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Bioresource utilization index – A way to quantify and compare resource efficiency in production

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ABSTRACT

The efficiency of renewable bioresources is becoming increasingly important. Along with the European Union's Green Deal and plans to decouple economic growth and prosperity from resource consumption, a new way of thinking must be adopted. Resource efficiency is no longer limited to electricity, heat or non-renewable resources. Previous studies have described the classification of the value of bioresources, which is usually formed as a pyramid depicting the values of the obtained products and the demand for their volume. The approach of the circular economy in the bioeconomy with its principles - reuse, recycle and regenerate - is also widely described in the scientific literature. Combining these two approaches, we created a bioresource utilization index, which would show the efficiency of bioresource use in an enterprise, along with the enterprise's contribution to the bioeconomy. In open interviews with representatives from multiple companies, we identified bioresource flows and mapped the factors that influence these flows in an enterprise. The proposed bioresource utilization index gives an insight into resource efficiency in a specific enterprise by quantifying the incoming raw material, the outgoing product, by-products, and waste. The elucidated factor nexus could be used as a map for easier detection of place for improvement.

1. Introduction

Although environmentally friendly consumer choice is an important driver toward sustainability, production companies have the biggest impact on resource efficiency. With the global efforts of disjointing economic growth and resource consumption it has come clear that resource efficiency is the most reasonable approach (Wood et al., 2018). Today bioeconomy is viewed not only as bioresource based economy, but bioeconomy also implies sustainable bioresource consumption by adding value to society.. Although, European Union directive 2008/98/EC (European Parliament and Council, 2008) defines that by-products of production are not classified as waste, in reality often by-products of production are treated as waste in enterprises and sent to waste streams or to low value streams like biogas or solid fuel production. Often small and medium-sized enterprises lack the skills, knowledge and capacity for scrutinous bioresource flow tracking, leading to inefficient by-product utilization and an increased enterprise's impact on the environment(Khalili et al., 2015). In this study we have evaluated various factors impacting by-product utilization or redirection to waste or low value product streams. All factors are interlinked in "bioresource nexus" and specific indicators can be used to describe these linkages (Fang and Chen, 2017). We propose a simple calculations' method to determine the by-product utilization efficiency describing the "Waste – bioresource" linkage. In conventional economics demand creates supply, in bioeconomy the demand for bioresource is often limited to technological capabilities and knowledge base of stakeholders. One resource can be used to produce products with various added value levels (Stegmann et al., 2020) and cascading is viewed as the most sustainable way of bioresource utilization. Cascading refers to bioresource utilization for higher added value product production where the created leftovers are redirected to production of another, usually lower value, product (Höglmeier et al., 2015). Cascading can be done in a production company by creating product driven biorefinery, but also it can be implemented by cooperation between enterprises and creation of industrial synergies(Ubando et al., 2020).

While technological approaches in food manufacturing have offered new markets and opportunities, they must also respond to the changing environmental concerns (Wu et al., 2010). Conservation of resources, recycling and reuse of materials, utilization of by-products and bioconversion of waste materials in addition to reduction of

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environmental loadings are contributing to sustainability (Afonso R.G. de Azevedo et al., 2019; Afonso Rangel Garcez de Azevedo et al., 2020; Kroyer, 1995). Waste is quite a broad term including wastewaters, agricultural residues as well as residues from slaughterhouses (Evans, 2013). Each of these types of waste burdens environment in different ways. Wastewaters might bring toxic pollutants within them causing stress to aquatic ecosystems and reducing biodiversity (Kuzmanović et al., 2016). In addition, elevated biological oxygen demand (BOD) can cause dead zones (Muñoz et al., 2006). Organic matter, like manure and agricultural residues, but mainly food waste are causing methane production due to anaerobic digestion taking place in landfills (Clemens and Cuhls, 2003). 18–68% of municipal solid waste can be organic (Ismail and Yusuff, 2013), moreover households with higher income level are producing more organic waste linking waste production with socio-economic factors (Bandara et al., 2007). Despite this link it is almost impossible to assess the waste to bioresource flow on national scale due to limitations of available data. Waste burden on the environment has led to development of various technologies to relieve the stress, the most noticeable being wastewater treatment, reducing BOD in natural waterbodies (Saad A, 2009) and landfill gas collection facilities (Trubaev et al., 2018). In many cases, reducing the burden on the environment has led to profit generation. For example, in Latvia, SIA "Getliņi Eko" – the biggest municipal solid waste management company has developed a profitable side business by collecting landfill gas. The use of heat energy and electricity generated from landfill gas combustion allowed them to successfully grow tomatoes ("Getliņi skaitļos | Getlini. Lv," n.d.), in this case an energy intensive culture (Dorais, M., Schwarz, 2018) is produced entirely using organic waste. Nexus impacting this decision is further investigated in this study using other enterprises.

The abovementioned example is an apt representation of bioeconomy, showing that waste can serve as raw material for acquiring other products (Evans, 2013). According to the European Commission "bioeconomy […] encompasses the production of renewable biological resources and the conversion of these resources and waste streams into value added products, such as food, feed, bio-based products and bioenergy" (EUROPEAN COMMISSION, 2012). OECD in their definition concentrates on the benefits bioeconomy is providing to the society: "bioeconomy to be the aggregate set of economic operations in a society that use the latent value incumbent in biological products and processes to capture new growth and welfare benefits for citizens and nations" (OECD, 2006). Though expressed differently, one can argue that waste is the very embodiment of "latent value" as often waste is sent to polygon despite the possibilities for acquiring higher added value products, like reducing sugars(Jiang et al., 2014; Rosales et al., 2002; Van Wyk, 2011) that can further be used for ethanol or even enzyme production (Rosales et al., 2002). Perhaps the most obvious use of waste is biogas production (Zhang et al., 2014), this can be done straight in polygon of municipal waste (Trubaev et al., 2018) or in biogas plants (Rasi et al., 2007). So, despite absence of the term "waste" in the OECD definition, it is still considered a crucial bioresource and its value depends on the selected management approach.

The OECD project to design a bioeconomy policy agenda for governments is strongly concentrated on biotechnologies like gene engineering not once mentioning waste (OECD, 2006). The EU approach is more grounded and oriented on managing resources to their full potential – using every bit of raw material The OECD approach is oriented on using bioresource to their highest potential – creating products with the highest possible added value. When it comes to the actual situation, there are plenty of companies producing waste, but fewer companies are applying biotechnologies-gene editing or modified organisms. There are almost half a million manufacturing enterprises in the EU using bio-based raw materials, and accordingly producing waste (eurostat, 2015). The actual amount of produced waste is unknown.

In this study using bottom-up approach we have investigated the enterprise level of biomass utilization – enterprises using biomass to produce specific products. By using cleaner production principles an enterprise can not only reduce its negative environmental impact, but improve overall bioeconomy (Khalili et al., 2015). Hence, from research point of view it is important to elucidate factors affecting the resource flow and the indicators that would show comparable reflections of bioresource utilization in any enterprise dealing with organic resource flows. We have analyzed the nexus involving biomass, waste and bioproducts, as well as additional factors in this nexus. In addition, we are proposing an indicator for evaluation of by-product utilization in an enterprise.

Waste and bioresource can be one decision away from each other. So far industrial energy efficiency is studied as the main position to cut down CO_2 emissions and reduce the industry's caused effect on climate change (Klemeš et al., 2012), "Our World in Data" reports that the electricity and heat production sector is the biggest CO_2 emitter (Ritchie and Roser, 2019). As our understanding of the natural carbon cycle and storage becomes broader, there are more policies aimed at preventing destruction of carbon rich biotopes (Janowiak et al., 2017; Sullivan et al., 2017) as well as stimulating circular economy. In 2015 the European Union adopted a whole Circular economy package including specific deliverables (European Commission, 2015). Nevertheless, there are ongoing discussions on how to evaluate and measure various factors impacting industrial energy efficiency (Cagno et al., 2013; Sorrell et al., 2011), but factors for bioeconomy have not been discussed enough. Industrial clusters have been drivers for development of various competences, there are clusters related to bioeconomy with respective key performance indicators (Axelsson et al., 2012), 78% of these indicators are economical in nature.

In line with bioeconomy, technology as a term covers a vast field – from mechanical technologies to biotechnologies like gene engineering. As bioeconomy is based on bioresources – increasing bioresource productivity means larger capital circulation in this field. In earlier stages of industrial development, increase of bioresource amount in economy was achieved by simply expanding land used for bioresource cultivation. With growing threats of climate change and decreasing area of wildlife habitats (Powers and Jetz, 2019), it has become clear that expansion is not an option anymore and other ways for acquiring greater amount of biomass needs to be found. Today it can be done by using biotechnology tools and techniques. Hence, there has been a great boost to bioeconomy from the field of life sciences. Possibilities for boosting lipid production in plants (Vanhercke et al., 2014) and microorganisms (Tai and Stephanopoulos, 2013) have been studied widely for further applications to biodiesel production, in addition, manipulations to achieve better lignin biomass for 2nd generation biodiesel production have been studied (Vanholme et al., 2012). EU is recognising the importance of technologies in life science. According to Deloitte research, EU has the biggest cited publication amount in the field of biotechnology in comparison to the United States and the major Asian countries (Deloitte, 2014). In addition, considerable amount of financial resources are dedicated to EU Food, Agriculture, Fisheries and Biotechnology programme Activity 2.3: "Life sciences, biotechnology and biochemistry for sustainable non-food products and processes" (Levidow et al., 2012).

When it comes to manufacturing companies, technologies usually are a crucial part of production. Applying effective technologies in the production process can reduce the amount of generated waste or simply increase the production yield. As food production companies are dealing with a considerable amount of organic matter, this could be a field with potential for bioeconomy development.

Nevertheless, there are multiple factors impacting bioeconomy adoption. In this study we elucidate factors affecting this segment of circular bioeconomy development and propose an indicator to characterize the utilization of bioresource's potential. As a case study we analyze two producers using the same type of biological raw material but creating different products. Varying waste types allowed us to calculate various scenarios for by-product utilization. Although the EU have clearly defined the difference dividing waste from by-product, after interviewing managers in three enterprises, we concluded that terms by-product and waste are used interchangeably. Fig. 1 represents a scheme adopted from Eurostat Manual on waste statistics (eurostat, 2013), with our modification to show the dissolved border between by-products and waste.

To evaluate reasons behind decision making leading to various choices, multiple interviews were conducted with production managers as well as representatives from companies dealing with produced waste. In real-life situations by-products and primary waste are not so clearly divided, as companies often discard by-products as waste, in some cases by-products are used, but not to their full potential.

In bioeconomy resource value can be estimated from the bio-based value pyramid representing five ways for biomass use: (1) Pharmaceuticals and Fine chemicals (PFCs); (2) Food and Feed; (3) Bioplastics and Polymers; (4) Bulk chemicals, and (5) Energy, Heat and Fuels in descending order of value (Stegmann et al., 2020). Although biogas fits in the fifth category as a source of energy, we argue that the fourth category would be better fit for biogas. As in the burning process organic compounds are oxidised to carbon dioxide (a well-known greenhouse gas) leaving only ash, after biogas production the leftover digestate can be used to improve the nutrient content in soil (Pubule et al., 2015). This classification is used by Stegmann et al., representing energy recovery and composting as part of circular economy, partially feeding back resources into sustainable biomass sourcing (Stegmann et al., 2020). In EU, biogas for the heat production [ktoe] has increased six times in the last 15 years and solid biomas use has increased only by 20%. Trends show that raw biomass proportion for heat and energy production has been reduced (Banja et al., 2019). In this study we differentiate solid biomass fuels from biofuels like bioethanol and biobuthanol that both are considered as bulk chemicals.

The top of the bio-based value pyramid is occupied by PFCs as usually these products have higher economic value due to their importance and small concentrations in the raw biomass. Depending on the extraction method of PFCs' their by-products could be further used (Kumar et al., 2017). . One example of bioresource use in PFCs is potatoes – a product that is typically used for food and feed, but can also be processed into PFCs such as ascorbic acid and phenolic compounds (Priedniece et al., 2017; Singh and Saldaña, 2011). More importantly, some PFCs can be extracted from by-products, for example ascorbic acid and some phenolic compounds can be extracted from potato peels increasing the added value of the by-product from food industry.

The goal of this study was to elucidate factors affecting the production by-product flow from waste to bioresource as well as to develop an index for bioresource utilization efficiency in an enterprise. In line with this study we conducted a deeper investigation of by-product flows in two enterprises using the same raw material. Investigating specific by-products and identifying alternative applications for those products gave us the opportunity to evaluate various scenarios of bioresource by-product utilization. In addition, the conducted interviews allowed us to elucidate factors and their interlinkages impacting the development of bioeconomy.

2. Methods

2.1. Interviews

To evaluate the link between waste and bioresource, as well as various factors impacting the proposed indicator of this link, qualitative interviews with managers from involved enterprises were conducted. The interview format was semi-structured, as this type of interview lets the interviewer to ask open questions and gives the possibility to go deeper into various aspects of the revealed facts (Jamshed, 2014). Semi-structured interviews have been already used in bioeconomy research (D'Amato et al., 2020; Gårdan et al., 2018). During the interviews, the overall attitude and motivation regarding bioresource, by-product and waste utilization was determined. Efficiency of by-product utilization was determined by collecting data from enterprises, including real consumption of raw materials as well as the produced bio-waste and by-products. Technical directors of three enterprises using the same bioresource as raw material were interviewed. Due to sensitive information interviewees were providing, interviews were not recorded, instead the interviewer produced comprehensive notes on the acquired information.

2.2. Nexus building

Bioresource nexus was created by analyzing the information acquired in the interviews and validated with literature analysis and by-product data from the enterprises in question. Qualitative and quantitative data were collected from interviews (see section 2.1.). The overall methodology for building of bioresource nexus is shown in Fig. 2.

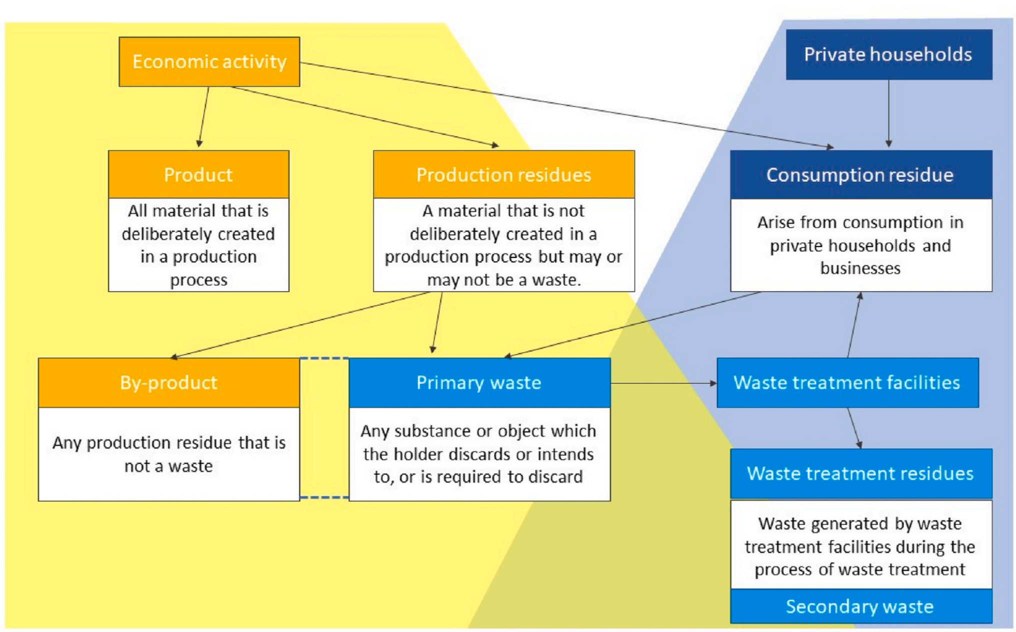

Fig. 1. Waste generation scheme (eurostat, 2013). Original source depicts waste generation streams represented by arrows. Scheme modifications include by-product-to-primary waste flow represented by dashed line, showing the fuzzy division of both. Flow is impacted by factors discussed further in this work. As in the original source, the economic activity excludes waste treatment facilities emphasizing the importance of keeping bioresource in the production sector represented by "Economic activity".

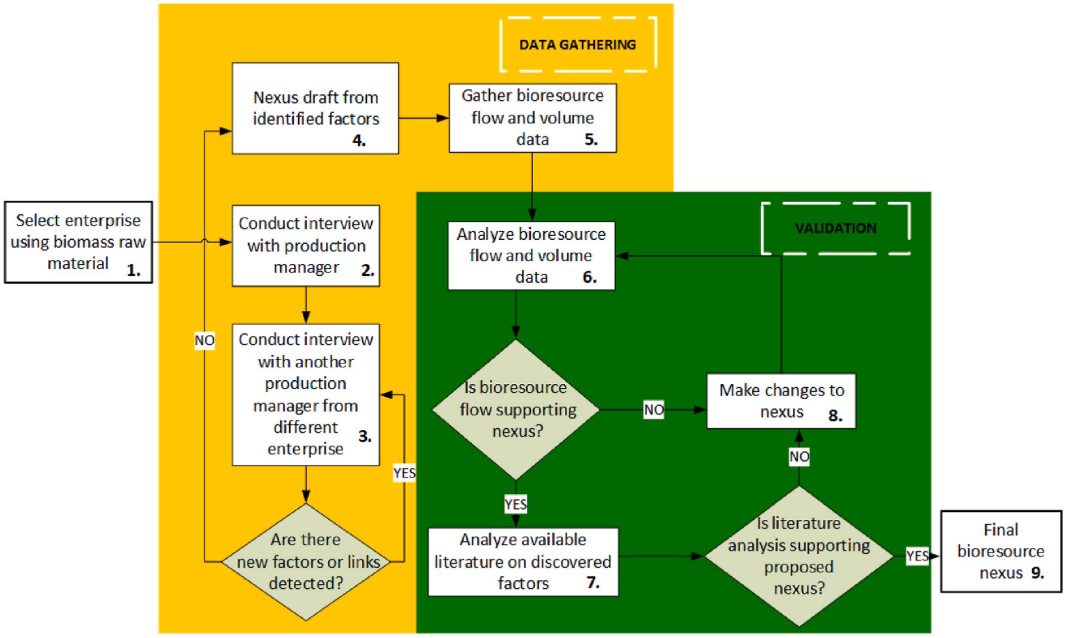

Fig. 2. Bottom-up approach for bioresource nexus building.

Following the algorithm, two interviews were conducted, then as the second interview elucidated new factors, a third interview was conducted. The created algorithm demands to continue interviews until there are no new factors. In this specific case study, three interviews were sufficient. Steps two and three represent the minimum interviews necessary to gain an overall idea of the factors impacting the specific subject. As during second interview some new factors were identified, third interview was conducted to see if more factors would be identified. If there are no new factors the algorithm continues. The research was divided in smaller modules for a structured approach. While picking enterprises for this research, various production companies using the same type of biomass as a raw material were considered. An important factor in choosing the enterprises was their willingness to participate. The overall methodology algorithm is depicted in Fig. 2. The study consisted of two parts: (1) data gathering and nexus building, as well as (2) nexus validation. Bioresource flow analysis was conducted, by analyzing bioresource and waste data acquired from the enterprises. After additional literature analysis nexus was completed.

The methodology depicted in Fig. 2 can be applied for evaluation and building of various nexus using a bottom-up approach. In this study the bottom-up approach allows to analyze factors for organic by-product flow back into bioeconomy through bioresource. Nexus provides information on factors impacting the system, but additional by-product data analysis provided information on effectiveness of this by-product – bioresource flow.

2.3. Alternative scenario analysis

Bioresource flow in an enterprise was evaluated by comparison with waste management hierarchy (Demirbas, 2011) and bio-based value pyramid (Stegmann et al., 2020) shown in Fig. 3 with the chosen coefficients from 0 representing no value and 1 representing the highest possible added-value to bio-based material. The bio-based value is assigned to the raw material or the by-product when it is used for the corresponding application in the bio-based pyramid.

For evaluation of bioresource utilization in the enterprise, alternative scenarios for two of the enterprises in study were designed. Only two out of three enterprises gave the consent for further data analysis,

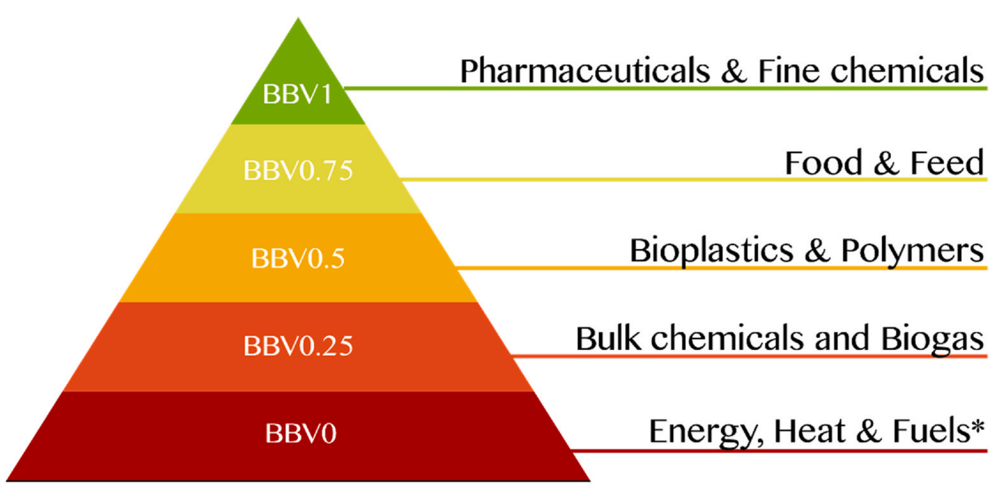

Fig. 3. Bio-based value pyramid. Five bioresource utilization options by categories and assigned coefficients corresponding to each group of bioresources (Stegmann et al., 2020) BBV – bio-based value and the corresponding coefficient, 1 representing the greatest value and 0 representing no value from the point of bioeconomy.

nevertheless due to the small number of enterprises in Latvia none of the companies gave the consent to reveal their company name. Hence, we could proceed with only two enterprises with specifics like enterprise name and specifics on production concealed. Each level in the bio-based value pyramid (Fig. 3.) was given a corresponding coefficient representing the value for bioresource utilization – coefficient of 1 was attributed to PFCs, coefficient of 0.75 to Food and Feed, 0.5 to Bioplastics and Polymers, 0.25 to Bulk chemicals and Biogas, but Energy, Heat and Fuels were assigned the value of 0. The bioresource utilization index provides insight into production efficiency regardless of the product type, hence no value is assigned to the product. The calculations were conducted with various generated by-product utilization options and attributing corresponding coefficients from the previously described bio-based value pyramid.

$$B_{u_{ind.}} = (P + BP_1 \times c1 + BP_2 \times c2 + BP_3 \times c3 + BP_4 \times c4 + BP_5 \times c5)/RM$$

$B_{uind.}$ – Bioresource utilization index; P – product [kg of dry weight]; BP_n – by-product [kg of dry weight]; c_n – coefficient assigned to bio-based value pyramid; RM – used raw material [kg of dry weight].

The calculations were made using dry weight. If there were no available data on the actual dry weight of the by-product, estimations were made by using values found in literature. To assign a specific bio-based value for each by-product, at first the data for by-product amounts were collected and the dry weight was determined by literature analysis. The main categories analyzed were peels, damaged raw material, raw material that does not meet production standards, products that do not meet the market standards, other production leftovers, dissolved sugars, and undissolved starch. As company managers disagreed to more detailed information disclosure, the raw material, product or production technology could not be described in this work.

3. Results and discussion

In this study, nexus of factors impacting waste to bioresource was built. In addition to the main bioeconomy impacting factors described by Zihare et al., (2020) (Zihare et al., 2020), a few new factors were detected using the bottom-up approach. Factors like Behaviour and Financial resources were elucidated only when bottom-up approach was used.

It is important to notice that a large proportion of biomass defined as waste is in fact by-products according to the EU definition, but in some cases, production managers are referring to by-products as waste. The by-product group might be referred to as waste only due to lack of technology – by-products might spoil due to inappropriate storage or they can be hard to retrieve, like sugars from waste after blanching. Nevertheless, behavior and knowledge strongly impact the by-product-to-waste flow. When enterprise's management does not want to deal with finding new applications or buyers of the by-products, the biomass is simply directed to waste stream. In addition, companies worry about disclaiming their practices publicly, this can slow down the progress and opportunities for innovation as there is no exchange of information amongst enterprises sticking to closed innovation.

According to Demirbas (2011), waste reduction is the most preferred waste management option (Demirbas, 2011), according to elucidated nexus, waste can negatively impact company's financial resources and positively impact available bioresource amount. In case of blanched, peeled, and ready to use vegetable production, more efficient peeling technologies might be implemented to reduce the total amount of peels generated. In many cases by-products properly treated would not become waste, hence proper utilization of them would reduce the relative waste amount in proportion to the product.

After analyzing links and respective products, we came to conclusion that indicators for these links might be economic or technologic in nature. An indicator can characterize the economic value of byproducts, energy efficiency of technology or efficiency of the production itself.

It is a frequent practice to motivate companies for research and development by providing incentives specifically for technologies reducing carbon emissions (Uyarra et al., 2016), alternatively fines are used as a tool to prevent companies from pollution.

In every enterprise there are already existing technologies affecting the overall production process. After interviews we concluded that the existing technologies are impacting the production efficiency, which is in turn affecting the amount of generated waste. As waste increases the risk of pollution (Van Wyk, 2011) and climate change due to methane production in landfills (Davidsson et al., 2007; Trubaev et al., 2018), these climate threats are leading to policy change from local authorities. Enforced policy might provide incentives for developing cleaner production, alternatively taxes might be enforced on the disposed waste (Dvulit et al., 2019). As these policies cause pressure on an enterprise's financial resources, enterprises are forced to invest in R&D to search for solutions that might reduce the amount of waste. This loop represents the decision making process, before implementing new technologies, their cost-benefit analysis is conducted. If a new technology costs more when introduced, causing new pressure on the financial resources, hence R&D phase continues starting the loop again. Two new technologies might be considered – one that reduces waste during production and another that allows to extract bioresources from waste. Both approaches can lead to reduction of waste. In terms of waste management – reduction is the most preferred option (Demirbas, 2011), but using waste to produce PFCs can be considered as a good option as well. As mentioned above – diverging by-product flows to production of another product group from the top of the bio-based value pyramid can lead to value cascading, hence prolong resource circulation in bioeconomy.

In the discussed examples of path B, the loop finishes with a positive feedback on financial resources. In this specific case study, two instances when R&D lead to path A and three leading to path B were detected. One instance from path A led to path B in a previously described manner (see Fig. 4).

The overall enterprise nexus was developed including additional factors. After analyzing information acquired in the interviews, we concluded that knowledge and behavior are crucial factors in this nexus. Although, companies are not always aware of this, knowledge and behavior in a company can lead to implementation of a new, more environmentally friendly, technology (Del Brío and Junquera, 2003). It is clear how financial resources in a company play a large role in environmental innovations (Uyarra et al., 2016), but behavior and company culture is often left out of the picture.

As can be viewed in Fig. 5, local policies, production as well as knowledge and decision makers in a company are impacting the link between waste and bioresources. The gray area in Fig. 5 represents factors that are out of enterprise scope, although climate change and pollution might have an impact on enterprise functionality – there could be a pressure to relocate the production site due to lack of resources (Gasbarro et al., 2016; Linnenluecke et al., 2011). These two factors have a long-term impact, hence policies imposing fiscal measures have a more noticeable and rapid impact. For bioeconomy evaluation a central core consisting of bioresources-production-waste leading back to bioresources was detected. In this case waste represents lost or disposed resources, by-products used efficiently lead back to bioresource and are used in the production of another product.

To evaluate company's added value to circular bioeconomy, a bioresource utilization index was calculated using the approach described in Methods section. For this analysis two enterprises from the three interviewed before were chosen. An overall bioresource utilization state in an enterprise is estimated – a bioresource utilization index closer to 1 shows better by-product (bioresource) utilization. The constructed scenarios with corresponding biomass utilization indexes are represented in Table 1.

Two studied cases and four alternative scenarios for each case. RM – raw material, BBV 1 to 0 represents bio-based value pyramid levels starting from the top. Percentages in the table represent the amounts of

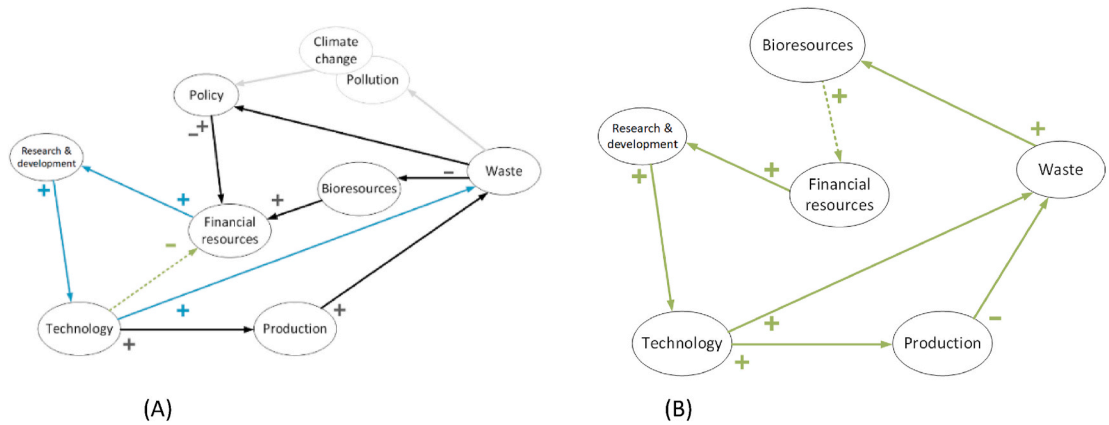

Fig. 4. Flows between various bioeconomy factors detected in the interviews. Path (A) on the left side is continuing and leading to path (B) on the right side of the illustration. Arrows illustrate the direction one factor is impacting the others. Dashed line represents a crucial place in enterprise for the change. Whether Technology impacts Financial resources in a positive or negative way and weather enough bioresources are retrieved from waste in order to be beneficial for Financial resources is shown with (+) – increases next factor (−) – decreases it.

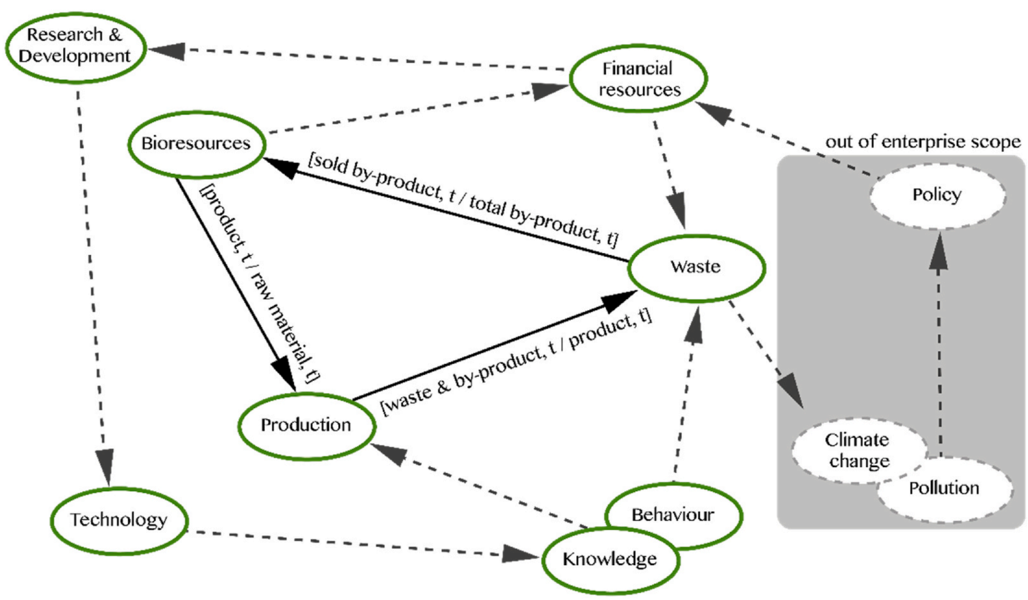

Fig. 5. The proposed nexus of bioresources flow in an enterprise showing all the relevant factors. Green – primary factors, gray dashed – secondary factors; arrows represent direction of what factors impact each other. Central arrows represent the bioresource-production-waste-bioresource factor cluster used for the proposed bioresource utilization index calculations.

Table 1
Alternative scenario representation by biomass allocation. By-product flows by dry weight. RM – raw material; BBV – bio-based value represents the added value to biomass. Added value is represented with corresponding coefficient 1-high value, 0.75- Moderately high value, 0.5-medium value, 0.25-low value and 0-no value. Table represents the allocation of biomass by dry weight in constructed scenarios (I, III to VIII and X) and detected scenarios (II_{case} and IX_{case}) for Enterprise No. 1 and Enterprise No. 2.

Scenario		RM	BBV1	BBV0.75	BBV0.5	BBV0.25	BBV0	Waste	Product
Enterprise No. 1	I	100%	0%	0%	0%	0%	0%	34%	66%
	II_{case}	100%	0%	0%	0%	34%	0%	0%	66%
	III	100%	0%	5%	0%	12%	0%	17%	66%
	IV	100%	0%	0%	0%	12%	7%	16%	66%
	V	100%	9%	6%	7%	12%	0%	0%	66%
Enterprise No. 2	VI	100%	0%	0%	0%	0%	8%	32%	59%
	VII	100%	0%	0%	0%	0%	0%	41%	59%
	VIII	100%	0%	0%	0%	37%	0%	3%	59%
	IX_{case}	100%	0%	5%	0%	32%	0%	3%	59%
	X	100%	9%	32%	0%	0%	0%	0%	59%

dry biomass sent to a specific product, waste, or by-product stream. Scenarios represent by-product use for pharmaceuticals and fine chemicals BBV1, food and feed BBV0.75, bioplastics and polymers BBV0.5, bulk chemicals and biogas BBV0.25, energy and heat BBV0. Waste is dry mass of wasted organic by-products and waste as rotten raw material. BU_{ind} – the calculated bioresource utilization index. Actual situations in respective two enterprises: II $_{base}$ – the base scenario for the first enterprise, IX $_{base}$ - the base scenario for the second enterprise.

Each company is represented by five scenarios, I to V and VI to X for each company, respectively, with base scenarios II for the first and IX for the second. For each enterprise in the worst-case scenario II and VII it is assumed that damaged raw material and all generated by-products, products that do not meet market standards, and other production leftovers are sent to waste and sugars along with starches that are not retrieved from water or used in any other way. By calculating the worst-case scenario, it is possible to evaluate the general efficiency of production process, as the index shows how much product can be acquired from a certain amount of raw material. There might be two explanations if the index is exceptionally low; in this case – first, the raw material contains a small concentration of the product or second, the technology is inefficient and there could potentially be a place for improvement. Base scenario for both production companies included storage of raw material, in this step material could be lost as it might get damaged due to incorrect storage conditions or simply prolonged storage. The enterprise represented in cases VI to X does not store the raw material as long as the first enterprise. The damaged raw material is stored as waste and sent to a biogas production plant along with other raw material that has been sorted out due to being unfit for production needs.

Scenarios I to V included peeling where up to 5% of raw material is excluded from further production. As scenario II (actual situation) shows – at this point peelings are stored as waste and transferred to biogas production plant. In scenarios II to V and VIII to IX still at least 12% of the raw material or by-product is sent to biogas production, this is the amount that is damaged during storage or sorted out for not meeting the safety standards for being used as food. In scenarios III, V, IX and X a significant amount of created by-products is used as food and feed. Usually, the sorting process is meant for sorting out damaged raw materials or products that are not meeting the market standards. However, in many cases the raw material or product is in good condition, it is simply misshapen, or size does not match the production line requirements, hence it could still be used as food or feed. In scenarios III and V peels are used for animal feed, in addition, in scenario V a small portion of the raw material was used as a food product, because the amount of raw material was too small for production line. Although it is quite easy to redirect such by-products as peels and misshapen vegetables to livestock feed, it might be more feasible to sell these by-products to food producers. The well-known Yurosek case proves that even misshapen vegetables can be used to produce higher added value foods - in 1986 Yourosek as an entrepreneur decided to try out producing “baby-carrots” from overgrown and misshapen carrots by cutting and physically shaping them into bite-size shapes (Sidhu, 2010), hence increasing the economic value of this bioresource from animal feed to food. The smaller size of the raw material was in higher demand from restaurants. Scenarios IV and VI both show that a portion of by-products is being used to create solid fuels. as energy recovery is considered downcycling of a material (Passarelli, 2019), this is the least preferable utilization option of a material. This idea is supported by the proposed bioresource utilization index, as scenarios IV and VI generate one of the lowest bioresource utilization index, lower being only scenarios where all generated side streams are redirected to waste. A portion of the analyzed material is leached into water by blanching in the form of simple sugars or as starch during washing and cutting or grinding process. Best case scenarios V and X explore the option for these carbohydrates to be used for fine chemical production by the mixotrophic cultivation of algae(Mitra et al., 2012) (Heredia-Arroyo et al., 2011) or other microorganisms. In addition, scenario V explores the option of leached starch to be used for poly-lactic acid production as in this enterprise a considerable amount of starch was lost as suspended solids in wastewater. As mentioned before, BBW0.25 is assigned to by-products used for biogas production. This is the most popular choice in enterprises dealing with organic by-products. The lowest bioresource index represents scenario where all by-products are wasted, in this case the index is dependent only on product/raw material ratio. As can be seen in Fig. 5., the highest bioresource utilization index calculated was 0.88. The highest score in bioresource utilization index is affected by best available techniques as well as the demand from PFC industry as in most cases status quo in this industry is to purchase raw materials with the highest purity. As more environmentally sustainable and safe options are becoming more popular in the PFC industry, more options for wood biomass utilization are surfacing in the market. Wood used to be on the bottom of the bio-based value pyramid, but today there are plenty of fine chemicals being extracted from it, such as terpenes (Tanzi et al., 2012), lignin (Alinejad et al., 2019) and betulin (Dehelean et al., 2012). It is expected that opportunities for vegetable and fruit peels and other food production by-product utilization will grow, as more research trying to find possible uses for them is taking place (Rafiq et al., 2018; Singh and Saldaña, 2011).

As mentioned before, production companies often choose to direct by-product to biogas production (in this study represented by BBW 0.25 or 4th level from the top), although this study shows that often by-products rich in reducing sugars might be used for PFCs production (Escaramboni et al., 2018; Priedniece et al., 2017), if veterinarian standards are met, by-product can be used as feed for livestock.

The overall comparison between scenarios can be seen in Fig. 6. In food processing industry, sugars and soluble proteins are lost during blanching (SELMAN, PRICE, & ABDUL-REZZAK, 1983), retrieving these compounds from wastewaters requires too much energy for this process to be feasible. Organic compounds like starch can be extracted from production wastewaters (Da et al., 2008). In addition, after starch extraction from the raw material, juice is produced as by-product, it is a colloid substance that can be used for soil fertilization or proteins can be extracted and used as feed (Priedniece et al., 2017).

Hence in these calculations, the weight lost during blanching is considered as lost raw material. For determination of bioresource potential use in the enterprise, all biomass materials should be considered as bioresource.

4. Conclusions

The elucidated nexus can help to identify potential factors for enterprise development towards bioeconomy and effective bioresource utilization. Deeper exploration of the Core of nexus (bioresource-product-waste) led to mathematical descriptions of linkages within this core. The proposed bioresource utilization index puts the state of by-product management in perspective. This indicator could be used to gain the first insight into by-product management in relation to best available techniques. Production of different products will give differing maximal real index values. If the company is producing frozen produce, it is expected for them to have a different amount and type of by-products than a company producing baby food Because quality standards as well as volumes and types of by-products differ. The work on the bioresource utilization index could be continued by investigating the maximal real bioresource utilization index for production of specific products, for example, wood fiberboard. The calculated maximal index would be useful for all fiberboard producers who would be interested in their by-product management efficiency and overall production compliance with bioeconomy. The index is not restricted to wood biomass; it could be calculated for any type of biomass or biomass combinations. Another factor affecting the biomass utilization index is product to raw material ratio, this ratio can be increased by improving production technologies. For example, reduction of vegetable peel thickness can decrease the amount of wasted product, instead of directing the material to by-

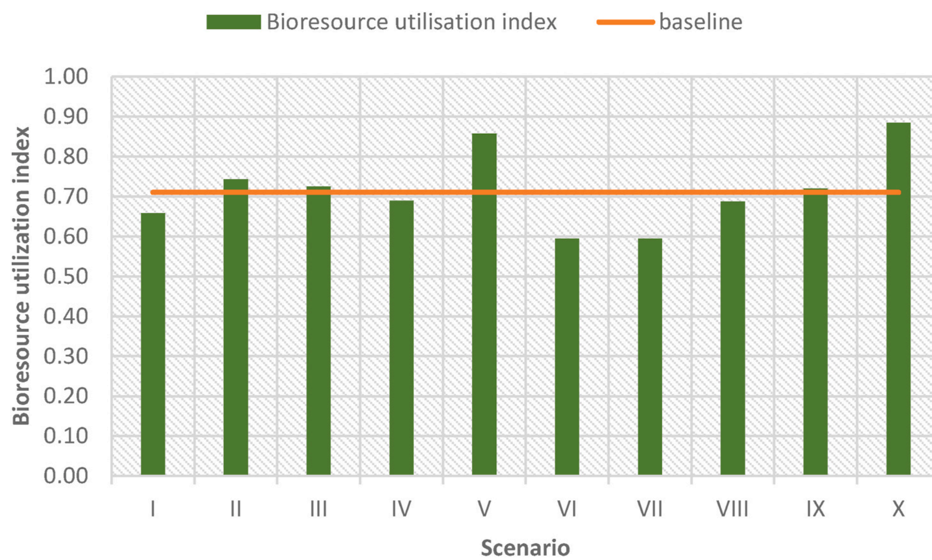

Fig. 6. Bioresource utilization index calculated for Enterprise No. 1 and 2. actual situations represented by case II and IX and four alternative scenarios (I, III to VIII and X). Baseline is represented by median from all ten scenarios as one bioresource is used in all cases. Baseline shows that actual scenarios are very close to median (orange), showing that actual situation is somewhat in-between of worst and best possible case.

product flow it could be used for target product production.

Policy trends in European Union are promoting waste reduction, in addition, reports on misclassification of waste have been published. With the coming years it is expected for enterprises to become more thoughtful with the by-product and waste utilization. We have shown that bioresources could be audited not only from the perspective of waste utilization but from the perspective of resources. Proposed bioresource utilization index gives an insight into resource efficiency in specific enterprise by quantifying incoming raw material, outgoing product, by-products, and waste. The elucidated factor nexus could be used as a map for easier detection of place for improvement. In the future work we plan to elaborate on the financial aspects of the utilization of production residues, to kick-start the bioresource evaluation discussion, in this paper we are offering coefficients based on existing bio-based value pyramid with 5 levels of values represented by five product groups.

CRediT authorship contribution statement

Ilze Vamza: Formal analysis, Conceptualization, Methodology, Original draft, Investigation, Visualization. **Anna Kubule:** Data curation, Investigation, Validation, review &editing. **Lauma Zihare:** Data curation, Investigation, Validation, review &editing. **Karlis Valters:** Conceptualization, Validation, Supervision. **Dagnija Blumberga:** Conceptualization, Validation, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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