, Exiobase also includes information on 33 different types of emissions, 14 types

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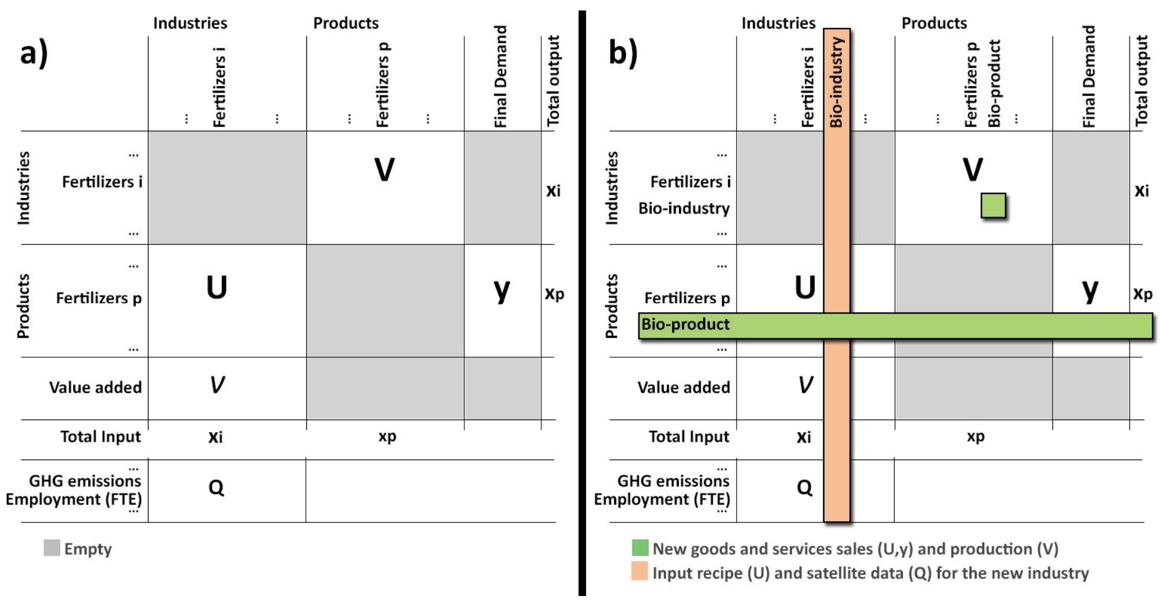
of land use, 48 types of materials, 172 types of water use, and three distinct levels of employment skills by gender (Malik et al., 2019; Nathani & Hellmüller, 2019).

2.3 Hybridization of SUT data

To better understand the impacts of new products on the current economy, IO frameworks can be coupled with process-based data by expanding the SUT with new columns and rows (Figure 1b). Matrix augmentation methods, also known as IO hybrid methods, are becoming an integral part of life cycle assessment (LCA) since they eliminate truncation error and offer a complete assessment of impacts (Crawford et al., 2018; Malik et al., 2019). Matrix augmentation can be used either to divide an existing sector into sub-sectors or to create a new theoretical sector (Crawford et al., 2018). In our case study, the Italian Exiobase SUT table (version 3.8, updated in November 2020) was augmented with a new industry and product. The new industry represents the investigated supply chain consisting of 45 wastewater treatment plants (WWTPs) and a biorefinery that processes the sludge that the WWTPs produce. The new product group includes biofertilizers, biosolids, and sludge treatment services provided by the biorefinery and the municipal waste treatment service supplied by the WWTPs.

Figure 1: a) Supply-use table; b) Schematic diagram showing the augmentation of an existing SUT



Source: Own elaboration

The single element added in the supply matrix (Figure 1b) includes the total value of goods and services provided by the new industry. The added column vector represents the production receipt input costs and the rewards for factor inputs (value-added components) for the new industry. Finally, to re-balance the augmented IO table, a row is inserted to include the internal and intermediate deliveries and the final demand for the supplied product. Augmentation includes satellite accounts for different indicators of the new industry.

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2.4 Measuring impacts

To measure both on-site (direct) and supply chain (total) impacts of the new industry, we apply Leontief's input-output methodology. The satellite data Q, containing employment, and any other measured indicator, can be introduced into the monetary IO model, and impacts can be measured as:

$$q = Q\hat{x}^{-1} \tag{3}$$

$$m = qL \tag{4}$$

where q is the vector of direct impact (e.g., employment intensity q_i of industry *i*); $\hat{x}$, the diagonalized vector of the total output of an economy; m, the total impact on the economy, containing all the supply chain repercussions.

The total multiplier m can be further decomposed to quantify the contributions of each industry in the so-called production layer decomposition process. Recalling that the Leontief matrix $L = (I - A)^{-1}$ can be written as $L = I + A + A^2 + A^3 + \cdots + A^n$, the basic IO equation now becomes:

$$Q^* = q\#Ly^* = q\#y^* + q\#Ay^* + q\#A^2y^* + q\#A^3y^* + \cdots + q\#A^ny^* \tag{5}$$

where # is element-wise multiplication; y^* is the non-zero element final demand vector, corresponding to the modelled monetary final demand shock. The term $q\#y^*$represents the on-site (direct) impact (layer 1); $q\#Ay^*$ is the impact from the suppliers (layer 2); $q\#A^2y^*$ is the impact from the suppliers of suppliers (layer 3) and so on.

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3 Case study

This case study evaluated the socio-economic impacts of the treated sewage sludge used as a fertilizer and biosolid. To this end, we investigated a bio-based supply chain located in Italy, producing and processing 165,000 tons of sewage sludge from municipal wastewater per year. Site selection was based on purposive and convenience criteria: 1) representativeness of a complete, qualified, and actual biobased ecosystem; 2) accessibility of processing plant data; and 3) willingness of the companies to participate in the study.

3.1 Unit of analysis

There are three main stages of the studied supply chain: the production of sewage sludge at municipal WWTPs; the withdrawal, transport, and treatment of sludge with the production of biosolids and fertilizers; and the distribution of sludge to local farmers. The biorefinery collects 165,000 tons per year of sludge from 45 WWTPs located throughout the country that serve 226 municipalities. Biomass withdrawal is handled by the biorefinery for 55,000 tons, while the rest is contracted to a land transportation service company. Before being collected and processed, the sludge is analyzed to validate the conformity of its chemical profile. The sludge is further treated as a resource rather than waste and conditioned by sulfuric acid, lime, and gypsum to produce 40,000 tons of fertilizers and 120,000 tons of biosolids (bio-sulphate and bicarbonates in ratio 1:2) per year. The produced fertilizers and biosolids are finally distributed to local farmers operating in the Lomellina and Piedmont area, replacing in part the use of conventional fertilizers. In addition to the distribution of bio-based products to farmers, plowing and fertilization consulting services (including soil chemical analysis) are also provided. Both products and services provided by the biorefinery are offered completely free of charge, therefore representing a cost saving opportunity for farmers.

3.2 Process-based data

Process data collection was led at both sectoral and product levels. Various sources of information, including interviews, questionnaires, legal reports, scientific literature, and policy strategies were triangulated to gather evidence. Figure 2 illustrates the foreground system referred to 1 ton of sludge processed as a resource for nutrient valorization.

At the sector level, we collected the input recipe associated with the production of biofertilizers and biosolids. The basic inputs (Table 1) for the WWTPs were derived from the academic literature, whereas the sludge treatment requirements were provided by personal communication with the biorefinery management. The average nominal capacity for each of the 45 WWTPs was estimated at 197,132.62 m^3 per year (Murray et al., 2008) to produce 165.000 tons of sludge at 22.2% of dry matter. The energy consumption of a WWTP with such an influent flow rate is 0.29 kWh/m^3 (Vaccari et al., 2018). The electricity price is 0.23 euros/kWh, taken from Statista statistics (Statista, 2021). With regards to the configuration, the plant includes wastewater disinfection with sodium hypochlorite (NaClO) and sludge thickening with polyacrylate, whose quantities and values come from Chen et al. (2020). The sludge is then handled by the biorefinery, which receives 100 euros/ton

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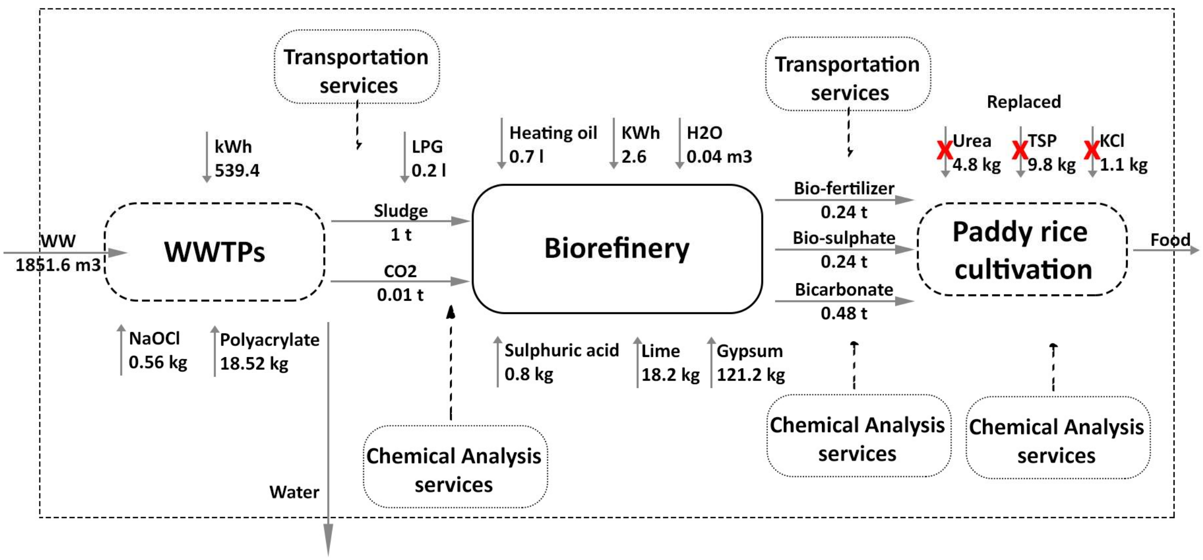
for the service from the WWTPs. Transport is contracted for 110,000 tons to a land transportation service company, with a cost of 13 euros/ton. The remaining transportation cost is accounted as LPG consumption. After the stabilization processes using sulfuric acid, lime, and gypsum, the biofertilizers and biosolids are spread on the land by contractors at the cost of 6 euros/ton. Production recipe also includes the chemical analysis performed on incoming sludge, outgoing products, and agricultural soils. Along with the operating costs, an inventory of fixed assets was also included. The capital cost was estimated with the Williams Law function $C = 18{,}200\ Q^{0.51}$ (Guo et al., 2014), where C is the capital cost, Q is the plant size as daily processed wastewater flow, and the two numbers are positive constants indicating the unit cost (18,200) and economies of scale (0.51). According to Chen et al. (2020) and the annual wastewater flow rate, we calculated material costs. Material costs were subtracted from the estimated capital cost to obtain the cost of civil work.

Figure 2: Foreground system referred to 1 ton of processed sludge.



Source: own elaboration

For value-added components, compensation of employees, consumption of fixed capital, and remaining net operating surplus were accounted. No subsidies or taxes were applied. Employee's compensation was calculated by multiplying the average annual labor expenditure per Full Time Equivalent (FTE) (1 FTE = 1 employed person working 40 hours per week) provided by the biorefinery by its 74 employees and by the 135 employees of the 45 WWTPs (assuming three operators needed to manage each plant). Consumption of fixed capital was derived by financial records for the biorefinery and estimated for the WWTPs, assuming 25 years as a life span. Municipal WWTPs have a net operating surplus of zero, while the biorefinery generates €59.38 per ton of sludge treated.

Table 1: Inputs demand per one ton of treated sludge

	Input items (Exiobase codes)	Unit	Quantity	Value (EUR)
WWTPs	Electricity by gas	kWh/t	539.40	125.14
	Plastics, basic	Kg/t	18.52	32.40
	Chemicals nec	Kg/t	0.56	0.56

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Biorefinery	Gas/Diesel Oil	l/t	0.69	0.48
	Liquefied Petroleum Gases (LPG)	l/t	0.20	0.23
	Chemicals nec	kg/t	0.78	0.05
	Cement, lime and plaster	t/t	0.14	2.49
	Electricity by solar photovoltaic	kWh/t	2.6	0.23
	Collected and purified water	mc/t	0.04	0.02
	Other land transportation services	-	-	14.48
	Other business services (74)	-	-	3.5
Construction costs	Cement, lime and plaster	Kg/t	11.67	0.37
	Stone	Kg/t	806.03	4.81
	Bricks, tiles and construction products	Kg/t	15.37	1.85
	Basic iron and steel	Kg/t	0.93	0.37
	Natural gas	MJ/t	5.93	0.19
	Rubber and plastic products	Kg/t	0.19	1.11
	Aluminium and aluminium products	Kg/t	0.19	0.37
	Other land transportation services	Tkm/t	2.96	1.30
	Construction work	-	-	26.98
Value added	Compensation of employees	FTE	204	32,754.41
	Consumption of fixed capital			41.82
	Remaining net operating surplus			59.38

Source: own elaboration

We also calculated the losses in the synthetic fertilizer industries due to the sludge treatment to produce bio-based fertilizers used in paddy rice cultivation. For this purpose, we collected data for the nutrient content in terms of NPK at the product level (Table 2) of both bio-based products and conventional commercial fertilizers used in rice cultivation in Italy (Fusi et al., 2014). The nutrient contents of bio-based products were personally communicated by the production facility, while those of synthetic fertilizers were derived by applying conversion factors for the respective N, P_2O_5 and K_2O contents of the three products. Unit prices for biofertilizers and biosolids were set equal to zero since they are offered free of charge by the biorefinery to farmers, while prices for the synthetic fertilizers were collected from Camera di Commercio Website.

Table 2: Nutrient content of the biorefinery products and substitution rates

Parameter	Bio-Fertilizer	Bio-solids	Urea	Superphosphate (TSP)	Potassium chloride (KCl)
SS (%)	20.6	32.4	100	100	100
N (kg/DT)	17	15	460	0	0
P (kg/DT)	24	11.4	0	200	0
K (kg/DT)	4.8	3.8	0	0	498
Efficiency coefficient	0.5	0.5	1	1	1
Price (Eur/t)	0	0	405	345	315

Source: own elaboration

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3.3 Context

The context plays a key role in this case study. Several forces drive the development of the bioeconomy and related phenomena. Kardung et al. (2021) summarize these forces as supply drivers (technology and innovation, markets, and climate change adaption), demand drivers (consumer preferences, economic development, and demography), resource availability, and government measures. According to these drivers, we investigated the context of our unit of analysis based on a semi-structured interview (Appendix A).

3.3.1 Resource availability

The biorefinery under study is located in the Lomellina region of the Po Valley in northern Italy. It is located in Pavia province, in south-western Lombardy and near Piedmont. Together these two regions account for 30.5% of the 18,140 wastewater treatment plants operating in Italy. In this area sewage sludge is, therefore, very abundant and readily available.

The territory of Lomellina is classified as a priority area for biodiversity conservation, and it plays an important role in the regional ecosystem, including several Special Protection Areas (Trouwborst, 2011). The ecological restrictions on the territory are well combined with the agricultural use of the area, notably the paddy fields, which provide habitat for several wildlife species.

The province of Pavia is the leading national and European producer of rice, with about 80,000 hectares cultivated. The area is characterized by intensive farming systems and low livestock farming density. This aspect has created over the years a great demand for organic fertilizers to restore soil fertility and correct pH variation due to mineral fertilization and submersion for rice cultivation. Given that, a very important resource for the business is a large number of farmers available and their willingness to receive biofertilizers and biosolids.

3.3.2 Climate and environmental change

The supply of the investigated biorefinery is aimed at meeting the needs of the agricultural sector, as well as offering a service for wastewater disposal. The increasing frequency of extreme weather events and the rising temperatures due to climate change put a strain on agricultural activities. Using biosolids as fertilizers or soil amendments offers farmers several advantages. Biorefinery products can partially replace synthetic fertilizer, having the potential to improve soil quality and correct pH changes that can arise from repeated mineral fertilization practices. Biosolids generally increase crop yields more than that of well-fertilized controls (Singh & Agrawal, 2008). However, special attention must be paid to the accumulation of toxic metals from excessive use over the years. Plants, however, differ in their abilities to absorb sludge-derived metals from the soil. For instance, Singh & Agrawal (2010) suggest that rice grown on sewage sludge amendment soil up to 4.5 kg/m^2 showed high yield without causing the risk of food chain contamination for nickel and cadmium concentrations in rice grains.

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3.3.3 Market organization

The market organization is primarily delineated by the business relationships among WWTPs, sludge treatment plants, analytical laboratories, and farmers. In the first step, where the WWTP pays the plant for the withdrawal and disposal of sewage sludge, there are formal written contracts, generally on a time basis (annual or bi-annual). Nonetheless, there is no univocity about the contract, and each WWTP calls for tenders independently. In the downstream operations, it is the local businesses' contacts and the trust gained from farmers over the years that determine the duration and extent of the relationships, which are often not formalized. In addition, the seasonality of agricultural activities causes a volatile demand for biofertilizers. For these reasons, contracts are written in many different ways in terms of duration and size to meet the needs of farmers. Horizontal integration occurs, instead, between the biorefinery and the chemical analysis laboratory. The lab has the key role of checking the compliance of sewage sludge on entry, verifying the chemical compliance of biofertilizers on exit, and testing the soil fertility where they are spread.

Due to the high volume of raw materials, there is a significant competitivity among processing plants. Such competitivity comes from the techno-economic conditions that each biorefinery can offer. The price of the services reflects the technological and scale level of the production. Innovation, patents, investments in R&D, plant efficiency, and the production of a wide range of biosolids with different fertilizing power are elements that influence the price and strategic competitivity of each plant.

Unpredictable changes in market conditions may occur and are generally caused by external factors. The most common is the change of legislation by government decision. In particular, spreading services might be affected by a change in the nitrogen efficiency rate, which strongly affects the demand for biofertilizers, causing overproduction and even a temporary stop of the sludge treatment activities.

3.3.4 Technology and innovations

Technology and innovation are fundamental along the entire supply chain, driving production security and plant efficiency. The studied biorefinery has four patents, concerning both the outputs and the technical process/plant to produce them. Growing attention in technological progress is also addressed to the agricultural level and the provision of services related to precision farming, such as the offer of detailed information maps on soil conditions for fertilization.

Along the supply chain, there are several examples of partnerships with the aim of technological innovation. Technology handovers from external stakeholders are common in the supply chain. Consulting services and projects that take advantage of the technical and scientific knowledge of research institutions are frequent within the chain. Constructive cooperation between public and private entities is also present.

3.3.5 Policies, strategies, and legislation

Policies play a crucial role for all the activities involved in the supply chain, regulating their environmental and health safety. The different policies around sewage sludge treatment and use

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create a multifaceted legislative profile on regional, national, and European scales (Table 3). These policies are subject to many debates and controversies.

Table 3: A summary of the legislative profile

Legislation level	Document	Content
EU	Directive 86/278/CEE	"on the protection of the environment, and in particular of the soil, when sewage sludge is used in agriculture."
EU	REG. UE 2019/1009	laying down rules on the making available on the market of EU fertilizing products. New rules for the "End of Waste."
National	D.lgs. 99/1992	Lays down condition of using sludges in agriculture
National	D.lgs. 152/2006 e s.m.i.	It confirms the definition of sewage sludges and mandates their use when possible. Regulates "End of Waste"
National	D.lgs. 75/2010 e s.m.i.	Reorganization and revision of the regulations on fertilizers (plasters and carbonates)
Regional	d.g.r. July 1st, 2014, n. 10/2031	Regional provisions for the treatment and use, for agriculture benefit, of sewage sludges
Regional	d.g.r March 2nd, 2020, n. 11/2893	Nitrate Action Plan 2020-23 regulating the quantities of nitrogen that can be spread to the field

Source: own elaboration

The hottest debate concerns EU directive 86/278/EEC enforced in Italy in 1992 with Legislative Decree 99/1992. This directive identifies the operational limits in terms of quantity and quality within which the biosolids chain must operate. Since that date, no substantial updates have been made despite the engineering, chemical, and agronomic progress that has affected this sector. Many parts of the legislative panorama are therefore dated. Referring to Directive 86/278/EEC, the European Commission itself stated that "*adopted 30 years ago, the Directive no longer matches current needs and expectations, such as properly regulating pollutants found in sludge.*"

In this national and European framework, regional legislation, on the contrary, has allowed processing plants in the Lombardy region to become the main recipients of Italian sewage sludge, favoring the development of business along the entire supply chain. In addition, Lombardy's R&D and innovation regulations provide important incentives for the sector to create applied research projects.

3.3.6 Consumer preferences, economic developments, and demographics

The demand for sewage sludge withdrawal and disposal is a key driver and is expected to increase in the coming years. The demand for organic fertilizers in the Lomellina territory is also important. Both WWTPs and farmers can be considered as users of the goods and services provided by the biorefinery. For the former, preferences are more related to the performance and price of the disposal service. For the latter, biosolids must meet essential characteristics such as good fertilizing capacity and an ease of use. In both cases, technological innovation plays a key role in satisfying the techno-economic characteristics of the goods and services provided by the biorefinery. Considering

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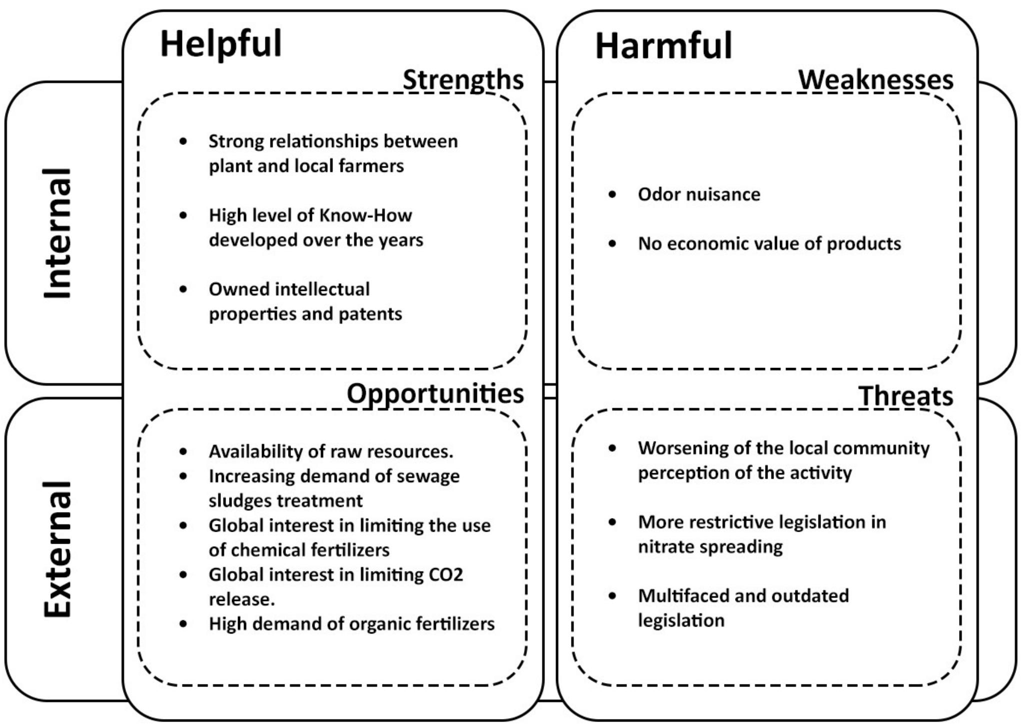
the end consumers of the agricultural products, instead, preferences generally point to local products produced without the use of biofertilizers.

From a social perspective, Lomellina territory has a low level of urbanization and a low population density, concentrated in small and middle-size towns. Nevertheless, there is a wide infrastructure system that makes logistic connections with the rest of the national territory very efficient. The low population density partly reduces the odor nuisance related to sludge collection, treatment, and disposal, one of the main problems related to the supply chain.

3.3.7 SWOT Analysis

Based on the information gathered and described in the previous sections, a SWOT analysis (Figure 3) was conducted. SWOT analysis is an effective conceptual framework which allows to understand the organizational 'Strengths' and 'Weaknesses' of the supply chain and to identify critical 'Opportunities' and 'Threats' in its competitive environment (Gürel & Tat, 2017).

Figure 3: SWOT Context analysis



Source: own elaboration

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4 Results and discussions

The augmentation approach allowed the assessment of both on-site (direct) and supply chain (total) impacts of the investigated waste management industry (Table 4). Direct impact occurs within the operating facilities of the new industry. The total impact includes, along with the direct effects, the indirect stimulus generated for all the upstream suppliers. A comparison of biofertilizers and biosolids with conventional fertilizer industries reveals that the former can stimulate the economy much more than the latter. In fact, both the direct and indirect economic effects of the bio-based industry are significantly higher compared to those of synthetic fertilizers. On the contrary, the employment indicator reveals that the two fossil-based industries are more labor-intensive and socially sustainable than the waste management industry. This indicates that in a theoretical scenario where the bio-based industry replaces the synthetic fertilizers industry completely, there would be a loss of jobs. However, the products provided by sludge treatment can only partially replace the demand for fertilizers. As will be illustrated later, even considering the employment social costs due to the replacement of synthetic fertilizers, the bio-based supply chain will lead to more job opportunities in the local context.

Table 4: Direct and total impact

Indicators	Bio-based industry		N-fertiliser		P- and other fertiliser	
	Direct (q)	Total (m)	Direct	Total	Direct	Total
Value Added (EUR per EUR)	0.31	0.85	0.13	0.77	0.22	0.65
Employment (FTE per MEUR)	2.76	8.47	9.85	20.73	20.10	25.79

Source: own elaboration

To understand first the details behind the socio-economic impacts, we decomposed the total multiplier **(m)** according to six production layers. The impacts were decomposed by simulating a demand shock **y*** per 100,000 tons of sludge processed by the supply chain. To satisfy such demand, around 28 FTEs will be employed by the bio-based industry, and 3.1 million in economic value will be generated. However, as can be seen from the production layer decomposition (Figure 4), job opportunities and economic value lie mainly in the upstream supply chain of the waste management industry. Layer 1 represents the direct social and economic development generated by the WWTPs and the biorefinery for processing wastewater and producing biofertilizers and biosolids from sludge; layer 2, the impacts for waste management's suppliers. After layer 2, additional social and economic stimulus is allocated to hidden sectors that provide inputs for the suppliers of the investigated industry. The new suppliers will increase demand for other products, triggering a ripple effect that generates economic growth in the country. In this case, six layers are sufficient to account for over 97% of the impacts without underestimating the economic and social development initiated by the new industry.

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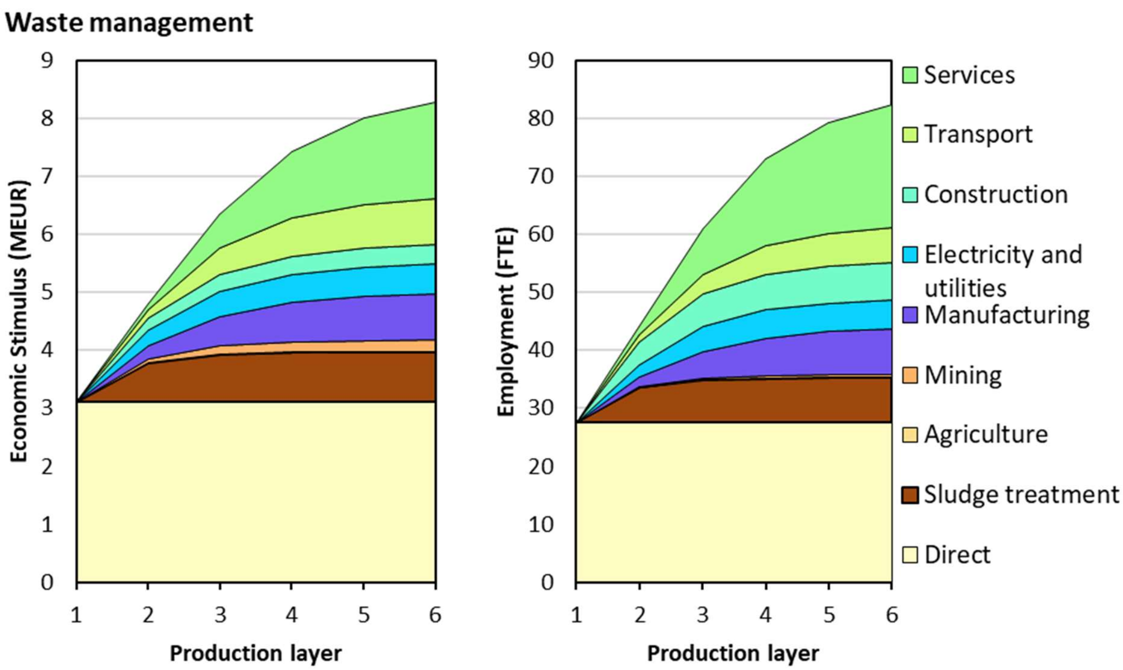
Figure 4: Economic and social footprints for 100,000 tons of sludge processed as a resource for nutrient valorization.



Source: Own elaboration

Several industries will provide goods and services for meeting the costs associated with the management of waste. Along the bio-based supply chain, business activities are the most positively impacted, in particular those sectors related to wholesale and retail trade services or technical testing and analysis services. Manufacturing sectors will also be highly involved in meeting capital costs, sourcing inputs for processed metal products, machinery, and equipment. On the contrary, agriculture and mining will experience less social and economic development being the least involved sectors as suppliers. This production layer decomposition, however, does not illustrate the down streaming effects stemming from replacing synthetic fertilizer use with a zero-cost source of nutrients.

As mentioned before, the use of sludge for the production of biofertilizers and biosolids is expected to impact agriculture sectors and existing fossil-based industries, such as the N, P, and other fertilizers. Using product-level data on nutrient contents, we calculated NPK fertilizer substitution rates (Table 5) as the ratio of nutrient concentrations in commercial fertilizers to the concentration in products from sludge treatment (Murray et al., 2008).

Table 5: Tons of fertilizers replaced for every dry ton of bio-based products.

Substitution rate	Bio-fertilizers	Bio-solids
N substitution rate	0.018	0.016
P substitution rate	0.060	0.028
K substitution rate	0.005	0.004

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For example, 0.06 tons of P fertilizer can be replaced with one dry ton of bio-fertilizer. According to this and the unit prices for conventional fertilizers, 100,000 tons of sludge treated by the plant can reduce the final demand for urea, superphosphate, and KCl fertilizers by 192,969.96, 333,822.18, and 35,895.78 euros, respectively. We used these values as demand shock (y*) for the production layer decomposition analysis (Figure 5 and Figure 6).

Figure 5: Loss of economic and employment stimulus resulting from replacing urea with the nutrient content valorization of 100,000 tons of sludge.

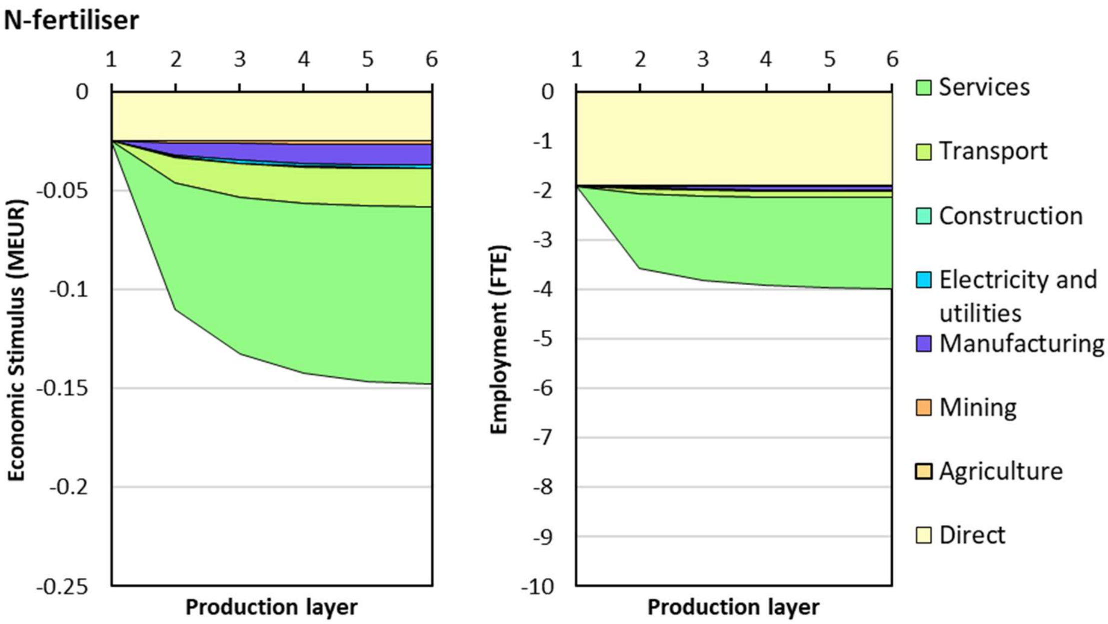
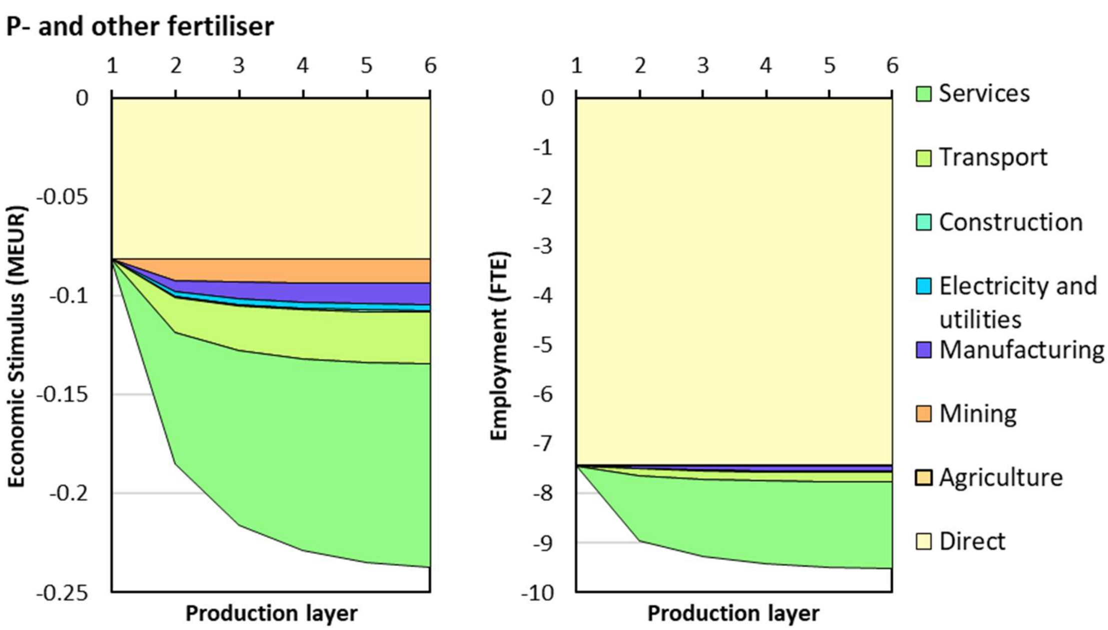


Figure 6: Loss of economic and employment stimulus resulting from replacing superphosphate and KCl with the nutrient content valorization of 100,000 tons of sludge.



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A comparison of the impacts resulting from the substitution of conventional fertilizers with bio-based fertilizers and biosolids reveals that the economic and social losses are much smaller than the benefits gained with the introduction of the new bio-based industry. The most negatively affected would be the P- and other fertilizers industry, with a loss of about ten jobs and 0.25 million euros.

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5 Conclusions

The present study was designed to assess the cascading socio-economic implications of nutrient valorization from organic residues for agricultural use. This research has shown that biofertilizers and biosolids can generate more value in the national economy than conventional synthetic fertilizers industries. For the production of a million euros, the bio-based industry stimulates a total of 0.85 million euros of economic growth compared to an average of 0.71 million euros from synthetic fertilizers. On the contrary, the latter are more labor intensive and socially beneficial than the waste management industry. However, considering only a partial demand substitution for fossil-based fertilizers, the bio-based industry led to new job opportunities in the local context.

Another important aspect is the importance of supply-chain analysis in assessing the impacts of the bio-based industry. The production layer decomposition analysis showed that more than 64% of the positive socio-economic impact of the waste management industry derives from upstream sectors. Wholesale, retail, and provision of chemical testing, are the most positively impacted sectors.

This study has also raised important evidence on the key role that context plays in the overall sustainability assessment of bio-based industries. The socio-economic sustainability of the waste management supply chain is supported by its local context. Biofertilizers and biosolids production from sludge benefits from the low livestock density and high demand for organic fertilizer,and from the high density in crops cultivation such as rice that shows substantial yield increases without hazardous accumulation of Ni and Cd in rice grains. In contrast, the bio-based supply chain is negatively affected by the seasonality of agricultural activities and by a multifaceted and outdated regulation that no longer matches current needs and expectations.

5.1 Caveats about the study and feedback

These findings are subject to certain limitations. Input-output analysis requires several assumptions: (i) fixed production structure of industries; (ii) constant returns to scale; (iii) and fixed commodity prices (Miller & Blair, 2009). These simplifying assumptions implicit in the classical input-output framework limit the ability to deal with important features of a modern economic system, such as prices or elasticities. On the other hand, the analytical simplicity renders the implementation of IO models for impact analysis easier in terms of data requirements.

Another limitation of this methodology concerns the level of sectoral and spatial detail in input–output databases. Several databases are available for IO analysis. The number of regions and industry sectors covered by each database are distinctive features of each source (Tarne et al., 2018): EXIOBASE features 163 sectors and 49 regions; the Eora global supply chain database, 26 sectors and 190 countries; the JRC Social Accounting Matrices BioSAMs includes 80 sectors for the 27 European Union member states and the United Kingdom; the Global Trade Analysis Project (GTAP), 65 sectors and 140 regions; the World Input-Output Database (WIOD), 56 sectors and 41 regions. In general, high sectoral aggregation yields significant errors and uncertain results, so-called aggregation bias (Malik et al., 2018), while databases with more detailed sectoral resolution

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generate more accurate results (Steen-Olsen et al., 2014). In accordance with the main findings of BioMonitor WP2 (see Figure B23, Appendix B – Radar Charts of Deliverable 2.1), we assessed EXIOBASE as a trustworthy data source for monitoring bioeconomy-related phenomena for the European Union member states given its disaggregated sectoral data completeness, geographical coverage, and time span. In addition, as demonstrated in this case study, the database meets the data needs for socio-economic indicators, not just for climate footprint assessments.

Finally, another source of weakness in monetary input-output tables (MIOTs) is that they do not account for all material requirements meeting the final demand. MIOTs do not express physical information within the inter-industry table unless such material flow has a traceable economic value. This implies that most of the flows between the economy and the environment or the recycling of waste as primary input are not expressed. As it was shown in this study, to analyze certain aspects and indicators, IO tables are coupled with non-economic, physical satellite accounts, such as GHG emissions or employment by sector. Another approach to addressing these issues is the use of Physical Input-Output Tables (PIOTs) that express all economic transactions in physical terms. Applying input-output analysis using data from PIOTs instead of MIOTs implies: (i) avoiding distortions of results due to the monetary structure of the economy; (ii) deriving directly conversion factors and multipliers; (iii) reducing uncertainty due to variation driven by changing prices and exchange rates (Giljum & Hubacek, 2004). Despite these advantages, the very limited and restrictive data situation and the lack of complete PIOTs hinder the application of physical input-output analysis. This aspect highlights the importance also for impacts analysis of monitoring and measuring all the material flows within the economy, and between the economy and the environment, as the WP8 Material Flow Monitor case study aims to do.

5.2 Recommendations and best practices

This study contributes to the growing body of research suggesting hybrid input-output models as a tool to monitor progress toward a more sustainable future. By considering impacts from the entire upstream supply chain, hybrid input-output analysis eliminates truncation errors caused by the selection of a sub-set of the sectors involved. This aspect makes this method particularly relevant for bioeconomy-related phenomena whose boundaries may not be immediately clear. Furthermore, as summarized in Table 6, most of the indicators defined within the BioMonitor project (Kardung et al., 2021) fit the Hybrid IO framework.

Table 6: Proposed list of indicators by societal objective

Main Indicator	Sub-indicators	Sustainability Dimension	Hybrid IO Analysis
1. Food and nutrition security			
Availability of food	Domestic food production; Food imports	Society	✓
Access to food	Income per worker n bio-based industries	Society	✓
Utilization	Meat- or plan-based protein ratio	Society	✓
Stability	Import dependency; value of food imports over total merchandise exports	Society	✓
2. Sustainable natural resource management			
Sustainability threshold levels for Bioeconomy Technologies		Environment	X
Biodiversity		Environment	X
Land cover	Forest area; agricultural area; surface water	Environment	✓

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Primary Biomass production	Forest; agriculture; fisheries	Economy	✓
Sustainable resource use	Sustainable agriculture	Environment	✓
3. Dependence on non-renewable resources			
Bio-energy replacing non-renewable energy	Biofuels, biogas	Environment	✓
Bio-material replacing non-renewable resources	Wood-based constructions; bio-based textiles; bio-based furniture; bio-based plastics; bio-based fertilizer	Environment	✓
Biomass self-sufficiency rate	Agricultural biomass; forestry biomass; aquatic biomass; biomass from waste	Economy	✓
Material use efficiency	Material and waste recycling and recovery rates; Recycling rate of bio-based products	Economy	✓
Certified bio-based products	(no sub-indicators)	Environment	✓
4. Mitigating and adapting to climate change			
Greenhouse gas emissions	Forest carbon emissions and removals; Agricultural GHG emissions and removals; Energy and industrial carbon emissions and removals	Environment	✓
Climate footprint	(no sub-indicators)	Environment	✓
Climate change adaptation		Environment	X
5. Employment and economic competitiveness			
Innovation	Innovation hurdle for different industries	Economy	✓✓
Investments	Private sector bioeconomy investments: R&D and others; Public sector bioeconomy investments/supports/subsidies. R&D and others; Establishment and Expansion of biorefineries	Economy	✓✓
Value Added of the bioeconomy sectors	Value-added of bioeconomy sectors; Turnover of bioeconomy sectors	Economy	✓✓
Comparative advantage	Revealed comparative advantage of biomass	Economy	✓
Production and consumption of non-food and feed bio-based products	(no sub-indicators)	Economy	✓✓
Import and export of bioeconomy raw materials and products	(no sub-indicators)	Economy	✓✓
Employment	People employed in the bioeconomy sectors; Quality of employment	Society	✓
Bioeconomy-driving Policies		Economy	X

Source: Adapted from Kardung et al., 2021

Note: “X” specifies indicators that were not considered applicable from a hybrid IO analysis perspective; “✓” specifies indicators that can be derived coupling MIOT with physical satellite accounts or using a PIOT; “✓✓” specifies indicators that are considered directly derivable with a MIOT.

Overall, using IO models allows a comprehensive approach for a systematic impacts quantification. The IO framework can handle multiple indicators for each social objective of the 2018 Bioeconomy Strategy and for all three dimensions of sustainability (i.e., environmental, social, and economic). This evaluation provides meaningful and comprehensive information that helps avoiding segmented policy making and accelerate society's transition towards the bioeconomy. However, not all indicators are readily measurable from basic monetary IO tables. The MIOT directly reports values on investment, value added, consumption, production, imports, and exports. Most indicators, instead, can only be handled using MIOTs coupled with non-economic, physical data (such as EXIOBASE reporting the number of employees or GHG emissions by sector) or Physical Input-Output tables (such as the PIOT modeled by CBS reporting (bio)mass flows for The Netherlands). Finally, some indicators do not fit IO models. The *Sustainability threshold levels for Bioeconomy Technologies* indicator*,* based on genuine investment theory, is better suited to other analyses, such as cost-benefit analysis. Indicators that measure *biodiversity* or *climate change adaptation* require detailed data, such as the number of animal species or crop varieties, which are incompatible with

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the current aggregation level of IO tables. The *Policy* indicator to assess policies, strategies, and legislation on the bioeconomy is mostly qualitative in nature.

A final recommendation concerns the main indicator of employment and its sub-indicators considered in the BioMonitor monitoring framework. It is important to note that for employment, available data are reported by gender and by low-, medium-, and high-skill level groups. These information can be used as other useful sub-indicators to address a more thorough social assessment of the bioeconomy within the BioMonitor monitoring framework. Gender classification can reveal some key features of women participation in bioeconomy activities and shed new light on gender equity in employment opportunities. The classifications based on different skilled labor can be appropriate to assess the role of bioeconomy as accelerator of technology and skill upgrading. For example, a lower ratio of low-skilled labor group compared to medium-skilled and high-skilled labor can be associated with high-tech, automated bio-based production in the country. Compared to environmental footprints, these indicators are imperfect measures because there is not a clear causal relationship between social issues and the bioeconomy activities. However, if these sub-indicators prove useful in assessing social progress triggered by the bioeconomy, there will be an incentive to improve or adapt the necessary data.

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Appedix A

Semi-structured Interview Guide for Context Analysis

Date:	Time:	Interviewee ID:

The bioeconomy is driven by several forces. They can be grouped under themes, respectively supply drivers (climate and environmental change, market organization and technology and innovation), demand drivers (consumer preferences, economic development and demographics), resource availability and governments' measure (policies, strategies and legislation). In this semi-structured interview, our aim is to understand which are the most impacting drivers for the adoption and development of the supply chain under study.

Since semi-structured interviews contain open questions and discussions may differ from the interview guide, it is best to record the interviews and transcribe them later for analysis. Therefore, we will first make sure that the respondent agrees with the recording.

0. *Do you have any objection to recording our interview?*

At the end of the interview, information is asked about the age, background, title and role of the interviewee. In this way, the interview does not appear as if it concerns the interviewee personally.

Resource availability

1. *Consider the supply chain, where are the key strategic stages in terms or product availability and processing? And what are the key stages in terms of knowledge availability? (Pay attention to the mention of the type of biomass used)*
2. *Could you describe briefly the geographical location of the supply chain?*
3. *Could you walk me through the main reason why it has been settled in that context? If you are aware of this, what other aspects of that area were considered before the development of the supply chain?*
4. *In terms of type of resources are there specific points worth to mention distinguishing natural and social capital (natural and human resources) and their interrelations?*

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5. *After the development of the supply chain and gaining experience on it, what do you think are the main strengths and weakness of the areas where your supply chain operates and that you could not anticipate?*

Climate and environmental change

Increase in Importance of Climate Change and Pressure on Ecosystems

6. *In which way you believe that climate change can affect the development of the supply chain and the resources availability of the area? What is the biggest change you expected in the next decade? Can this change be linked to the measured or measurable indicators in the supply chain?*
7. *Now, I'd like to know the different types of activities adopted to prevent or minimise the damage climate change can cause, or on the contrary actions planned to take advantage of the opportunities that may arise at the local or more global level.*

Market organization

Advances in Horizontal and Vertical Integration

(Which is the level of vertical and horizontal integration?)

8. *For each of the stages of the supply chain, could you describe the type of existing market relationships between actors? Are they spot ad short-term relationships, or do they require closer relationships or even vertically integrated structures, upstream or downstream?*
9. *For the same identified stages, would you describe the markets as perfectly competitive, oligopolistic or monopolistic? Do you feel any market power is present? That is, is there a supply stage were one or more companies are dominating and "making" the rules of the game?*
10. *Are there points along the supply chain where unpredictable changes are possible? (e.g. price volatility, shortage or abundance of products)*
11. *At the different stages what are the sources of competitive advantage? (e.g. innovation, knowledge, cost leadership, reputation…)*

Globalisation

12. *Are there global integrations that you consider important to mention about the supply chain described? (NOTE: in terms of product flow and know-how) If any, how are these integrations impacting the supply chain? E.g. they provide low cost inputs, key innovative products or services?*
13. *Could you describe an international integration that failed and the reasons why it failed?*

Technology and innovation

14. *In the described supply chain, are there steps where key proprietary technologies are used? Are patents a commonly used tool in the described supply chain?*

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15. *How is the innovation process carried out along the different stages of the supply chain? Is it a closed process within single enterprises or are there specific partnerships in place or any form of open innovation?*
16. *Are forms of technology transfer from external stakeholders (i.e. universities, consultancy, etc.) experienced along the chain?*

Policies, strategies and legislation

17. *Considering the described supply chain, which EU, National and Regional policies (and legislations) come to your mind as having potentially impacted to the structure of the chain, its competitiveness, innovation, or product availability and flow?*
18. *How much do you think the observed supply chain and its dynamics are shaped by public policies and how much by pure market forms?*
19. *How local do you think the dimension of most bio-economic activity is? In this respect, how relevant are regional policies compared to national and EU ones? Do you think EU initiatives (such as the Regional Innovation Strategies for Smart Specialization, the RIS3) get effectively and efficiently translated at the regional level? If not, what do you think are the hurdles?*

Consumer Preferences, economic development and demographics

20. *What is the relative importance of demand-side factors in stirring the growth and, in general, the dynamics of the supply chain we are considering? How do you think the demand-side drives of the bioeconomy will influence the supply chain? How important are demand versus supply drivers?*
21. *What do you think about the sophistication of consumer preferences in relation to the dynamics and development of the supply chain?*
22. *Do you think consumers are fully aware of what the value added is of the bioeconomic (final) products manufactured? If not, how do you think signaling might be implemented so that information gets properly conveyed?*

At the end of the interview remember to ask information about the age, background, title and role of the interviewee.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 773297.