Tampere University

Tran Ngo

THE OPERATIONAL ENVIRONMENT OF CIRCULAR BIO-BASED SIDE AND WASTE STREAMS FOR BIOGAS AND NUTRIENT RECOVERY

Master's thesis
Faculty of Engineering and Natural Sciences
Examiners: Hannele Auvinen &
Annina Takala
March 2023

ABSTRACT

Tran Ngo: The operational environment of circular bio-based side and waste streams for biogas and nutrient recovery
Master's thesis
Tampere University
Environmental Engineering
March 2023

The current linear economy system has failed to preserve nature and induced severe environmental burdens such as pollution and climate change threatening the living on Earth. The shift to circular economy is then crucial. As a major source of waste and by-product generation while possessing high potentials of nutrient and energy recovery, bio-based side and waste streams valorization and utilization play a crucial role in establishing the circular bioeconomy within the big picture of the circular economy.

In dedication to foster the transition to circular bioeconomy, this thesis aims to create an overview of the operating environment of circular bioeconomy for biogas and nutrients and identify its associated challenges and opportunities. To reach the goal, the research work was conducted following the literature review of the state-of-the-art valorization and digitalization technologies and legislations, 10 stakeholder interviews and 1 questionnaire for the 3 case studies of HAMK manure hygienization project, MTK e-marketplace and ECO3 industrial ecosystem. Those 3 case studies represent the 3 circular bioeconomy operational models of self-sustaining circularity, rural-urban symbiosis, and industrial ecosystem to be assessed for circular bioeconomy systemic operation. PESTLE analysis is utilized to assess the circular operational environment from different perspectives of political, economic, social, technological, legal, and environmental factors. The operational challenges and opportunities are determined through literature review in addition to the validation and opinion of stakeholders on the practical operational environment.

According to the literature review and stakeholder interview, key elements impacting circular bioeconomy operation are feedstock availability and quality, technical operation, financial viability, policy and legislation change, social acceptance, resource competition and virgin material alternative.

The common adopted valorization technologies for BSWS are biological methods including composting and anaerobic digestion. The main technical challenge following it is to ensure product quality whose root causes are from feedstock quality and availability and unsustainable material design. Technological cure solving the problem from the earlier cause can bring more efficient and cost-effective effects. Data and digitalization technologies can foster the transition to circular bioeconomy through e-marketplace, artificial intelligence, and blockchain-based value chain management system. The challenge for it remains in the high-tech adaption and digital infrastructure requirements.

The policies and legislation are moving towards CBE promotion through biowaste separation mandate and renewable energy target. However, unharmonized regulations, restriction on BSWS product entry, taxation and low circularity incentives are the noticeable legislative challenges. In addition, more financing and fiscal supports for small operation are needed as developing small self-sustaining circularity model can reduce great burden for further logistics and treatment.

Initiating systemic transition to circular bioeconomy requires close interlinkage between small self-sustaining circularity, medium rural-urban symbiosis, large industrial ecosystem operation models, and stakeholder engagement. The driver for transition is the combination of technological push, market pull, political support, and sociocultural change to adopt circular products and services. The role of the system orchestrator is crucial to foster stakeholder collaboration and make that combination feasible.

Keywords: Circular bioeconomy, bio-based side and waste stream, valorization, digitalization, legislation

PREFACE

This master’s thesis is commissioned by VTT Technical Research Centre of Finland Ltd for the TREASoURcE EU-project. The thesis work particularly focuses on the circular economy research of the bio-based side and waste streams in dedication to project work packages 1 and 5. The aim is to create an overview of the operational environment relating to the bio-based side and waste value chain to identify challenges and opportunities in the transition to circular bioeconomy.

TREASoURcE

TREASoURcE is a four-year project (2022-2026) receiving funding from the European Union under the Horizon Europe research and innovation programme. TREASoURcE aims to initiate systemic change by developing systemic circular economy solutions in cities and regions for currently underutilized or unused plastic waste, end-of-life electric vehicle batteries and bio-based waste and side streams. Implementing these solutions together with companies, societies (including citizens, consumers, communities, and regional actors) and experts in the field is expected to significantly increase product and material circulation in the Nordic and Baltic Sea Regions. TREASoURcE is coordinated by VTT Technical Research Centre of Finland Ltd and the whole project consortium consists of 17 partners from 7 European countries.

Funded by
the European Union

ACKNOWLEDGEMENTS

This master's thesis marks as the closing of my master's degree study and the beginning of my professional career. I am thankful to be able to go through this milestone as a Tampere University student and a thesis worker at VTT (Technical Research Centre of Finland) for TREASoURcE project. Through the last 6 months of conducting the thesis, I am grateful for all the supports and guidance from my thesis supervisors, thesis worker fellow and TREASoURcE project partners.

Firstly, I want to express my gratitude to my thesis supervisor at VTT, Anna Tenhunen-Lunkka. Thank you for trusting me from our first job interview till now, for giving me this opportunity to conduct my thesis under your great guidance, for encouraging me to do the work with my creativity and for comforting me even when I could not express my feeling. I appreciate all your emotional support and work advice.

Secondly, I want to say many thanks to my university supervisors Hannele Auvinen and Annina Takala. My gratitude is not only for your guidance and feedback on this thesis work but also for your support during my degree study at Tampere University.

Thirdly, for my thesis worker fellow Nina McDougall and Mikko Myrä, thank you all for the journey we went through together, for sharing the experiences and learning from each other.

This thesis work cannot be completed without the support from the TREASoURcE project partners for the stakeholder interview network and questionnaire spreading. Special thanks to Riina Kärki, Nora Berglund and Olga Vatka from MTK (The Central Union of Agricultural Producers and Forest Owners in Finland) for helping me develop the questionnaire, translating it into Finnish, spreading it to the respondents and all your feedback on my thesis work. Thank you a lot for finding and sending the questionnaire to over 200 contacts to get 28 answers for me.

Last but not least, I am grateful and happy to be surrounded by the unconditional love from my family and friends who supports me in all the decisions I make and the path I choose. Finally, the last person that I am thankful to is my younger self, from a kid till now becoming an adult. Thanks for keeping faith and growing up into a person you wished to be. Though there is still a long way ahead, you get what you deserve, kiddo.

Tampere, 13th March 2023

Tran Ngo

CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

AD	Anaerobic digestion
AI	Artificial intelligence
BSWS	Bio-based side and waste streams
BSFT	Black Soldier Fly Treatment
CBE	Circular bioeconomy
CEAP	Circular economy action plan
EFR	Environmental Fiscal Reform
ESPR	Eco-design for Sustainable Products Regulation
GDPR	General data protection regulation
HAMK	Häme University of Applied Sciences
IoT	Internet of Things
ISCC	International Sustainability and Carbon Certification
MTK	The Central Union of Agricultural Producers and Forest Owners in Finland
PAYT	Pay as you throw
SSC	Self-sustaining circularity
SMEs	Small-medium enterprises
RED	Renewable energy directive
RUS	Rural-urban symbiosis
VFAs	Volatile fatty acids
VTT	Technical Research Centre of Finland
WFD	Waste Framework Directive

1. INTRODUCTION

The current linear economic system has thrived over history but failed to preserve nature. As there is no planet B, there is no future for this conventional economy to succeed anymore. A future with sustainability is vital to prevent civilization collapse. The path to a sustainable future is unpredicted but invented with circular bioeconomy as a pivotal change. (World Economic Forum, 2020)

The linear economy of raw materials extraction, production, and waste disposal or ‘cradle-to-grave’ model is unnecessary wasteful use of natural resources. In resonance with the world’s population growth, economic development and urbanization, the linear economy is driving the extensive consumption and unsustainable production that leads to the planet crisis of biodiversity loss, environmental pollution, climate change and consequently threatens human existence. (United Nations, 2022)

In 2022, Earth Overshoot Day, which denotes the date when all the regenerative biological capacity of the Earth during the entire year is used up, was on July 28th (Earth Overshoot Day, 2022). The overconsumption of Earth's biocapacity is 5 months ahead of the planet boundary and must be stopped by reducing raw material extraction, efficiently circulating resources, and limiting waste disposal. To deal with the linear economy challenges, circular economy, a ‘cradle-to-cradle’ model, which circulates materials in the closed loop and decouples economic growth from the consumption of finite resources, has been adopted (Ellen MacArthur Foundation, n.d.).

Bio-based side and waste streams are key material streams for circular economy. In Europe, 118 to 138 million tons of biowaste derive annually, of which only approximately 40% is effectively recovered into high-quality compost and digestate (European Compost Network, n.d.). Biowaste represents the single largest component of 34% of total municipal waste generation in Europe (United Nations, 2022). That is not to mention the considerable amount of bio-based side streams generated from agricultural and industrial activities and the unreported or uncollected bio-base side and waste streams. As a major source of waste and by-product generations while possessing high potentials of nutrient and energy recovery, bio-based side and waste streams valorization and utilization play a crucial role in establishing the circular bioeconomy within the big picture of the circular economy.

In many cases, the use of fossil energy is dominating in the production of synthetic fertilizers and energy usage. Bio-based side and waste streams recovery potentials of bioenergy and organic fertilizers can then back the transition from unsustainable fossil to a sustainable bio-based economy (Vaneeckhaute et al., 2013). Furthermore, whereas costs for energy and fertilizers are increasing, bio-based side and waste streams recovery can bring real potential economic benefits. In addition to that, utilizing biogas and biomethane, locally produced from bio-based waste streams as an alternative to imported fossil products, can generate jobs and foster gross domestic product growth (Interreg Europe, 2021). Indeed, in Europe, biogas production industries are accountable for more than 210,000 sustainable jobs nowadays with the expectation to create around 420,000 jobs by 2030 and over one million jobs by 2050 (Interreg Europe, 2021). Hence, the global challenges of significant bio-based side and waste streams generation can turn into new opportunities of the circular bioeconomy.

Circular bioeconomy can simultaneously tackle the environmental crisis, nutrient depletion, and energy shortage. Despite the environmental and potential economic benefits, the transformation from the prevailing linear economy to the visionary circular bioeconomy is challenging because of the complexity and interdisciplinary operating environment involving multidisciplinary stakeholders. Therefore, the understanding of the circular bioeconomy operational environment needs to be broadened to overcome the challenges and take advantage to initiate the paradigm shift to the circular bioeconomy. The operational environment is the environment where circular bioeconomy practices function within. This environment can be affected by the single or interlinkage of technical, economic, social, and legislative factors which are dependent on geographics and local conditions.

In dedication to fill the research gaps and foster the transition to circular bioeconomy, this thesis aims to create an overview of the operating environment of circular bioeconomy for biogas and nutrients at the European level in general and Finland national level in specific. Other purpose is to identify challenges, opportunities and lessons learned for future development and the transition to circular bioeconomy. To reach these aims, this thesis work deals with 4 main research questions:

- What are the state-of-the-art valorization and digitalization technologies for circular bioeconomy operation?
- How do the policies and legislations affect circular bioeconomy operation in the EU?
- What are the challenges and opportunities in circular bioeconomy operations?
- How do the circular bioeconomy models operate and interlink in systemic view?

The operational environment research is conducted through literature reviews of technologies and legislations in addition to stakeholder interviews for practical circular bioeconomy implementation. The thesis is structured with the starting background research on the circular bioeconomy concepts. It then proceeded with the literature review on the state-of-the-art valorization technologies of bio-based side and waste stream for biogas and circular nutrients, and the innovative data and digitalization innovations in circular value chain operation. Next, the policy and legislation are reviewed to provide knowledge on the current European and Finnish legislations relating to circular bioeconomy development. After the technological and literature reviews, the methodology explains the process of stakeholder interview to assess the circular bioeconomy operational environment and presents the case studies' description of the 3 circular bioeconomy models: self-sustaining circularity, urban-rural symbiosis, and industrial ecosystem. In the following results and discussion section, 3 dedicated case studies of the corresponding circular bioeconomy models are analyzed through stakeholder interview inputs to explore the challenges and opportunities in circular bioeconomy practical implementation at different operational models. In addition, the interlinkage of the circular operations and stakeholder engagement in circular bioeconomy systemic view is discussed. Finally, future research and development recommendations to initiate circular bioeconomy transition are concluded.

2. CIRCULAR BIOECONOMY

This chapter consists of defining the circular bioeconomy concept and strategy, categorizing bio-based side and waste streams, and discussing its collection practices.

2.1 Concept

Circular bioeconomy (CBE) is approached as the intersection of the circular economy and bioeconomy. Circular economy is a model that is restorative and regenerative by design to save raw material usage by efficiently valorizing materials at their end-use and circulating them within the closed production loop for as long as possible (Ellen MacArthur Foundation, n.d.). On the other perspective, bioeconomy stands for a sustainable economy whereas renewable biological resources, as an alternative to non-renewable fossil, are utilized to produce food, materials, and energy (Feleke et al., 2021). The main difference between these two concepts is the material flow where circular economy promotes cascading use of secondary materials, only 10-15% of these BSWS can become the input for bioeconomy (Gatto & Re, 2021).

Circular economy and bioeconomy are widely adopted to deal with sustainability challenges, however, they both have some debatable limitations. Criticism of the circular economy emphasizes on the rebound effects of the circulation process that not every stream can be recovered sustainably and may result in worse environment impact. As for the bioeconomy, bioproduction may intensify the biomass harvest which conflicts with saving virgin materials. Therefore, the circular bioeconomy concept emerges to address circular economy principles in conjunction with the sustainable valorization and utilization of bio-based side and waste streams (D’Amato et al., 2020).

Considering the strategy for circular economy, 9R framework introduced by Potting et al. (2017) cover the circular economy stage comprehensively ranging from the highest circularity of the upstream ‘smarter product use and manufacture’ (R0-R2), ‘extend life span of product and its part’ (R3-R7) to the lowest circularity of the downstream ‘useful application of materials’ (R8-R9) (figure 1).

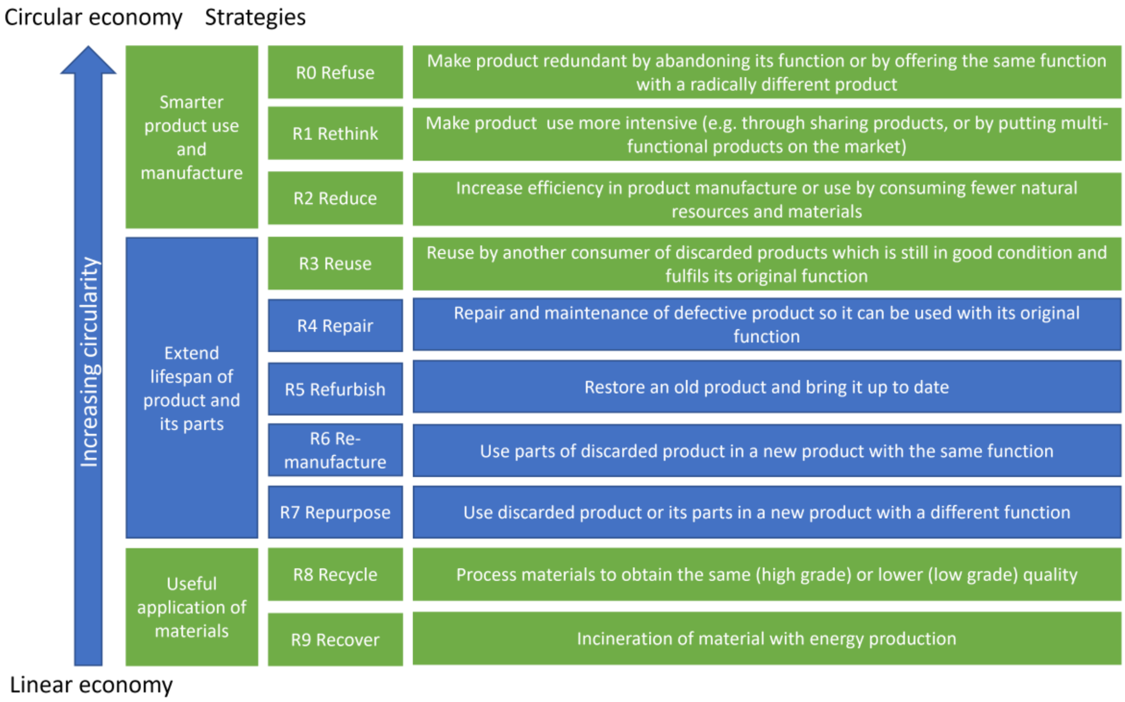


Figure 1. *9R circular bioeconomy strategies (Adapted from Potting et al., 2017)*

Taking into account circular bioeconomy strategies, the adapted 9R framework can be reduced to the prevention of bio-based side and waste streams (BSWS) generation (R0-Refuse, R1-Rethink, R2-Reduce), R3-Reuse and the BSWS valorization process (R8-Recycle and R9-Recover) whose strategies are marked green in figure 1. Due to the biodegradable characteristics of BSWS, it is hard to extend the product lifespan and requires the need for material processing to recover the value. R3-Reuse is only adaptable to food waste to be redistributed for people or animal feed. Although recycling and recovery are the least circularity practices in 9R framework, they are the main targets for CBE development now. According to 9R framework, within CBE, R8-Recycling strategy adapts to the nutrient and biogas valorized from BSWS which has higher added value than R9-Recover strategy of incineration for energy recovery which is often last disposal stages for treating the non-valuable leftovers. However, in CBE practices, the term ‘Recover’ can be exchangeable to ‘Recycle’ such as nutrient recovery and biogas energy recovery instead of recycling.

2.2 Bio-based side and waste streams

Bio-based side and waste streams are the liquid or solid organic, biodegradable by-product or waste resulted from the production and consumption activities (Center for Integrated Biowaste Research, n.d.). The Waste Framework Directive (2008/98/EC) defines ‘waste’ as ‘a substance or object which the holder discards or intends or is required to discard', and 'by-product' or side stream as 'a substance or object, resulting from a production process, the primary aim of which is not the production of that item' (European Commission, n.d.-e).

According to the classification of LUKE (Natural Resources Institute Finland), bio-based side and waste streams are divided into 5 categories below (Biomass Atlas, n.d.):

- Forest: They are side streams resulting from the felling of commercial timber (logging residues, stumps, etc.)
- Field: They are the side streams from crop harvesting (stem, top or straw biomasses of seed, grain, tuber, bulb, root crops, etc.)
- Garden plants: They are horticultural crops ruined by the weather or pests, and plant parts other than those produced for food (tops, leaves, roots, etc.)
- Waste: They are the biodegradable waste from industrial operation and municipal waste generation (food waste, sewage sludge, waste from slaughter, animal fat, paper, cardboard, etc.)
- Manure: It is the mixture of faeces and urine excreted in animal husbandry

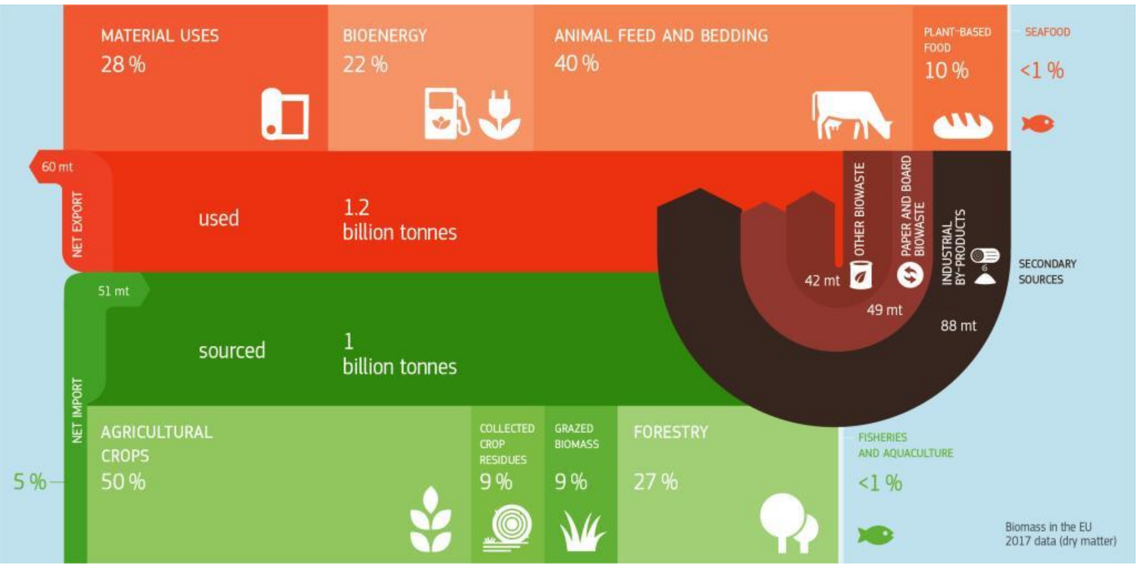


Figure 2. *Dry biomass source in EU in 2017 (European Commission, 2022)*

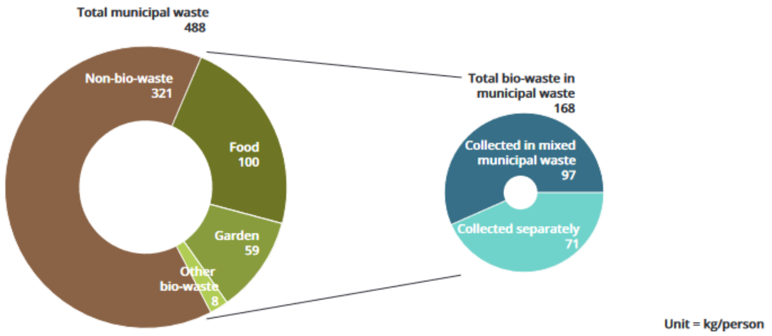
Figure 2 illustrates the statistics of dry biomass sources generated in Europe in 2017. Biomass secondary sources accounting for 0.2 billion tones represent the BSWS supplied from industrial by-products such as forest-based industries and biowaste (European Commission, 2022). In addition, the collected crop residues account for 0.09 tones (European Commission, 2022). When it comes to wet BSWS, approximately 1.4 billion tons of manure was generated annually by animal farming during the period 2016–2019 (Köninger et al., 2021).

BSWS valorization and utilization are the fundamental development of CBE. Some of BSWS are rich in nutrient value such as agriculture streams (field, garden plants and manure), which are potential for nutrient recovery and bioenergy production input, forest-based and industrial waste which are promising feedstock for biofuel production (European Biomass Industry Association, n.d.). While others such as food waste and municipal waste are considered as less valuable due to its mixed nature, the treatment of them is necessary to reduce environmental impact and brings added value for materials (European Environment Agency, 2020). To realize the BSWS added values and back up the commercialization of BSWS, separated collection and valorization technologies are the key to bring secondary materials to the new cycle of CBE.

The sustainable treatment and valorization of BSWS demands it to be separated at source from other residues. Separation is the prerequisite for BSWS recovery as it reduces the impurities and contaminations which improves the value capture for circular BSWS products to be used as soil amendment, organic fertilizer, and biogas. (European Environment Agency, 2020)

It is mandated in Waste Framework Directive 2018 that biowaste must either be separated and recovered at source or separated at source and collected by 2023. The more sustainable way of BSWS treatment is the first option which can be known as the self-sustaining circularity practices. As an illustration of municipal biowaste, home composting or community composting are encouraged to reduce the need for collection, waste management costs and its associated environment impact. The challenges for the separation and recovery at source lay in awareness for waste sorting and knowledge for recovery practices to minimize the environmental impact such as odor and ensure process and product quality. These practices are more familiar in the rural area compared to the urban due to space flexibility and more demand for BSWS recovery product usage. (European Environment Agency, 2020)

Separate collection practices have been introduced in several countries in Europe. In 2017, considering 28 European countries, on average about 43% of the municipal biowaste was collected separately and the remaining 57% was collected in mixed waste (figure 3) (European Environment Agency, 2020).



Source: ETC/WMGE compilation based on data provided by the European Environment Information and Observation Network (Eionet) through an EEA and European Topic Centre on Waste and Materials in a Green Economy (ETC/WMGE) survey (ETC/WMGE, 2019a), complemented with data from the European Reference Model on Municipal Waste (ETC/WMGE, 2019b) and Eurostat (2019).

Figure 3. *EU biowaste collection in 2017 (European Environment Agency, 2020)*

Besides BSWS separation awareness and knowledge from people, the challenges to adopt separated collection widely are the initial investment cost for the changing collection and transportation system and new infrastructure required. However, the cost benefits for BSWS separated collection and valorization can overweight the initial investment in the long run together with the optimization of logistics and BSWS management practices. (European Environment Agency, 2020)

3. STATE-OF-THE-ART REVIEW

3.1 Valorization

The generalization of the current established and noticeable technologies to valorize BSWS for biogas and circular nutrients are direct use (direct land application and direct animal feed), biological conversion (composting, vermicomposting, Black Soldier Fly Treatment, and anaerobic digestion) and thermo-chemical conversion (pyrolysis and gasification) (figure 4).

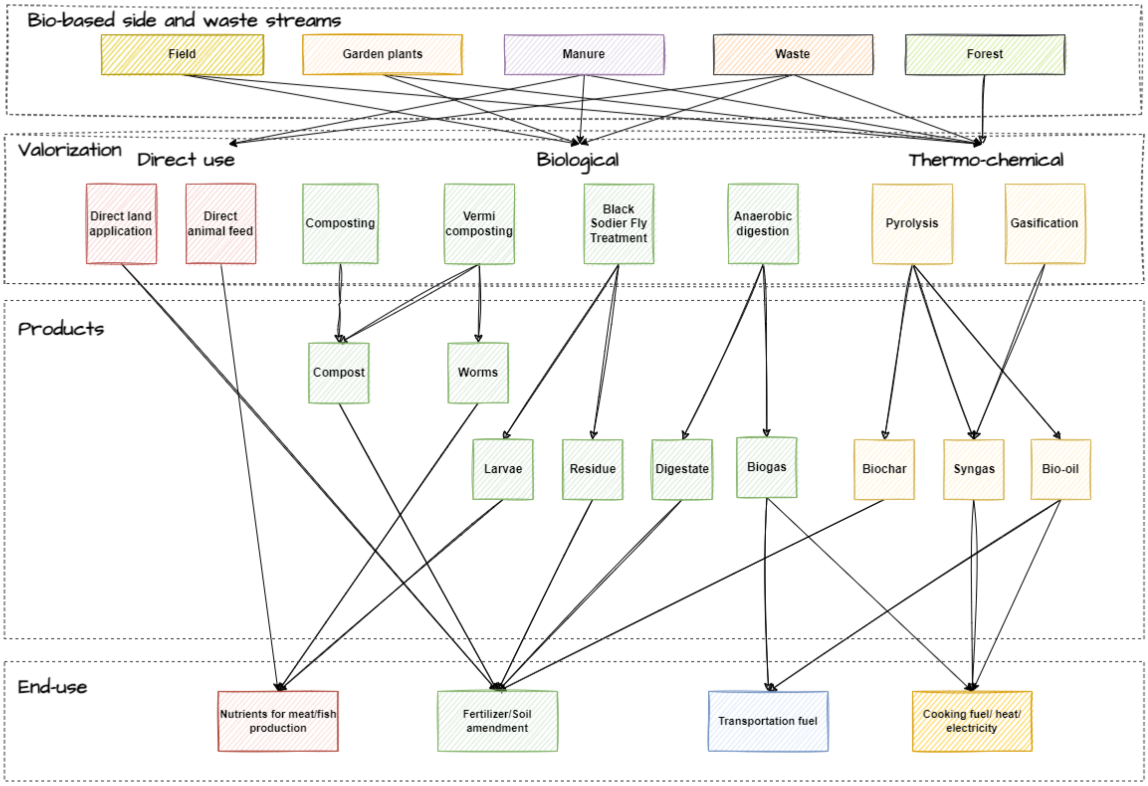


Figure 4. *Overview of valorization technologies (Adapted from Lohri et al., 2017)*

The valorization process is outlined from the perspective of BSWS input, conversion process, products to end-use. In the following sub-sections, this flow of valorization process will be reviewed for each technology.

3.1.1 Direct use

The direct use of BSWS is a traditional and simple way of treatment. Its operation is mostly self-sustaining circularity practices including direct land application and direct animal feed.

3.1.1.1 Direct land application

Direct land application refers to the spreading of raw organic waste onto the land field. It is specially applied for growing crops that demands large amount of organic nutrients or improving arid field (Lohri et al., 2017). Input material for direct land application is typically animal manure accounting for more than 90% of land spreading in Europe and the remaining 10% is food waste (Lohri et al., 2017). The characteristic for its material input is pure organic waste since non-biodegradable matter or pollutant may deteriorate the soil and crop. Considering the conversion process, the BSWS go through the natural aerobic biodegradation where the soil microorganisms decompose the waste whose process releases nutrients such as nitrogen, phosphorous, potassium and organic contents into the soil (Jakobsen, 1994). The product and usage of direct land application is soil amendment that improves soil characteristics and crop production (Huguier et al., 2014).

The challenge of direct land application is the untreated waste which may contain pathogens, heavy metals and pollutants that can result in bioaccumulation in plants and soil and cause environmental pollution and health threat from food contamination (Smith et al., 2015). Other than that, because of the uncontrol of nutrient content from the raw BSWS, leaching nutrients into groundwater causing contamination, eutrophication of surface water or the ammonia volatilization can happen when the BSWS contain rich nutrients (Lohri et al., 2017).

3.1.1.2 Direct animal feed

Direct animal feed is straightforward feeding the selective BSWS to animals. The input material is mainly food scraps which should contain reasonable amount of essential nutrients, carbohydrates, amino acids, fibers, and fats meanwhile limiting pollutants that endanger the animals or human when consuming the animal products (Lohri et al., 2017). For example, vegetable and fruit wastes are the suitable feed to animal husbandry. The conversion process utilizes livestock animal to operate as bio-processor for transforming BSWS to animal feedstock that improves husbandry yield (Dou et al., 2018) The product of this valorization is livestock production such as meat, milk, eggs, or leathers.

Besides the benefits of sustainable waste management and food security, the biggest challenge is ensuring the waste quality and waste selection to feed animal. Feed selection is based on the digestive system of the animal whereas only animals with complex digestive system such as ruminants can consume cellulose materials (straws and grass), while others like pig cannot digest it. Potential quality risk is animal infection to disease from the food waste, especially food in contact with meat can cause salmonellosis. (Lardinois & van de Klundert, 1993)

3.1.2 Biological conversion

Biological treatment is considered as the conversion of materials by living organisms. It includes composting, vermicomposting, Black Soldier Fly Treatment, and anaerobic digestion. Because the microorganism requires moisture environment to grow, the biological conversions are mainly applied to high moisture feedstock. It is originally a natural biological process and has been developed into several conversion technologies with pre-setting environment and conditions to speed the process, control the operation and desirable products. It requires notable less external energy input than other thermal and physical and chemical processes. (Lohri et al., 2017)

3.1.2.1 Composting

Composting is an aerobic process in which microorganisms through its complex metabolic processes decompose the organic material in the present of oxygen (Sayara et al., 2020).

The input materials for composting are varied within the condition of high moisture nature for microbial growth environment (Lohri et al., 2017). Food waste, garden waste, agricultural waste and manure are ideal substrates whereas mixed BSWS such as municipal waste are not encouraged due to resulting in low quality products (Epstein, 2017).

The composting process undergoes 3 main stages which are (1) mesophilic stage, (2) thermophilic stage, and (3) cooling and maturation phase. In the first state, the microorganism breaks down the easily degradable organic content. These microbial activities generate heat and increase the temperature passing through the mesophilic range (25-45 ℃) to enter the thermophilic stage (45-65 ℃). However, over 65 ℃ can kill the needed microorganism for decomposition, hence, the temperature and aeration in addition to other predominant parameters such as moisture, pH, and organic composition (carbon-nitrogen ratio) need to be controlled to keep the environmental in the optimum range (Lohri et al., 2017). In the second stage, the high temperatures help eliminate the pathogen and ensure improve the hygiene of the compost material. As the degradation of organic matters become exhausted, the supply of heat from microbial activities decreases and the cooling and maturation phase is reached. In maturation phase, the organic decomposition still occurs naturally with low microbial activities and the process ends when the inner temperature reaches the ambient temperature. (Sayara et al., 2020)

The main output of composting is compost, a stable, nutritious, and contaminant-free soil-like texture. Compost is rich nitrogen, phosphorous, potassium and beneficial minerals and microorganisms which can be utilized as soil amendment and organic fertilizer for plant growth (Polprasert, 2007).

Among the biological technologies, composting has been a long traditional and developed method of organic matter treatment. Composting can be conducted on various scales from small household composting bin to large industrial level composting reactor. Composting has advantages of simple, low operating cost and robust technology. However, the challenges of this method are to segregate pure organic input for good quality compost result, the lack of control in microbial biological process causing nuisance such as odor and vermin (Lohri et al., 2017). Furthermore, the long processing time of several months to fully go through 3 composting stages can be a drawback (Epstein, 2017).

3.1.2.2 Vermicomposting

Vermicomposting is defined as the biological decomposition process in which earthworms and microorganisms convert organic matter into humus-like material which is called vermin-compost (Muralikrishna & Manickam, 2017).

The input materials for vermicomposting can be household wastes, municipal organic waste, and organic residues from industries (paper, wood, and food). Noticeably, some food wastes such as dairy products, grease and oils, meat and fish, salty and vinegary foods cannot be digested by earthworms (Lohri et al., 2017).

The conversion process of vermicomposting involves microorganism and earthworm interaction that at the first phase, microorganisms in the BSWS decompose the organic matters at the aerobic degradation process to prepare the feed on the earthworm (Lohri et al., 2017). Therefore, composting can be considered as the pre-treatment step of vermicomposting. Earthworms then act as the main drivers in the decomposition of organic materials by fragmenting and conditioning the feed substrate so that the microorganisms in the worm digestive system can continue to decompose the organic material into finer particles and nourish the worm (Alshehrei & Ameen, 2021). In that process, the worms in turn produce microbial fecal material that promotes microbial activity and is beneficial for quicker organic degradation (Singh et al. 2011). The most used earthworm specie for vermicomposting is *Eisenia Fetida* thank to its high adaptability with different BSWS and converting capacity, the whole complete *Eisenia Fetida* lifecycle in vermicomposting takes approximately 70 days (Lohri et al., 2017). The ideal temperature condition for earthworm activities is mesophilic in the range of 10-35 ℃ and other factors to be controlled during vermicomposting process are stocking density (earthworm population density), feeding rate of BSWS, moisture, carbon to nitrogen ratio and pH (Lohri et al., 2017).

The output of the process is vermicompost which is a brownish black material with high porosity, aeration, rich in micronutrients, and soil beneficial microbes. It is a sustainable alternative to synthesis fertilizer and soil enrichment (Bin Dohaish, 2020). Other product is the nourished earthworm, which are rich in protein and considered as good pro-biotic feed to fish and animals (Lohri et al., 2017).

Vermicomposting has advantages over the composting such as shortened processing time, more nutritious, physical and biochemical efficient compost (Alshehrei & Ameen, 2021). It is low cost and simple technology which can be widely adapted in various scales. Nevertheless, the challenges of vermicomposting include large space requirement, low quality feedstock for earthworms, and skilled labor needed with the understanding of worm life cycle and biological process. Moreover, as pre-treatment of composting is already required, the second treatment of vermicomposting can be considered as more effort. (Lohri et al., 2017)

3.1.2.3 Black Soldier Fly Treatment

Black Soldier Fly Treatment (BSFT) is an emerging technology in BSWS treatment that transforms organic material into insect biomass of protein and oil (Kim et al., 2021).

The input materials for BSFT are diverse. Livestock manure, food waste, vegetable waste, compost, and municipal organic waste can be suitable feedstock (Cai et al., 2018). The moisture level in feedstock is an important factor that larvae develop better under moist environment. Ideally, wet and dry matter can be mixed to generate better larva feed (Lohri et al., 2017).

Considering the conversion process, the black soldier fly, *Hermetia Illucens* larve has the appetite for decaying organic matter which is taken advantage of to feed organic matter for incorporating nutrients into growing the insect biomass of extra protein and fat (Cai et al., 2018). The total larval development lasts for about 20-35 days (Zhou et al., 2013). The optimum temperature and moisture level during the process are 26–27 °C and 60–70% respectively (Kim et al., 2021). Further, larval density needs to be controlled to prevent competition that adversely decreases larval survival rate. The effective ratio of the number of larvae to grams of feedstock is 2:1 (Kim et al., 2021).

The output of the BSFT is the larval biomass as the main product and residues. The high protein and fatty acid content of larvae make them a great nutrient source for animal and fish feedstocks (Kim et al., 2021). In addition, the larvae can be extracted for oil for further biodiesel production. The quality of lipids contained in larva is comparable to the conventional biodiesel (Kim et al., 2021). The residues from BSFT still retain nutrients and can be applied as soil amendment (Lohri et al., 2017).

BSFT is a novel technology with high potential for industrial application and economic success. Its advantages include short processing time, high nutrient conversion rate, and economic-attractive products. However, the challenges remain in the large space required and the highly skilled labor needed to control the insect behavior and ensure the larval survival rate due to the insect colony. In addition, because the larvae are utilized as animal feed, the hygiene factor needs to be concerned, which can be solved by eliminating contaminant feedstock in the first place. (Lohri et al., 2017)

3.1.2.4 Anaerobic digestion

Anaerobic digestion (AD) is the biological decomposition of both liquid and solid organic matter by microorganisms in the absence of oxygen to produce biogas (Molino et al., 2013).

The input organic materials for AD process are varied ranging from agricultural, municipal to industrial BSWS as a single substrate or in co-digestion with high methane conversion potential substrates such as animal manure to improve the product yield (Rocamora et al., 2020). Lignin-based BSWS like forest residues are not suitable substrates because its nature cannot be decomposed by microbial activities (Lohri et al., 2017).

The AD conversion process involves a series of microbial activities: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. In the first hydrolysis stage, the bacteria convert the insoluble complex organic matter (lipid, protein, carbohydrate) into simpler soluble compounds such as amino acids, sugars, and long chain fatty acids. In the acidogenesis stage, these compounds are continuously broken down by acid forming bacteria into volatile fatty acids (VFAs) with ammonia, carbon dioxide, and hydro sulfide as by-products. It is followed by the acetogenesis stage where VFAs are further decomposed by acetogenic bacteria into acetic acid, carbon dioxide, and hydrogen. In the last stage, the methanogenic bacteria degrade acetic acid into methane and carbon oxide. In addition, methane can also be produced by the reduction of hydrogen with carbon dioxide. (Molino et al., 2013)

The output of AD process is the biogas containing methane (55–60%), carbon dioxide (35–40%), and other impure gases such hydro sulfide, hydrogen, and nitrogen. The typical processing time is 30 days. This biogas can be burned directly for heat generation or can be put into gas generator for electricity. Moreover, the biogas can be upgraded by technologies such as membrane separation, physical and chemical scrubbing to purify biomethane (90-95% CH_4) from impurities which can then be used as vehicle fuel and supplied to the natural gas grid. Other product is the digestate which is rich in nitrogen and can be used for agricultural enrichment. (Lohri et al., 2017)

Anaerobic digestion is a robust and well-developed technology in various scales and operating environment (wet and dry, mesophilic and thermophilic), reactor types (batch and continuous) (Lohri et al., 2017). Nowadays, biogas plants often utilize mechanical-biological technology which is the combination of mechanical sorting of heterogenous waste as pre-treatment to separate biodegradable input for the biological process of anaerobic digestion to yield biogas (Garg, 2014).

The advantages of AD are its widely adaptative application for different scales and BSWS type, a sustainable technology to convert BSWS into renewable energy and plant nutrient. On the other hand, the challenges are the low energy yield of biogas which could be solved by co-digestion to improve feedstock quality, VFAs generation causing foaming, and over acidification which can inhibit microbiological activities. (Lohri et al., 2017)

3.1.3 Thermo-chemical conversion

Thermo-chemical conversion is the process that uses heat to foster chemical reaction to convert the materials into value-added products. The valorization processes for gases and nutrients involve pyrolysis and gasification.

3.1.3.1 Pyrolysis

Pyrolysis is the thermal decomposition of organic materials under the absent oxygen condition. The process uses heat to disintegrate the weak thermal stability of chemical bonds and transform the material into new molecules. (Zaman et al., 2017)

The input materials for pyrolysis are BSWS that meet the requirements of dry, unmixed, and homogenous substances. Wood waste, paper and carboard, lignocellulosic biomass from garden waste, agricultural waste are suitable inputs (Lohri et al., 2017). High moisture stream can also be applied with pre-treatment of drying to a suitable range 10-15%. Pre-treatment also includes the grinding of material into smaller sizes and delignification for more efficient pyrolysis conversion. (Isahak et al., 2012)

Pyrolysis conversion undergoes complex thermal decomposition to break down large complex hydrocarbon molecules of biomass into smaller and simpler molecules of gas, liquid, and char (Basu, 2013a). Pyrolysis conversion is divided into fast pyrolysis and slow pyrolysis processes. In a fast pyrolysis process, the input is quickly heated to high temperatures between 650-1000°C in seconds. The fast pyrolysis results in the main product of bio-oil and a lower yield of biochar and gas. On the other hand, slow pyrolysis operates in longer residence times (range from minutes to days), lower temperatures (300-500°C) to convert biomass into the main product of biochar, gas, and lower bio-oil yield. (Zaman et al., 2017)

The outputs of the pyrolysis conversion are solid (biochar), liquid (bio-oil, tar, and water), and a mixture of non-condensable gases (H2, CO, CO2…) (Basu, 2013a). Biochar can be applied for soil amendment, burning fuel, adsorption media, and carbon sequestration (Krueger et al., 2020). Bio-oil can be used as combustion fuel in boilers, and engines or upgraded to biodiesel for transportation fuel (Kan et al., 2016). The gases can be utilized directly for heat generation and gas power generators for electricity or to produce individual gas components (Kan et al., 2016).

Considering the advantages, in comparison to other biological or physical treatment methods, the high temperature operation in pyrolysis provides highly hygienic products, and the rapid retention time of the pyrolysis process requires smaller space and size of the reactor (Krueger et al., 2020). In addition, the storage, transport, and usage of the pyrolysis products are also simplified by its reduced volume and biochemical stability (Krueger et al., 2020). When it comes to the challenges, the process is energy intensive due to high temperature operation. There is a need for flue gas treatment for carbon monoxide and particulate matter. The potential formation of organic contaminants such as polycyclic aromatic hydrocarbons (PAHs) in biochar also needs to be considered. Other barrier is the undesirable properties of bio-oil which induce costly and complex upgrading efforts. (Lohri et al., 2017)

3.1.3.2 Gasification

Gasification is the partial thermal decomposition process under oxygen-deficient conditions to convert carbonaceous feedstocks into gas that can be burned for fuel usage or further chemical production. The main difference between incineration and gasification is that incineration oxidizes the carbon and hydrogen completely into carbon flue gas and water to release heat by breaking the chemical bond while gasification packs energy into the chemical bonds in the gas by stripping away carbon from feedstock into fuel syngas. (Basu, 2013b)

The input materials for gasification are dry BSWS with a moisture content of 10-20% or pre-treatment is needed to dry the input (Ahmad et al., 2016). The most prevailing material for gasification is wood or wood pellets resulted from densification to improve the energy value. Other suitable BSWS are peat, agriculture residues and black liquor (by-product of the paper industry) (Kirkels & Verbong, 2011).

The gasification process involves the complex thermal and chemical breakdown of organic matter into gases under a deficient oxidizing environment (limited air, oxygen, or steam) and temperature between 700-1000 °C (Fodor & Klemeš, 2012). In typical gasification, drying is the first treatment and it is followed by thermal degradation or pyrolysis that breaks down large hydrocarbon material into gas, solid, and liquid. These compounds continuously react among themselves and the partial oxygen during several oxidation and reduction reactions to generate the final syngas. (Basu, 2013b)

The output of gasification is the syngas containing incomplete oxidized products. The gas mixture contains carbon monoxide, hydrogen, methane, carbon dioxide, light hydrocarbons such as ethane and propane or heavy carbons such as tars (Arena, 2012). Other by-products which can be formed are hydrogen sulphide, nitrogen, and hydrogen chloride (Molino et al., 2016). Syngas can be used in burners, boilers, steam turbines, or gas turbines to generate heat and electricity (Arena, 2012). It is also a key substance in the chemical industry to produce the synthesis of chemicals and fuels (Ahmad et al, 2016).

The benefit of the gasification process is that it requires less pollutant control. Even though the gasification process demands high energy usage, the large-scale gasifier nowadays can self-sustain by returning produced heat into the process which improves overall process energy efficiency (Song & Hall, 2020). The products are valuable to renewable energy and sustainable chemical production. The disadvantage of gasification is that it is a complex technology and highly controlled process. The development challenges are to deal with heterogenous feedstock, maximize syngas yield, and separate gas impurities and tar generation. (Lohri et al., 2017; Watson et al., 2018)

3.1.4 Summary

There are several technologies that have been developed to valorize BSWS back into the material value loop. The selection of technologies depends on the characteristics, quantity and quality of feedstocks, the specific operating conditions, processing scale and desired outputs.

In general, direct uses are the simplest way of treatments. Manure is the main input for direct land application as more than 90% of manure is directly reapplied to soils as organic fertilizer (Köninger et al., 2021). However, there are several risks of hygienization and contamination coming together with the untreated manure for direct land application and food waste for direct animal feed. Therefore, the quality of feedstocks needs to be concerned critically for these methods.

Biological methods are the popular treatments due to their almost natural processes that requires less energy. Composting and anaerobic digestion are the most popular treatments that are traditional and well-developed in various scale. Considering the separately collected municipal and industrial bio-wastes, around 71 million tons were valorized through composting and anaerobic digestion annually in Europe. Out of that, composting represents 59% treatment capacity and anaerobic digestion accounts for 41%. (European Compost Network, 2022)

Black Soldier fly Treatment is the more emerging biological treatment which has high potential for industrial application and economic success due to its high nutrient value product of larval biomass. When it comes to challenges, biological methods often take long processing time and face difficulty in microbial process control to ensure the yield and product quality.

Thermal treatment methods such as pyrolysis and gasification have faster processing time, more hygienization impact due to high temperature operation, however, it requires more energy consumption in comparison to the biological treatment. Moreover, its thermal-chemical processes may result in additional flue gas treatment which adds up to the production cost.

Overall, the main challenges of the technologies are to ensure product quality, to upgrade and remove unwanted substances products from the output to reach the desired usage level. This challenge can be traced back to the upstream process challenge of ensuring feedstock quality and pre-treatment.

The summary of the technological review including input, output, conversion process, pros and cons for circular BSWS for biogas and nutrients are presented in table 1.

Table 1. *Valorization technologies summary*

	Direct use		Biological treatment				Thermal-chemical treatment	
	Direct land application	Direct animal feed	Composting	Vermicomposting	Black Sodier Fly Treatment	Anaerobic digestion	Pyrolysis	Gasification
General	Direct spreading on the field	Direct nutrient feed to animal	Aerobic process in which microorganisms through its complex metabolic processes decompose the organic material in the present of oxygen	Biological decomposition process in which earthworm and microorganism converting organic matter into humus-like material	An emerging technology that transform organic material into insect biomass of protein and oil	Biological decomposition of both liquid and solid organic matter by microorganism in the absence of oxygen to produce biogas	Thermal decomposition of organic materials under the absent oxygen condition.	Partial thermal decomposition process under oxygen-deficient condition
Input	Manure, food waste	Food waste (vegetables, fruits)	Varied with high moisture such as food waste, agriculture waste and manure	Municipal organic waste and organic residues from industries (paper, wood and food)	Diverse: Livestock manure, food waste, vegetable waste, compost, and municipal organic waste	Varied as single or co-digestion, not suitable for lignin-based BSWS like forest residues	Dry, unmixed substances: Wood waste, paper and carboard, lignocellulosic biomass, agricultural waste	Wood and wood pellet from densification, peat, agricultural residues
Conversion	Natural aerobic biodegradation that microorganisms decompose organic material into nutrients	Utilize animal digestive system to operate as bio-processor for transforming BSWS to animal feedstock	Three main stages which are (1) mesophilic stage, (2) thermophilic stage and (3) cooling and maturation phase	Microorganism and earthworm (mostly *Eisenia Fetida*) interaction, microorganisms decompose the organic matters to prepare the feed on the earthworm	*Hermetia Illucens* larve has the appetite for decaying organic matter which is taken advantages to feed organic matter for incorporating nutrient into growing the insect biomass of extra protein and fat	Series of microbial activities: hydrolysis, acidogenesis, acetogenesis and methanogenesis	Fast pyrolysis: temperatures between 650-1000°C in seconds, Slow pyrolysis operates in longer residence times (minutes to days), temperatures 300-500°C	Under 700-1000°C, thermal degradation breaks down large hydrocarbon material into in gas, solid, and liquid. These compounds continuously react among themselves and with the partial oxygen to form syngas
Output	Soil amendment	Livestock production (meat, milk, eggs)	Compost, rich N, P, K and beneficial minerals, soil amendment and organic fertilizer	Earthworm as nutrient feed to fish and animal, vermin compost as soil fertilizer	Larval biomass, animal and fish nutrient feed, residue as soil amendment	Biogas containing methane (55–60%), carbon dioxide (35–40%) and other impure gases, biogas can be upgraded to transportation fuel, digestate can be used as fertilizer	Fast pyrolysis: main product of bio-oil and lower yield of bio-char and gas. Slow pyrolysis: into main product of biochar, gas and lower bio-oil yield.	Syngas, can be used in burner, boiler, steam turbine or gas turbine to generate heat and electricity, or use in chemical synthesis
Pros	Simple	Sustainable food waste management	Simple, low operating cost and robust technology	Shorten processing time compared with compost, low cost, simple technology	Short processing time, high nutrient conversion rate and economic attractive product	Robust, well-developed in various scale	Highly hygienic products, rapid retention time require smaller space and size of reactor	Less pollutant control, self-sustaining process by returning heat
Cons	Untreated waste may contain pathogen, heavy metal	Ensure food waste quality, infection risk, food selection for animal	Long processing, may cause odor and vermin, segregate pure organic input to yield good quality compost	Large space required, composting as pre-treatment, understand the worm life cycle	Large space, ensure larval survival rate due to the insect colony, upgrading residues	Microbial control, product quality, VFAs may cause foaming and acidic condition that inhibits microorganisms	Energy intensive, need for flue gas treatment, undesirable properties of bio-oil require upgrading	Complex technology, highly controlled process, deal with mix feedstock to maximize gas yield

3.2 Data and digitalization

Data and digitalization are the driving forces behind the “fourth industrial revolution” (Collacott, n.d.). Within the digital transformation, digitization enables the conversion and exchange of data in digital format over the interconnected network while digitalization enables the utilization of digitized data and digital technologies to augment process control and performance (Wynn & Jones, 2022). Digital technologies and services are constantly evolving and being adopted to gain more agility and insights for the decision-making process and improve the efficiency of supply chain, manufacturing process and automation in operational management. (Collacott, n.d.).

The two megatrends of digitalization and circular economy are correlated. While the world is shifting from linear to circular economy practices, data unavailability and lack of integration are the issues that hinder the ecosystem levels of transformation (Chauhan et al., 2022). Digitalization can help bridge the transition gaps by the effective utilization of data and digital technologies (Chauhan et al., 2022). According to a study from Deloitte, digitalization can spark the transition toward circularity through 7 recipes: 1. Understand, 2. Focus, 3. Rethink operation, 4. Connect, 5. Create and sell an experience, 6. Communicate and empower, 7. Learn and adapt (figure 5).

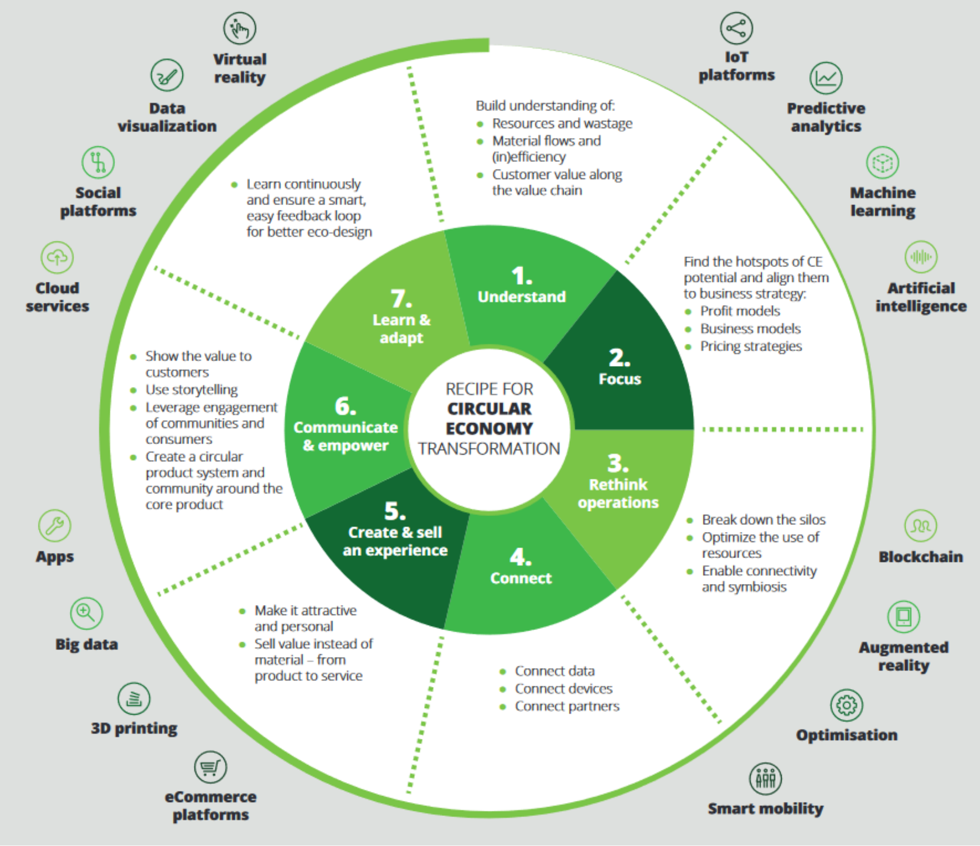


Figure 5. *Digitalization recipe for circular economy (Deloitte, n.d.)*

The continuing sections introduce some digital applications and the emerging technologies: artificial intelligence and blockchain in circular bioeconomy transition.

3.2.1 Digital platform

Under the recipe 5 (create and sell an experience) of the digitalization recipe for CE transformation from Deloitte, eCommerce platform is a digital marketplace to buy, sell or exchange materials with the aim to retain value, upcycle product and reduce waste generation. As an example of digital platform to support circular bioeconomy practices, “Materiaalitori.fi”, managed by the Finnish Ministry of Environment and Motiva, is an eCommerce platform for trading broader waste and side streams in general. In addition to that, users of Materiaalitori.fi can also search and offer related waste management services of logistics and experts (Materiaalitori, n.d.). This digital market promotes the utilization of secondary materials and help create a resource map of material flow and its supply and demand (recipe 1 – understand) for further circular bioeconomy strategic development. As illustration, under Materiaalitori.fi, there are data visualizations (recipe 7 - learn and adapt) to map out the supply and demand and geological statistics about material flow. This information and understanding of material flow are very crucial for building plan for new biorefinery facilities, reducing logistic and supply constraints, and making the best out of secondary materials.

Under the recipe 3 (rethink operation) and receipt 1 (understand), smart waste management are the digital optimization in the use of resources in waste collection and transportation efforts. For example, “ConnectedBin” is a start-up company that develops and supplies IoT platform for waste management. Their initiative utilizes the sensor device attached to the waste container to send real-time information of waste monitoring to the IoT platform (ConnectedBin, n.d.). Through the IoT platform, waste collectors can access all data (waste segregation and its quantity, location, waste filling level, waste collection time, and frequency) to determine optimum waste collection and transportation route schemes. Moreover, through waste monitoring, further data analytics can be conducted to determine waste container distribution plans to optimize container value and waste process. Smart waste management also supports the introduction of PAYT (Pay-As-You-Throw) strategy for better waste monitoring to charge people accordingly (SENSONEO, n.d.). Consequently, it incentivizes people to produce less waste.

3.2.2 Artificial intelligence

Artificial intelligence is defined as the machine ability to perform the work that normally demands human intelligence. AI function depends on the large dataset, algorithm, and advanced data analytics to recognize the patterns and trends that can be turned into automated actions. (Hedberg & Šipka, 2020)

Under the recipe 2 (focus), AI can be deployed to find the hotspots of circular economy potential to improve circular design, revise circular business model and optimize circular operation. Considering circular bioeconomy, Ellen MacArthur Foundation and Google study has proved that AI deployment can help avoid food and agriculture waste and valorize the unavoidable food waste and by-products in the vision of circular agriculture and food system (Ellen MacArthur Foundation & Google, n.d.).

Precision farming with the backup of AI technology to visually analyze the drone or satellite images of the crop field can help farmers remotely monitor their production in real-time, track the crop growth, detect crop defects, disease, and anomalies to make the optimum decision to enhance crop yield and limiting agriculture waste (Ellen MacArthur Foundation & Google, n.d.). “Atfarm” is a digital platform for precision farming which has been developed by Yara company. It combines the AI analytics and satellite image for remote crop monitoring. Besides precision farming, Yara develops its own N-sensor devices and technologies that can measure nitrogen content of the crop on field and update that information on the digital monitoring map. This practice supports precision fertilization that helps provide the right amount of fertilizer needed for crop, enhance yield, prevent overfertilization that can cause land pollution, reduce fertilizer waste. (Atfarm, n.d.)

Another AI application in avoiding industrial food processing is AI-based food processing and sorting technologies from TOMRA company. TOMRA uses AI camera sensor-based solution to evaluate the food, detect and measure food, sort food based on intended use, and redirect food that is not qualified for consumer use but still has good quality to other usage to prevent food waste. (Ellen MacArthur Foundation & Google, n.d.)

When it comes to valorization of the unavoidable waste, AI application can analyze and improve the information about the composition of the BSWS. It is crucial to understand the nutrient content and the presence of micropollutant to valorize BSWS in the right way and provide it to the right market. “Underworlds” is the smart sewage monitoring platform developed by Massachusetts Institute of Technology. It combines physical infrastructure of biochemical monitoring and AI to illustrate and act on measurement insight about composition and pathogen level in sewage. It then facilitates the valorization of safe-quality sewage for agriculture use and regenerative food production (Ellen MacArthur Foundation & Google, n.d.)

3.2.3 Blockchain

Blockchain is a decentralized distributed ledger for recording, sharing data and making transaction secure. Information is uploaded and stored in single blocks that together form a blockchain. The sharing of data block through the blockchain are only made available to those with access. (Hedberg & Šipka, 2020)

Under the digitalization recipe 3 (rethink operations), blockchain shows great potential in improving transparency for value chain operations by connecting data across the value chain (recipe 4 – connect) and empowering the communication between stakeholders across the value chain (recipe 6 – communicate and empower). These practices can help tackle the circular economy transition barrier of lacking integration and data availability.

As a good practice, “Circularise” is a blockchain-based supply chain traceability platform. Besides being a platform for gathering material flow across the value chain, they are partnering with ISCC (International Sustainability and Carbon Certification) to develop the blockchain application in a mass balance scheme for sustainability credit verification.

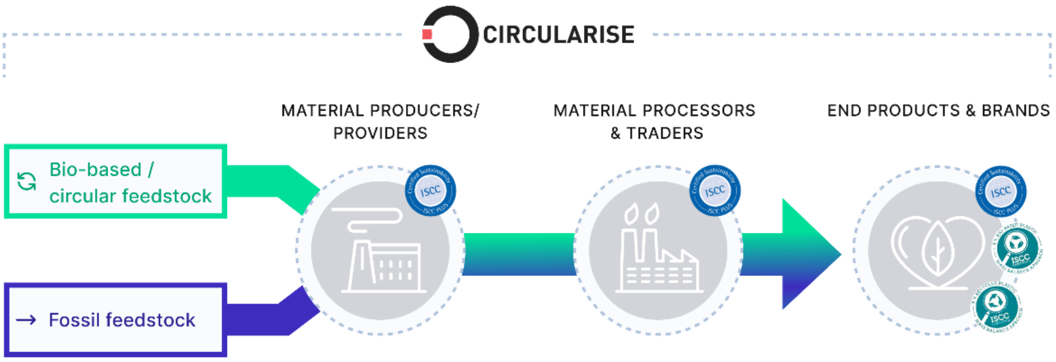


Figure 6. *ISCC mass balance scheme (Circularise, 2022)*

Mass balance scheme is the initiative to measure sustainability performance based on the mass balance of the material flow across the value (figure 6). It is hard to determine the sustainable content of a single product as bio-based and circular feedstock and fossil feedstock are mixed and transformed during production. However, with the mass balance between input and output, the sustainable content of the overall production can be estimated by assessing the total mass of sustainable feedstock over the total mass of products produced. The mass balance and sustainability content are calculated at every individual site across the value chain to reassure the overall sustainability assessment. For this practice, all data is uploaded to Circularise block-chain platform for bookkeeping so that ISCC can verify the circular BSWS feedstock content, sustainable performance and give sustainability certification to businesses conveniently through digital procedure.

Blockchain application helps improve the transparency of sustainability accounting, reporting and crediting process that in the end enables businesses to become more sustainable and foster the use of BSWS and circular solutions. (Circularise, 2022)

Other blockchain application supporting circular economy is digital product passport. Company "Minespider" is developing the blockchain-secured digital identification of product. People can access the digital passport through scanning the QR code that directs to a website or mobile application. Under the digital passport, key material composition, sustainable content, its environmental footprints, compliance certificate, recycling information are traced across the value chain. This practice enhances transparency to support circular material use and communication of recycling or possible reserve logistics between the producer and user that further supports sustainable production and consumption. (Minespider, n.d.)

3.2.4 Summary

The summary of the data and digitalization review is presented in table 2.

***Table 2**. Data and digitalization summary*

	Application	Opportunities	Challenges
Digital platform	eCommerce	Connect sellers and buyers, promote the BSWS utilization and income generation, help create a resource map of material flow and its supply and demand	Data protection and privacy Digital infrastructure Digital adaption
	Smart waste management	Support waste monitoring, data analytics to optimize waste management practices, contribute to Pay-As-You-Throw scheme	
AI	Precision farming	Monitor plant production in real-time, track the crop growth, detect crop defect, disease, and anomalies to make optimum decision to	Data quality and accessibility

		enhance crop yield and limiting agriculture waste	Standardize data as desired input for AI processing Highly skilled capability to develop and adopt AI
	Food processing and sorting	Evaluate food quality, sort food based on intended use, and redirect food that is not qualify consumer use but still has good quality to other usage to prevent food waste	
	Smart sewage monitoring	Act on measurement insight about composition and pathogen level in sewage and facilitate the valorization of safe quality sewage	
Blockchain	Supply chain management	Improve material traceability, find the hotspot for circular development, sustainability accounting and crediting	Ensure reliable data input Lack of regulations and standards for development
	Digital product passport	Improve the transparency on product, circular material usage and recycling information, support sustainable consumption	

Data and digitalization applications have the potentials to leverage circular bioeconomy through process optimization, sharing of information, connecting data, devices, and stakeholders in isolated parts of the value chain to implement the circular design and solutions. Digital platforms can help build an understanding of BSWS flow and customer value along the value chain to develop the circular strategy for CBE deployment. Despite advantages, digital transformation in circular bioeconomy transition is adopting slowly as it faces many challenges in terms of data protection and privacy, building digital infrastructure, social resistance to the new digital technologies, capacity building for digital adaptation and economically viable issues. As an illustration, selling, donating, or exchanging secondary products in eCommerce platform can be unattractive to businesses and individual sellers if they are charged with value added tax and service fee. (Hedberg & Šipka, 2020)

AI with advance monitoring, evaluation and decision-making can enhance process optimization through automation, determining hotspots of circular potentials and early detection of failure to avoid the generation of BSWS and valorize the unavoidable BSWS. The challenges associated with AI development are the flow and quality of data. AI is built on data; however, data are not always available due to restrictions on General Data Production Regulation (GDPR) on data flow. In addition, data are not always standardized as a digital input for AI use, low input data quality can lead to poor AI performance. Another challenge is the requirement of high expertise to develop and adopt AI technologies. (Hedberg & Šipka, 2020)

Blockchain can accelerate circular bioeconomy when applied to BSWS value chain management, bio-based content crediting, and improving transparency of product origin that can further support eco-design and labeling of bio-based materials and products. On the other hand, the challenge for blockchain applications can be their energy-consuming operation. Recently, blockchain is evolving and the current revolution can operate with less energy and the follow-up environmental impact. Other challenge is to ensure data reliability as blockchain is typically dependent on human input to intake data and cannot assess its quality of it. Therefore, the information uploaded must be accurate through the whole blockchain. As a common understanding of blockchain is still lacking, there is a lack of standards and rules for blockchain development. (Hedberg & Šipka, 2020)

4. POLICY AND LEGISLATION REVIEW

This chapter reviews CBE related policy and legislation landscape at European and Finnish levels to figure out how regulations can enable, promote, or inhibit CBE implementation. Before going into the review, the legislative terms are explained below.

- Regulation is a binding legislative act that must be applied entirely across the Europe (European Union, n.d.).
- Directive is a legislative act that sets out the target that all EU countries must achieve. On the other hand, it is up to the individual countries to set up their own binding laws to reach that target (European Union, n.d.).
- Strategy is the political goal that outlines the future vision and resource needed to reach the targets. It can be developed further into policies, actions, and initiatives (Elyea, 2022; European Commission, n.d.-d).
- Action plan is the set of programs, activities, allocation of resources and timeline to reach the desired goals (Elyea, 2022).
- Roadmap is the strategic action plan which defines goal, desired outcomes and includes action steps and milestones needed to achieve it (ProductPlan, n.d.).

4.1 European policy and legislation

The European Green Deal is the set of policy initiatives from the European Commission with the goal of making European the first climate-neutral continent by 2050 (European Commission, n.d.-a). The European Green Deal sets up the standards, regulations, strategies for actions to achieve its goals in 9 crossing-cutting themes (energy, climate, environment and oceans, agriculture, transport, industry, research and innovation, finance and regional development, new European Bauhaus. Among it, the environment and ocean, energy and agriculture are the most related themes to CBE.

Under the environment and ocean theme, the circular economy action plan (CEAP) adopted in 2020 determine legislative and non-legislative actions to promote circular economy through the whole product life cycle from sustainable design, processes, consumption, and resource recovery. Food and nutrients are among the focused value chains for CEAP which directly promote CBE development. As an illustration, CEAP proposes to set a target on food waste reduction, develop an integrated nutrient management plan to ensure a more sustainable application of nutrients, and stimulate the markets for recovered nutrients (European Commission, 2020a).

Other indirect CBE promoter within CEAP is the proposal of Eco-design for Sustainable Products Regulation (ESPR). ESPR proposal published in 2022 is developed based on the existing Eco-design Directive (2009/125/EC) (European Commission, n.d.-b). The new ESPR will allow for a wide range of circularity requirements rather than only energy like the old one, such as sustainable content, resource efficiency, carbon and environmental footprints and digital product passport (European Commission, n.d.-b). ESPR can ultimately promote the utilization of BSWS and its valorized products for sustainable design, production, and consumption.

Under the same theme, Waste Framework Directive (WFD) (2018/851/EU) makes all member states legally binding to separate biowaste at the source for collection by 31 December 2023 (Favoino et al., 2020). In addition, WFD requires at least 55 percent the municipal waste must be recycled by 2025, with the increase to 60 percent by 2030 and to 65 percent by 2035 (European Commission, n.d.-f). As biowaste is the main composition of municipal waste generation, these practices drive CBE transition by improving biowaste separated collection for further utilization. Furthermore, WFD lays down the End-of-waste criteria which defines when waste ceases to be waste and becomes the product or secondary materials. According to Article 6 (1) and (2) of the WFD, certain specified waste ceases to be waste when it has undergone a recovery operation and complies with existing legislation and standards applicable to products (European Commission, n.d.-f). The mandate to set End-of-waste criteria was introduced to foster material circularity. Set of End-of-waste criteria for priority waste streams such as iron, steel, and glass have been laid down while for BSWS are still lacking (European Commission, n.d.-f; Urban Agenda for the EU, 2020).

Under the energy theme, Renewable Energy Directive (RED) (2018/2001/EU) sets up binding renewable energy target of 32% by 2030 which was proposed in 2021 to 40% (European Commission, n.d.-c). Biomethane plays important role in contributing to this target by generating heat and electricity. Hence, the CBE of BSWS recovery to biomethane will be promoted. However, there is an inhibited factor about RED that biofuel production from raw biomass and energy crops may be exploited to meet renewable energy goals. In the meanwhile, CBE aims to reduce direct biomass use for energy and to focus more on cascading of biomass (Stegmann et al., 2020).

Under the agriculture theme, the Farm to Fork Strategy builds up the sustainable food system scheme. It targets to increase organic farming to 25% of total farmland by 2030, to reduce 50% of the use of chemical and hazardous pesticides by 2030, to reduce nutrient losses by at least 50% to ensure soil fertility by 2030, and reduce fertilizer use by at least 20% (European Commission, 2020b). These practices support the nutrient recovery from BSWS as fertilizer and soil amendment to fulfill the targets.

Before European Green Deal, the earlier European Bioeconomy Strategy 2018 focused on strengthening and scaling up the bio-based sector by launching a €100 million Circular Bioeconomy Thematic Investment Platform for research and development and to bring bio-based innovations into the market. It spreads bioeconomy through strategic deployment agenda for sustainable food, forestry and bio-based product, and bioeconomy innovation in local areas. It creates guidance to understand the ecological limitations of the bioeconomy and operate bioeconomy within safe ecological boundary. (European Commission, 2018)

In the version approved in July 2022 of Fertilizing Products Regulation (2019/1009/EC), the market for bio-based fertilizer and the organic-mineral mixing fertilizer have been opened to trade freely in European (Fertilizers Europe, 2022). In addition to that labeling for wide range of bio-based fertilizers, rules on safety and quality are also provided. It is a movement to legalize the market for BSWS recovery products, through that, business activities can be improved and BSWS recovery practices can be fostered. However, this new regulation is unharmonized with the existing animal by-product regulation in terms of allowing manure recovery products on the market. Indeed, Animal By-products Regulation (1069/2009/EC) strictly regulates the manure derived product’s access to the market while the Fertilizer Products Regulation opens the market for bio-based municipal waste which contains an inevitable amount of manure (Urban Agenda for the EU, 2020).

The Animal By-product Regulation could inhibit the market placement of bio-based digestate without considering the sanitizing effects of various processing methods. It does not take into account the technology innovation to safely treated and recovered animal by-products which can be the barrier to market and technology developments of strictly regulated BSWS like manure. (Urban Agenda for the EU, 2020)

Despite the legislative driver effort, high taxation on personal income, labor cost, and VAT on products are the economical inhibitor that makes circular products and services cost more significant compared to traditional raw material production. This demotivates the CBE market transformation from traditional linear production. (Pantzar & Suljada, 2020)

The possible solution for this issue is the Environmental Fiscal Reform (EFR) proposed by European Environment Agency since 2010. It aims to make CBE practices economically attractive and enhance CBE development by reducing taxation on labor and investment in the circularity field (income tax and corporation tax) and shifting the tax to the production and consumption of unsustainable practices. Another target of EFR is to remove subsidies for fossil fuels and use that revenue to support circular-based materials and fuel (European Environment Agency, 2013). However, this EFR practice is lacking in official binding for European and national legislations.

Furthermore, even though legislations support waste reduction, the critical sustainability issue of the linear economy relating to the extraction and processing of raw materials remains unaddressed in mandatory legal (Johansson, 2021).

4.2 Finnish policy and legislation

Considering the national level, Finnish roadmap to a circular economy 2016-2025 is the world’s first national circular economy roadmap published in 2016. It points out initiatives to grow circular economy in 5 areas (sustainable food system, forest-based loops, technical loops, transport and logistics, and common action) in which sustainable food system and forest-based loop are dedicated to CBE development. In 2019, road map 2.0 is upgraded as it brings the whole stakeholder value chain into action to develop the predefined 5 circular economy growing areas. (Sitra, n.d.)

In addition to the roadmap, the Finnish Ministry of the Environment adopted the strategic programme for circular economy in 2021 with the goal of transforming Finnish economy into circular economy principles by 2035. The program is guided by 3 objectives: ‘The consumption of non-renewable natural resources will decrease, and the sustainable use of renewable natural resources may increase to the extent that the total consumption of primary raw materials in Finland in 2035 will not exceed what it was in 2015’; ‘The productivity of resources will double by 2035 from what it was in 2015’; ‘The circular material use rate will double by 2035’. (Finnish Ministry of the Environment, n.d.)

The roadmap and strategic program promote CBE under the overarching of CE through strategic actions in cross-sectoral approach to develop circular business model, decouple economic growth and well-being from the wasteful use of natural resources, improve resource efficiency and adopt intelligence-based digital solutions.

In 2022, the latest adopted Finnish Bioeconomy Strategy 2022-2035 dedicates to more than a bioeconomy with the vision towards circular bioeconomy. The main objectives of the Bioeconomy Strategy by 2035 are to double the value added of bioeconomy, to increase resource efficiency and recycling rate, to reduce dependency on fossil fuels with bio-based alternatives, to utilize BSWS and adopt circular economy operating model. (Bioeconomy, 2022)

The reform of Finnish Waste Act (646/2011) is stepping towards circular bioeconomy promotion. The amendment to the Finnish Waste Act (438/2019) obligates waste holders who need municipal secondary waste management services (management of waste that does not fall into municipal waste collection schemes such as agriculture, forestry, animal husbandry side and waste streams) worth more than 2000€ per year to use the Materiaalitori.fi (Materiaalitori, n.d.). This regulation practice promotes the trading of BSWS and increase transparency by mapping BSWS resource and their supply and demand through a digital platform to accelerate the CBE transition.

Finnish Ministry of the Environment is continuously developing a Government Bill amending the Finnish Waste Act (646/2011). Government Bill draft sets a new goal of reusing or recycling 55% of municipal waste by 2025 and 65% by 2035 which aligns with the European WFD (Snellman, 2020). The Government Bill also proposed a change to centralize the waste collection and transportation to the municipality which means waste collection and transportation could no longer be organized by the waste holder. This waste management centralization attempt is good for optimizing the logistics and collection system for better treatment and valorization practices. (Snellman, 2020)

Finland is a developed country with high personal income tax. Finnish VAT are at 24%, the fifth highest rate among the EU Member States (Ministry of Finance Finland, n.d.). Finnish corporate tax was at 20% in 2021, which is still significant but a good rate when considering that the European Union average is 21.9% (Saldo, 2022). The high taxation may lead to economical constraints in competing circular practices with traditional linear practices. This impact may be lowered when operating at corporate scale

4.3 Summary

The summary of the policy and legislation review is presented in table 3. The regulation is placed within 4 categories based on their impact on CBE development. The 4 categories are driver, inhibitor, both driver and inhibitor, and missing factors.

***Table 3**. Policy and legislation review summary*

	Regulation	Content	Impact
Driver	EU Circular Economy Action Plan 2020	Food and nutrient as focus circular value chain, food waste reduction target, integrated nutrient management plan	Enhance circular food system and nutrient recovery

	Upcoming Ecodesign for Sustainable Products Regulation	Circularity requirement of product design (sustainable content, environment footprint, digital product passport)	Sustainable design that boosts the use of BSWS products and recycling at the end
	Waste Framework Directive (2018/2001/EU)	Mandatory biowaste separation and collection by 2024, 55% of municipal waste recycled by 2025	Boost biowaste collection and recovery
	Farm to Fork Strategy	25% organic farm by 2030, reduce fertilizer use by 20% by 2030, reduce 50% nutrient loss in soil by 2030	Boost BSWS recovery as organic fertilizer and soil amendment for organic farming
	EU Bioeconomy Strategy 2018	Launching a €100 million Circular Bioeconomy Thematic Investment Platform, sustainable food, forestry, and bio-based product	Finance CBE innovation and market adoption Promote the utilization of BSWS and circular bioeconomy operation
	Finnish Circular Economy Road Map 2019	Sustainable food system and forest-based loop	Improve food and forest based BSWS recovery
	Finnish Strategic Programme for Circular Economy 2021	Decrease raw material extraction in 2035 to 2015 level, double resource efficiency, double circular material use rate by 2035	Improve BSWS product as circular material use
	Finnish Bioeconomy Strategy 2022-2035	Double the value added of bioeconomy, increase resource efficiency	Promote the utilization of BSWS and circular bioeconomy operation
	Finnish Waste Act (438/2019)	Obligate waste holders who need the municipal secondary waste management service worth more than 2000€ per year to use the Materiaalitori.fi	Promote BSWS trading for better resource recovery and transparency in BSWS flow and management
	Government Bill amending Finnish Waste Act	Centralize waste collection and transportation to	Optimize waste transportation for centralized recovery practices
Inhibitor	Animal By-product Regulation (1069/2009/EC)	Does not consider sanitising effects of various manure processing methods and technological innovation	Strict requirements for products derived from animal by products, inhibit the placement on the market of bio-waste based digestate
	Income and corporate tax	Tax on labor cost for CBE operations	Make the use of raw material cheaper than CBE recovery practices, make CBE unattractive to get people involved
	VAT	VAT on CBE products	
Both	Fertilizing Products Regulation (2019/1009/EC)	Open the single market for bio-based fertilizer to trade freely in EU, provide labelling for wide range of fertilizing products such as organic fertilizers, organo-mineral fertilizers, growing media or bio-stimulants, provide rules on safety and quality	Improve BSWS recovery fertilizer production through market development. However, it is unharmonized with animal by product law in term of strict manure content

	Renewable Energy Directive (2018/2001/EU)	32% of renewable energy production by 2030	Boost BSWS recovery as biogas and biofuel but can exploit raw biomass usage for renewable production
Missing	Virgin material	Binding legislation on reducing raw material use	Boost BSWS products as raw material alternative
	Environmental Fiscal Reform	Decrease tax (VAT, personal and corporate tax) for circularity practices, remove subsidy for fossil fuel	Make CBE practices economically attractive
	End-of-waste criteria	Lack of End-of-waste criteria for BSWS	Boost the recovery and placement of BSWS products on the market as they are not considered as waste anymore

From the policy and legislation review, many regulations have been enacted and developed with goodwill to promote circular bioeconomy. Within that, the RED and WFD are the critical ones that support the circular bio-based side and waste streams for biogas and nutrient recovery. The promising regulation is the awaiting Eco-design for Sustainable Products regulation and its labeling scheme. Bio-based labeling and eco-design criteria can be expected to revolute the transition to circular bioeconomy from the upstream of the value chain which is designed for sustainability. Moreover, digital product passport, the instrument proposed together with the upcoming Eco-design for Sustainable Products Regulation with the aim to improve product transparency and the promotion of Materaalitori.fi, the e-marketplace for BSWS in Finnish Waste Act open the door for data and digitalization innovation to support CBE transition.

When it comes to the barriers, the harmonization between new regulations and existing ones needs to be concerned as the conflict of Fertilizer Products Regulation and Animal By-product discussed above. Considering technological innovation to boost the recovery and utilization of strictly regulated BSWS is needed when enacting laws. Taxation and incentives for circular bioeconomy development are critical to build sustainable circular business model and market development of BSWS which can be supported more by regulations. The focus on reducing virgin material usage could be more concerned in regulations as virgin material extraction is a critical problem that harnesses circularity. Lastly, providing a wider framework on End-of-waste criteria for BSWS can boost its recovery and placement of its products on the market.

5. METHODOLOGY

The CBE operational environment is reflected through the literature review of technologies and regulations and stakeholder interviews of 3 case studies representing 3 CBE operational models of self-sustaining circularity, rural-urban symbiosis, and industrial ecosystem. The research workflow of the thesis work will be explained as a starting point of describing CBE operation environment research process. The description of 3 case studies where stakeholders represented is depicted in the following sections together with the stakeholder interview process and questionnaire formation. The data collection, processing, and limitation are also addressed.

5.1 Research workflow

The research workflow of the CBE operational environment study follows the sequence: (1) state-of-the-art review to determine the critical valorization and digitalization technologies affecting CBE operation, (2) policy and legislation review to define regulatory factors affecting the CBE operation, (3) stakeholder interview and questionnaire to gain insights on the practical CBE operational environment of the three case studies, (4) CBE operation environment analysis to identify the challenges and opportunities in CBE operation, (5) CBE systemic management discussion to define the operational interlinkage and stakeholder engagement in CBE transition (figure 7).

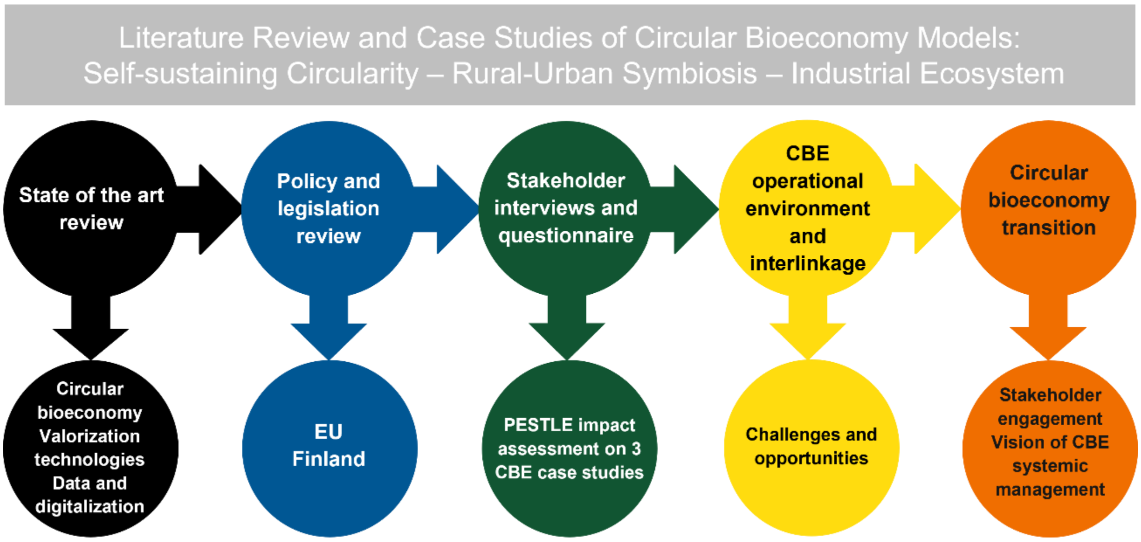


Figure 7. *Research workflow*

The literature review on state-of-the-art technologies and legislations acts as the fundamental background to develop the interview discussion and questionnaire content for the

3 case studies' stakeholders to analyze the CBE implementation in practice. PESTLE analysis was utilized to assess the CBE operational environment from different perspectives of political, economic, social, technological, legal, and environmental factors. The CBE operational challenges and opportunities are determined through literature review in addition to the validation and opinion of stakeholders within 3 case studies. Lastly, from the pieces of the 3 CBE operational models discussion, the operational environment interlinkage is drawn. The role of stakeholder engagement within the vision of CBE operation to solve the identified challenges and leverage the opportunities is discussed.

5.2 Circular operational models

The operational environment of CBE is varied from small to large scale with different treatment recommendations following the BSWS management hierarchy. Zero Waste Europe developed the hierarchy for reducing and recycling food scraps and other organic discards based on the general waste management hierarchy proposed in Waste Framework Directive. This hierarchy suggests the most preferred treatment ranging from source reduction, home-based solution to small-scale decentralized composting to large-scale mechanical biological mixed waste treatment, incineration, and landfill as the final steps (figure 8). (Zero Waste Europe, 2016)

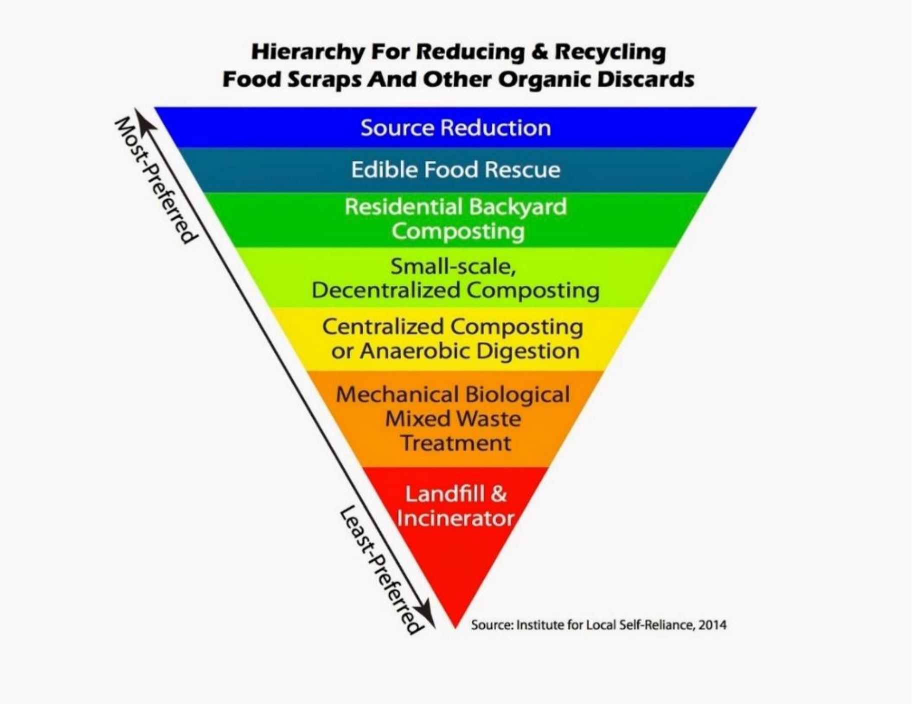


Figure 8. *Hierarchy for BSWS treatment (Zero Waste Europe, 2016)*

To realize CBE practical implementation following the BSWS management hierarchy, 3 operational models (self-sustaining circularity, rural-urban symbiosis, and industrial ecosystem) are generated to study the common and differences in operational challenges and opportunities at different scales. Self-sustaining circularity operational model is the representation of the onsite treatment such as residential backyard in the hierarchy. Rural-urban symbiosis operational models represent the small-medium scale decentralized solution for BSWS recovery. Industrial ecosystem operational model reflects the centralized solution. These 3 CBE operational models are expanded from small to large scale, decentralized to centralized solutions in terms of BSWS quantity and stakeholder collaboration (figure 9).

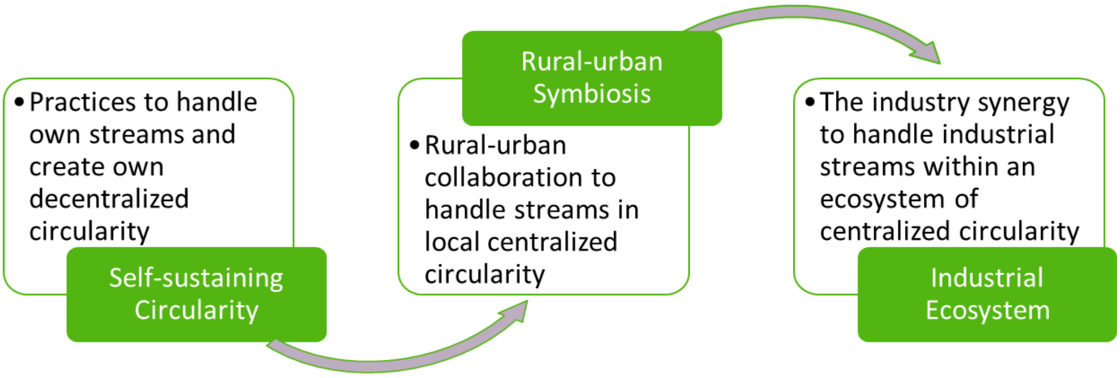


Figure 9. *Circular bioeconomy operational models*

Self-sustaining circularity is the emerging concept proposed in this thesis work to interpret the circular economy implementation that the BSWS are produced, recovered, and utilized within own production. It means the primary producers of the BSWS can sustain their own material circularity for their own usage. As illustration, household composting is an example of self-sustaining circularity in which the kitchen and food waste are composted in household's compost bin to be utilized as fertilizer for the garden. Another example is Vuorenmaa dairy farm in Haapavesi, Finland which supplies milk to food production brand Valio. The farm owns a biogas plant that can turn its cow manure into 1200 MWh of biogas annually, which is used to produce heat and electricity needed at the farm (Renewable Energy Magazine, 2020).

Rural-urban symbiosis (RUS) is the concept introduced by The Central Union of Agricultural Producers and Forest Owners in Finland (MTK). RUS is the multidimensional collaboration between the rural and urban areas that brings benefits to both parties (MTK, 2020). The elements for RUS are diverse ranging from energy, raw material to housing and tourism. Considering the CBE operation, RUS resonates on the cooperation between rural and urban actors to collect and handle large BSWS quantities in centralized practices to maximize the material circularity and bioenergy production. For instance, in Finland, the wood chips and forest residues from the rural Pirkanmaa region forests are the input to the centralized urban Naistenlahti power plant to generate heat and electricity for the urban region and national grids (MTK, 2020).

Industrial ecosystem is a web of interactions between industries where the residuals of one facility become the feedstock of another (Lowe & Evans, 1995). The CBE operation of industrial ecosystem transforms sustainable production beyond individual plant or industry into the inter-industry collaboration (Lowe & Evans, 1995). It is the broad centralized application of CBE that tackles the vast amount of industrial material flows. The industrial ecosystem synergy creates resource exchange symbiosis, material use efficiency, supports ecological resilience, and brings added profit to the companies. The first industrial ecosystem in the world is Kalundborg symbiosis in Denmark. It has been developing since 1972 and in 2022, more than 20 different streams including wastewater sludge, biomass residues are circulated among 15 companies within Kalundborg ecosystem (Kalundborg Symbiosis, n.d.).

In CBE operational environment, BSWS are circulated within these 3 operational models that initiates a closed-loop material flow and secondary material market in different scale, environment, and stakeholder involvement.

5.3 Case study description

Case study is adopted for stakeholder interview practice with the goal to study CBE within a pre-determined operational environment and stakeholder groups so that challenges and opportunities can be analyzed in specific cases. 3 case studies evaluated in this thesis work are HAMK manure hygienization project, MTK e-marketplace and ECO3 industrial ecosystem. The cases are chosen based on its location in Finland and connection to the TREASoURcE project. As all the case studies are in Finland, they are under the same operating and legislative environment so that result findings can be compared to each other to withdraw the collective understanding. Manure treatment is a big issue in Finland with large quantities and strict regulation, HAMK manure hygienization project is a promising on-site solution that has been noticed on the media. Therefore, it has been chosen for the self-sustaining circularity case study. Rural-urban symbiosis operational model is initiated by MTK, one of the project partners in TREASoURcE project. MTK is developing an e-marketplace within the TREASoURcE project to demonstrate its rural-urban collaborative model. In addition to the project partner support, studying the application of digital application in CBE development is crucial factor when choosing this case study. ECO3 industrial ecosystem is connected to TREASoURcE project on the development study and demonstration of CBE practices in Pirkanmaa region, Finland. ECO3 area with its future development and industrial collaboration expansion is then a good selection for industrial ecosystem operational model. The 3 case studies representing 3 CBE operational models and their according stakeholder interviews are summarized in table 4.

Table 4. *Case studies analysis*

CBE models	Case study	Interviewees and their organization role within the value chain
Self-sustaining circularity	HAMK manure hygienization project	1. Company developing the technology
		2. Research and education
Rural-urban symbiosis	MTK e-marketplace	3. E-marketplace developer
		Primary producer of BSWS questionnaire
Industrial ecosystem	ECO3 industrial ecosystem	4. CE platform developer
		5. Biogas buyer and fuel distributor
		6. Fertilizer producer
		7. Sustainability consultancy
		8. Waste collector and biogas producer
		9. Business consultancy
		10. Research and education

The manure hygienization project is a joint project of IPFur Consulting Oy and Häme University of Applied Sciences (HAMK). This project evaluates the operation of IPFur Consulting Oy's ManPas manure hygienization device to hygienize horse manure onsite in small scale with the production of 1.5 m^3 hygienized manure per week. The device possesses a quick hygienization method in which the temperature of the manure reaches 70°C for 1 h in accordance with the EU by-product regulation. This method can turn manure into a marketable soil improver and bedding solution for animals. The total processing time ranges from 1-4 days. This onsite hygienization practice represents self-sustaining circularity by recycling manure back into soil improver and bedding for animals within the livestock farm. (HAMK, n.d.)

“KiertoaSuomesta.fi” initiated by MTK (The Central Union of Agricultural Producers and Forest Owners in Finland) is an e-marketplace to sell and buy agriculture by-products. Within this online marketplace, BSWS producers can sell their BSWS and generate additional income while the BSWS recyclers can find the available BSWS input for their BSWS recovery practices or leave the notices of materials they need. The e-marketplace is still under development for launch. (KiertoaSuomesta, n.d.)

It represents the rural-urban symbiosis operation model because it connects the rural BSWS primary producer to BSWS buyer for recovery practices that generates added values of nutrients and energy providing to both rural and urban area.

ECO3 is a business area developing bio and circular practices at industrial scale in Nokia, Finland (ECO3, n.d.). It is developed by Verte Oy and the City of Nokia with the cooperation of 18 companies within the area and an outside network of several companies and universities. It represents the industrial ecosystem with the development concept (figure 10) as an industrial synergy for boosting the nutrient, wood, energy cycles, and improving the material flow between the companies and regional actors.

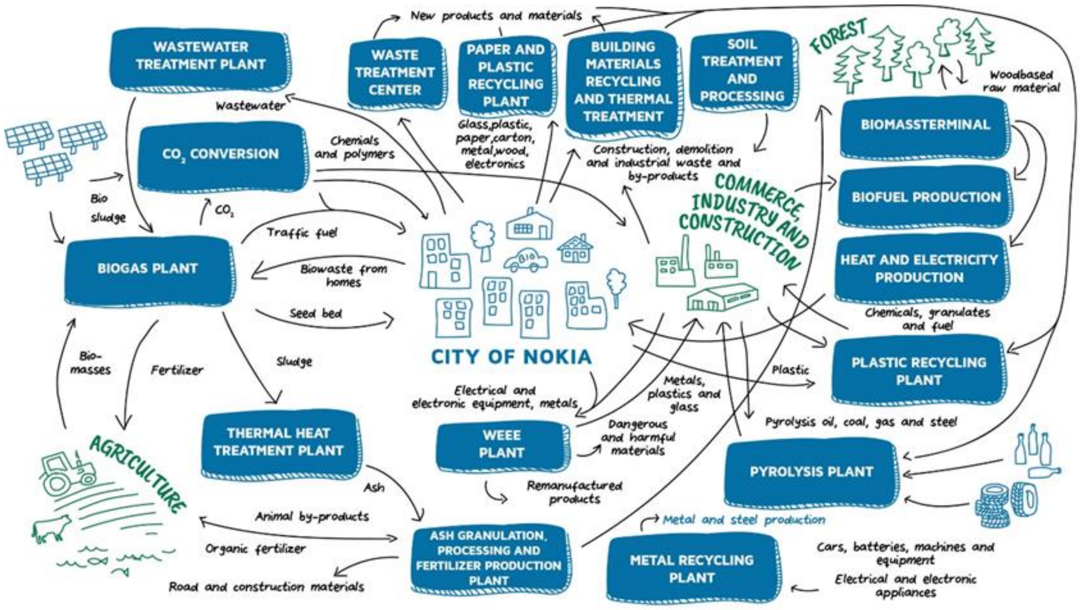


Figure 10. *ECO3 concept (ECO3, n.d.)*

5.4 Stakeholder interview and questionnaire development

The stakeholder interview structure and a part of the questionnaire were developed based on PESTLE analysis. PESTLE describes different affecting factors and is expanded as Political, Economic, Social, Technological, Legal and Environmental. Political factor concerns the influence of government (legislations, strategies, taxation) on the subject. Economic factor concerns the economic performance and market influence on the subject. Social factor concerns the social environment affecting the subject. Legal factor concerns the mandate laws and regulations on the subject. Lastly, environmental factor concerns the sustainability of the subject operation. It is the analysis concept to assess the operational environment through 6 PESTLE angles to give an overview of the picture and keep track of the development. (PESTLE Analysis, n.d.)

The interview questions are divided into 6 PESTLE categories of Political, Economic, Social, Technological, Legal, and Environmental. Under each category, there are key factors from which the questions are revolved (table 5). From the literature review finding, EU and national legislation and taxation and incentive are the two political and legal key factors to concern. To elaborate on economic factors, market creation for BSWS and cross-sectoral collaboration in circulating BSWS are concerned. Consumer awareness and job creation are the two crucial key factors to concern. Virgin material reduction needs and BSWS environmental benefits are mentioned in the literature review as critical elements to concern for environmental factors.

Table 5. *PESTLE key factors*

Categories	Key factors
Technological	Constraint
	Development
Economic	Market
	Cross-sectoral collaboration
Social	Consumer awareness
	Job and skilled labor
Environmental	Virgin material
	BSWS recovery
Legal and Political	EU/national legislation
	Taxation and incentive

The interview process is the combination of the qualitative semi-structured interview and semi-quantitative PESTLE impact assessment on CBE development. Semi-structured interview is the qualitative data collection practice by asking the questions within a pre-determined thematic framework (PESTLE framework in this thesis) while allowing interviewees to investigate different perspectives of the question (George, 2022). Semi-quantitative method means providing approximate proportion of the analyte when the exact numerical result can not be produced (Law Insider, n.d.). The PESTLE impact assessment gives an overview of the impact rating proportion based on the total number of interviewees.

The interview questions were formulated to identify the challenges and opportunities in circular bioeconomy development through 6 PESTLE perspectives and their associated 10 key factors. In addition, PESTLE impact assessment was utilized to assess the influence of the 10 key factors on the CBE development practices. After answering all questions under each key factor, the interviewees were asked to evaluate the key factor's impact on the CBE development as Positive/Negative impact and its rating Low/Medium/High or Neutral based on their own experiences and opinions (figure 11).

Figure 11. *PESTLE impact assessment scale*

The impact assessment scale implies that the higher the positive rating, the more opportunities and beneficial impact on the CBE practices. On the other hand, the higher the negative rating, the more challenges and unbeneficial impact on the CBE practices. By doing so, the PESTLE impact for each key factor can be semi-quantitatively evaluated as result. The PESTLE impact assessment result is determined based on the major proportion of the rating among the stakeholders involved in each case study. Furthermore, interviewees were encouraged to give recommendation for future development and how to overcome the identified challenges. The detailed stakeholder interview question list formation is attached in the appendix A. 9 stakeholder interviews were conducted online through Microsoft Teams and 1 interview was face to face at the interviewee's premises.

The questionnaire for BSWS primary producers were formulated in Microsoft Forms to identify the BSWS production and treatment practices and its challenges from the primary producers' point of view. In addition to that, respondents' thoughts on the e-marketplace for BSWS trading were also investigated. In the end of the questionnaire, there was a PESTLE impact rating which is the same as the one for stakeholder interview. The detailed questionnaire content is attached in appendix B.

5.5 Data collection, processing, and limitation

Data for the research was collected based on pre-generated stakeholder interview and questionnaire structure. Other relevant topics discussed during the interview and comments given through the questionnaire were noted beside the original structure. Interview answers are voice recorded through Microsoft Teams with the consent of the interviewees and transcribed for further analysis. Questionnaire results were generated in Microsoft Forms and downloaded as Excel file for further analysis.

Interviewees and questionnaire participants' personal information and contact details collected are not used for research purposes, only for communication. All published data is research data, not personal data, and any interview and questionnaire comments and inputs are anonymized and not connected to interviewees and questionnaire participants. Citation for the research data is referred as interviewee 1, 2 or 3 as listed in table 4 above. All generated data is stored in VTT secured Microsoft Teams private project workspace environment. The workspace has limited access to necessary VTT project personnel only. The main person handling the data is the thesis worker, Tran Ngo.

The data was processed by analyzing every PESTLE category to generate an overview of the case. The results are presented as the generation of PESTLE stakeholder impact assessment graph within a single case study and followed by key discussion of 6 PESTLE angles.

Since all case studies and results were collected from Finland, the data and result analysis may limit to the Finnish operational environment. The result discussion and lessons learned may not represent other circumstances and stakeholders in Europe and globally. Moreover, circular bioeconomy implementations are varied depending on single case to case. Therefore, the 3 case studies analyzed in this thesis cannot represent the whole circular bioeconomy operational environment. The number of interviewees and questionnaire respondents is small and cannot represent the whole value chain. Indeed, only 1 to 2 stakeholders were represented for 1 value chain role, in addition to their specific operational environment and individual opinions. Hence, the result reliability may have limitations to the specific cases and do not represent the overall viewpoint on the circular BSWS value chain.

Data transferability concerns the applicability of the data and results in other circumstances and geographies. As all of the case studies are located in Finland, a Nordic country within Europe, the policy and legislative environment follow the European framework in addition to the Finnish own ambitious strategy to become the circular economy pioneer. Hence, the legislative environment can be transferable between Europe. Finland has a low population of 5.5 million people and is a developed country with strength in engineering and digitalization (Finland Toolbox, n.d.). Those characteristics can make Finland more feasible to adapt to new CBE innovation socially and technically. Hence, those factors need to be concerned when transferring and comparing Finnish case study data to other geographies.

6. RESULTS AND DISCUSSION

In this chapter, the result of the stakeholder interviews of 3 case studies is illustrated under 3 operational models' viewpoints of self-sustaining circularity, rural-urban symbiosis, and industrial ecosystem. The PESTLE impact rating and the following analysis of key findings through 6 PESTLE perspectives are presented. The results are discussed in addition to the literature review of regulations and state-of-the-art technologies to identify the challenges and opportunities in CBE development. Furthermore, the interlinkage of CBE operation models in the systemic operational environment and stakeholder engagement in accelerating the CBE transition will also be addressed.

6.1 Self-sustaining circularity operational environment

HAMK manure hygienization project which recovers horse manure onsite into soil amendment and animal bedding is an example of the technological innovation for self-sustaining circularity practices. Two stakeholders coming from the company developing the ManPas device and the research and education organization in charge of the experiment participated in the interview. The general PESTLE impact rating resulted from the interview discussion is illustrated in figure 12.

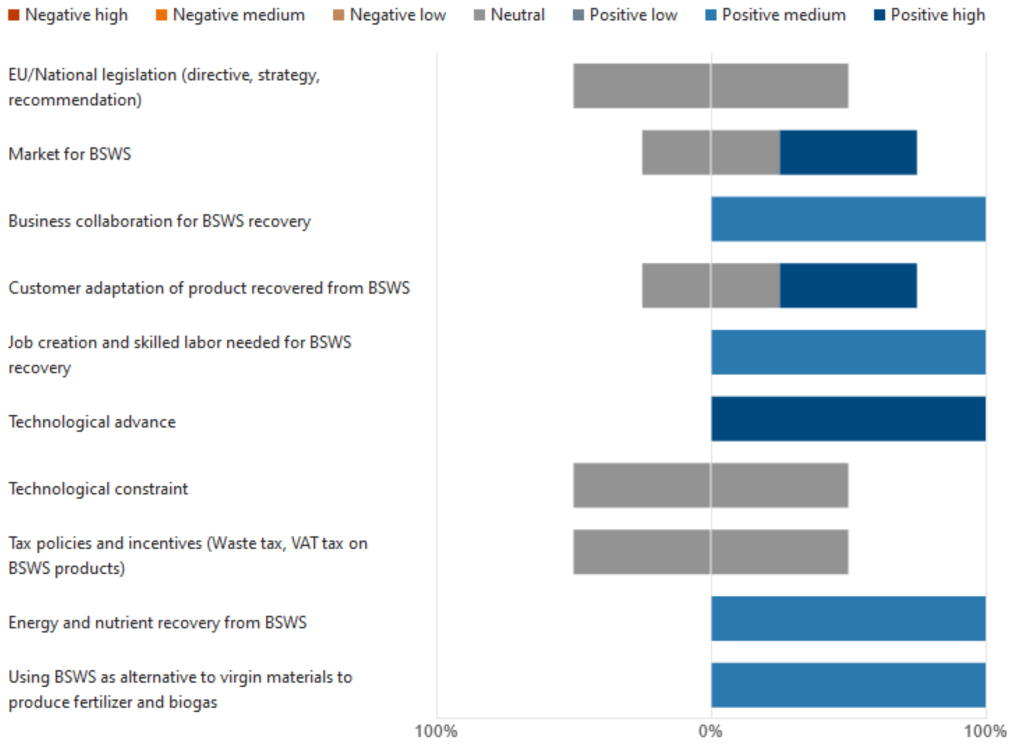


Figure 12. *Self-sustaining circularity PESTLE impact assessment (n=2)*

The general PESTLE impact assessment result through 10 key factors based on the stakeholder rating proportion is positive medium to high. The operational environment for the practice at small testing scale is in a favorable direction to develop, however, the challenge for scale-up remains, especially in technological, economic, and political factors.

As for technological factors, the initial experiment of ManPas device in treating horse manure brings a good result of short processing time, low energy consumption, and hygienized products. Considering the technological constraint factor, the challenge is to fully inactivate all contaminants and risk of microbe diseases though the risk is quite small. Interviewee 1 stated that this challenge can be solved by keeping track of animal feed to ensure the manure quality without expensive technology development. The focus on technology development is to verify process and product qualities on large scale.

Considering economic factors, the market is assessed in the positive situation as onsite treatment can save costs related to manure treatment in which high volume causes logistics costs very high for off-site treatment practices. It is not to mention the saving from manure recovered products for soil amendment and animal bedding. Interviewee 1 emphasized that although the benefits are seen, finding initial investment to adopt the innovation is an issue. These funding challenges can be greatly supported by political and legal instruments. In addition to that, the economic factors can also be improved by creating a new business model and commercializing recovery products. However, the policies are very strict on the manure derived products and require many permits for the device process operation and the product quality that could hinder the large-scale adoption of the innovation and product market entry. On the advantageous side of policy and legal factors, 50% of subsidies for machine investment will be given to the producers who participate in the experiment to adopt the device.

When it comes to the social factor, creating new jobs is a positive possibility in the case of large-scale commercialization. Consumer acceptance is good. Interviewee 2 commented that farmers are familiar with manure treatment and utilization for a long history, so they do not hesitate but the one who has concerns is the law-making people. It has both a good side of preventing manure contaminant spreading and the other side of inhibiting nutrient circularity. Hence, the result for social factors is positive and policy assessment is neutral.

The environmental assessment is high positive as onsite manure recovery with ManPas device is more ecologically friendly than offsite treatment such as manure incineration which causes greenhouse gas emission and requires chimney emission control.

Findings from this case study, the onsite innovation to valorize BSWS can generate great positive impact from many perspectives, especially in tackling the logistics problem, reducing environmental burdens, and saving money. The contamination related technological challenge can be solved by intake contamination prevention rather than finding technological cure. The main challenge for wide scale adoption is initial funding, process validation, and product entry permission in which policy and legal supports play a vital role in leveraging the circularity innovation while controlling the process and product quality.

6.2 Rural-urban symbiosis operational environment

The rural-urban symbiosis model is analyzed through the challenges in managing BSWS from primary producers' point of view and the possibility to utilize e-marketplace to circular BSWS and foster circular bioeconomy development.

The key parameters of the questionnaire respondents are presented in the figure 13.

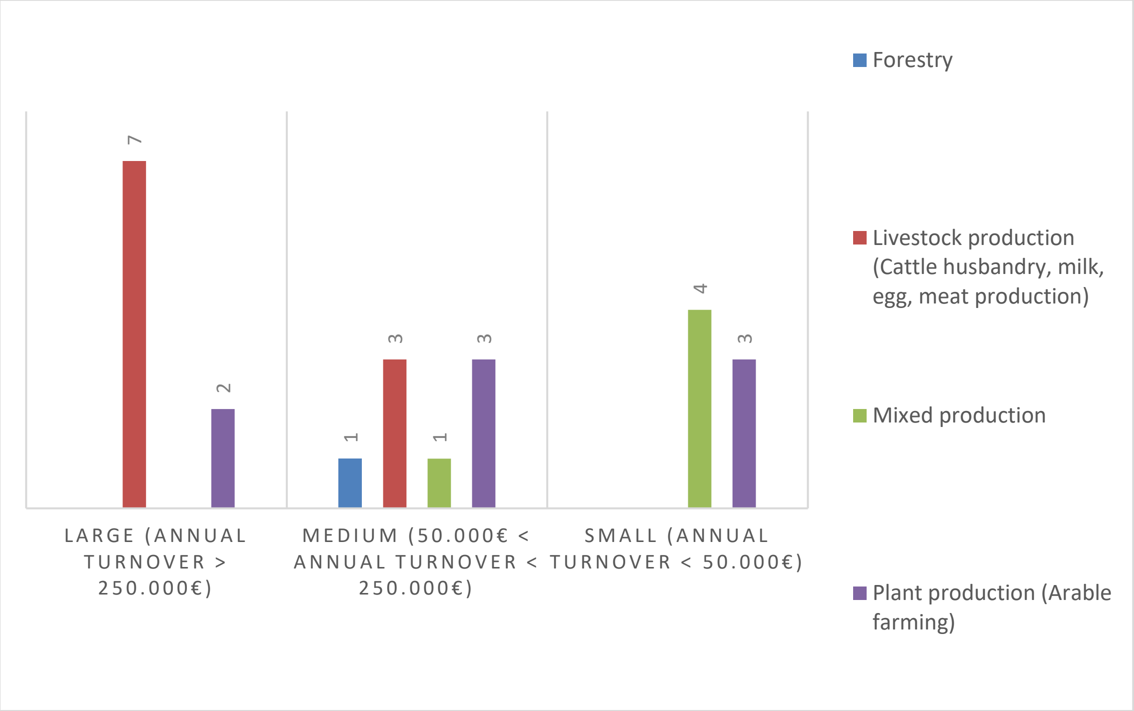


***Figure 13.** Questionnaire respondents' parameters*

In total of 28 questionnaire respondents, the dominant production lines of the BSWS producers are livestock production and plant (arable farming). Their production sizes are 39% large (annual turnover > 250.000€), 36% medium (50.000€ < annual turnover < 250.000€), and 25% small (annual turnover < 50.000€) respectively.

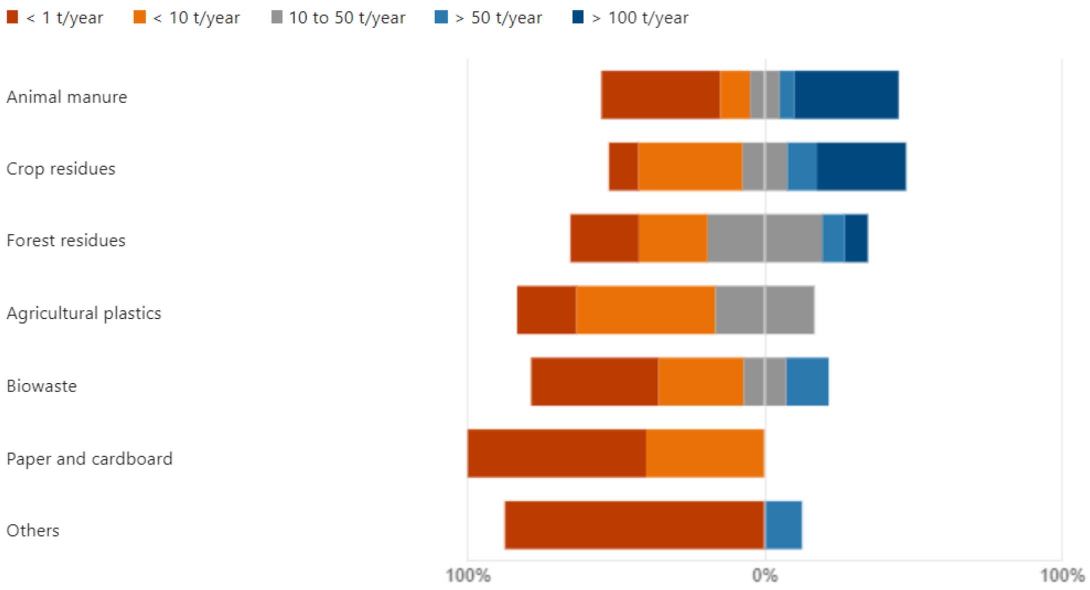


Figure 14. *BSWS production*

As a result of large production size in livestock production (figure 14), manure is the main BSWS production of the questionnaire respondents with more than 35% percent answers of more than 100 tons annually (figure 10). It is followed by crop residues with around 30% of answers producing more than 100 tons annually.

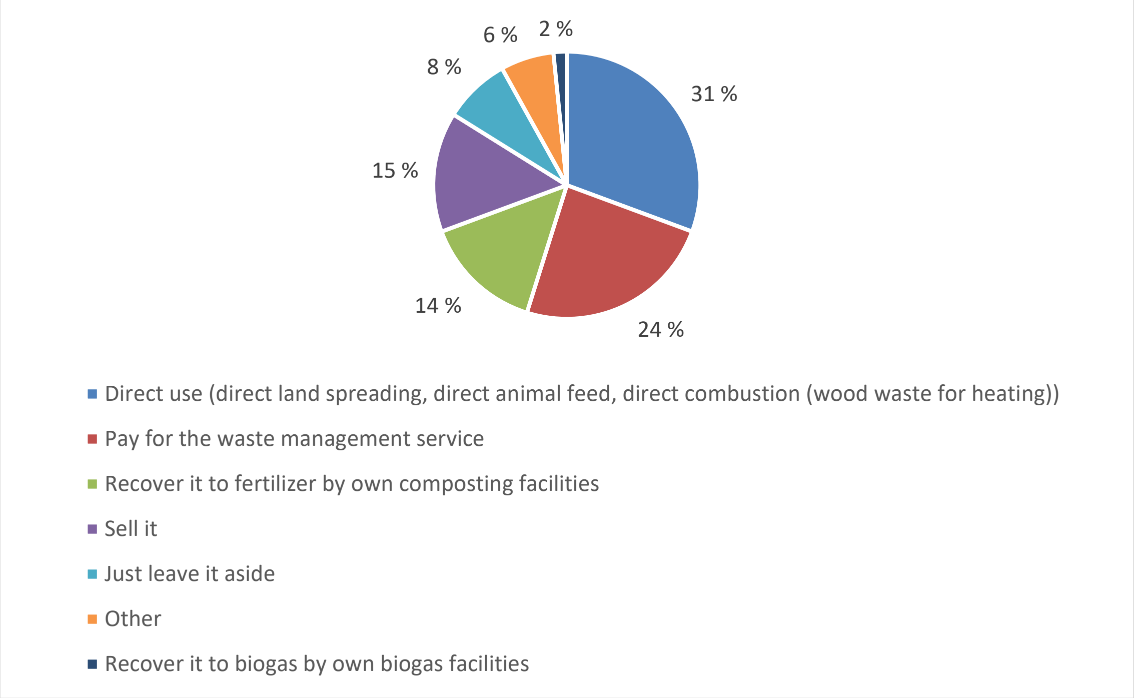


Figure 15. *BSWS treatment*

The most common treatment and recovery practices are direct use (direct land application and direct animal feed), and paying for waste management services (figure 15). The following popular choices are fertilizer recovery and BSWS trading. There are 8%

answers of leaving the BSWS aside without any treatment. Responding the question about challenge in handing BSWS with those current practices, the remarkable answers are the lack of guidance for BSWS disposal (especially agriculture plastic so it is often ended up in mixed waste), logistics obstacle in remote area, expensive BSWS management costs, making the recovery practice economically viable and discovering the BSWS market.

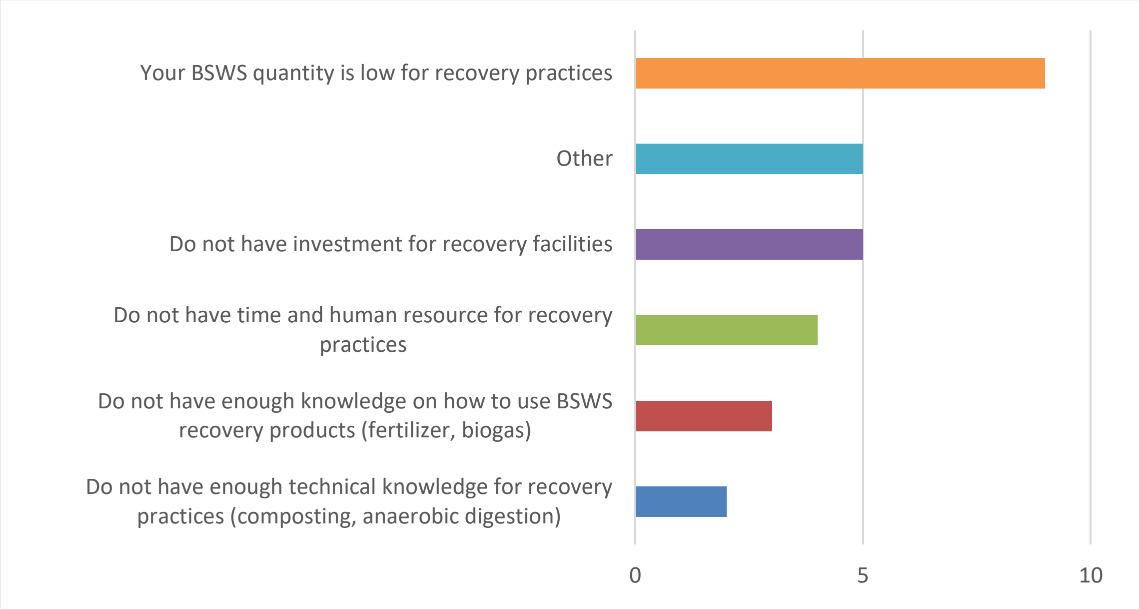


Figure 16. *BSWS self-sustaining circularity challenges*

Going further to the inhibitor factors for BSWS own self-sustaining practice and trading possibility for rural-urban symbiosis development, the main reason for not having own BSWS recovery practices is not having sufficient BSWS quantity (figure 16). It is followed by not having investment and not having enough time and human resources. In one respondent's comment, they stated that utilizing BSWS takes more resources than the benefits it creates in their case.

When it comes to selling BSWS, besides respondents who recover BSWS themselves, the noticeable hindrances are not having enough BSWS quantity to sell and not having enough buying demand (figure 17). Despite those challenges, the trading practice is still one of the solutions for 15% of the respondents (figure 15).

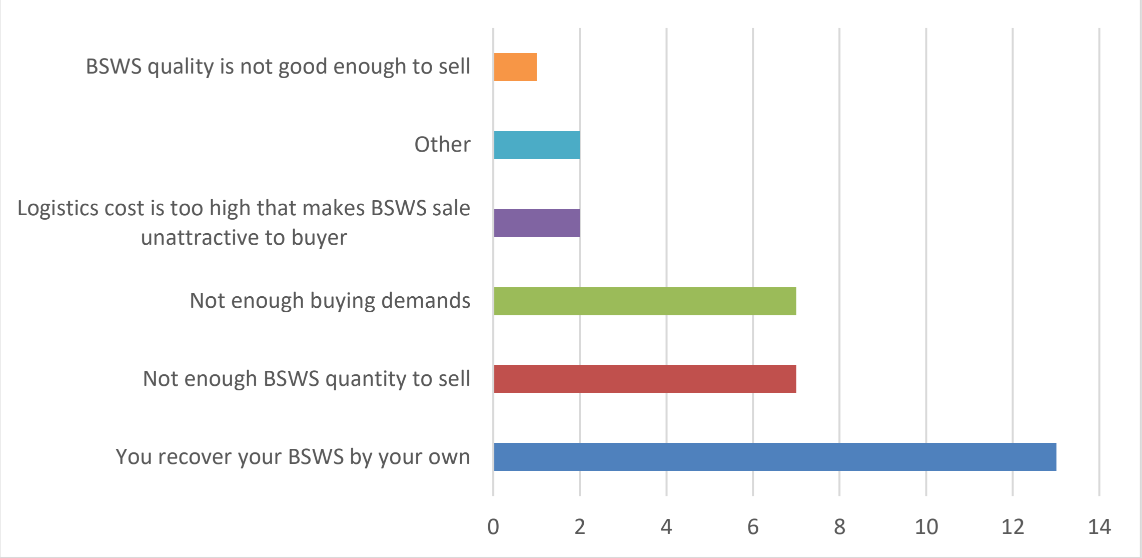


Figure 17. BSWS trading challenges

To boost BSWS circulation which implies boosting secondary material flow and recovery between rural and urban contexts, the digital solution e-marketplace has been introducing and developing for BSWS trading. Responding to the e-marketplace adaptation and hesitancy, 54% of respondents may use e-marketplace, 28% yes and 18% no. The figure 18 illustrates the questionnaire participants' hesitancy to adopt e-marketplace for selling their BSWS.

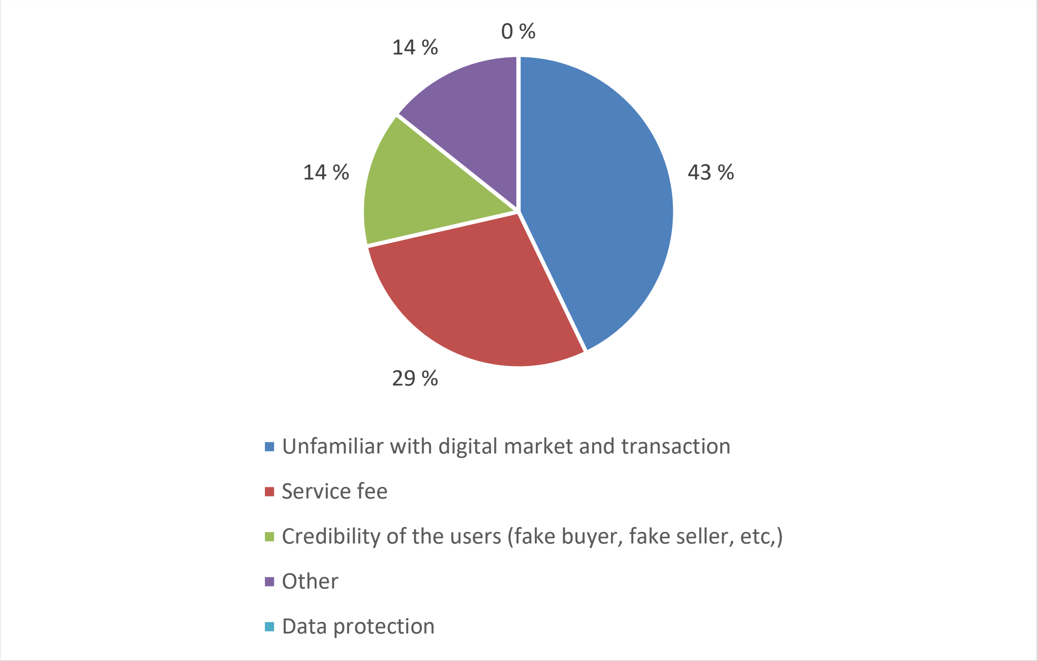


Figure 18. *Hesitancy in utilizing e-marketplace*

The main hesitancy is the digital market unfamiliarity and follows by the service fee. In other reasons, one respondent stated that the digital market and its sale competitiveness may cause negative false impression on the recovery and treatment activities. The PESTLE impact assessment results from this case are illustrated in the figure 19.

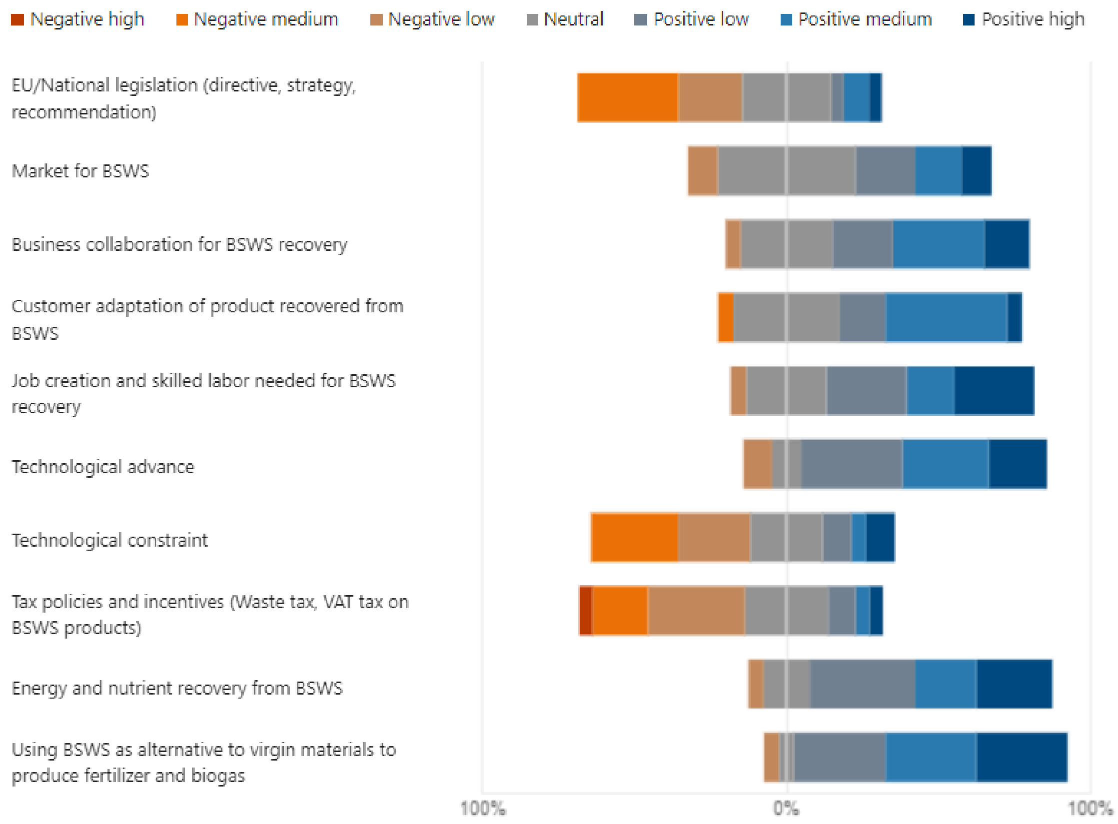


Figure 19. *Rural-urban symbiosis PESTLE impact assessment (n=28)*

The general impact assessment result based on the stakeholder rating proportion is neutral to positive low, and the noticeable negative factors are technological constraint, political and legal factors. Discussing technological constraints in rural-urban collaboration practices, interviewee 3 stated that the critical problem is logistics, feedstock quality, and quantity. To elaborate, the water content in feedstocks makes them large in volume and quantity which adds up to the logistics burden. In addition, logistics in rural areas are challenging in terms of cost and connection. According to interviewee 3, the feasible distance for BSWS transportation is under 80 km. The feedstock quality and availability are challenging since the industry demands large and high BSWS quality (dry enough, unmixed) while primary producers produce in small quantities, and it is hard to ensure the required industry quality. To solve those challenges, the recommendations are to apply drying pre-treatment and recovery onsite or decentralized local facility, build gathering terminal to collect BSWS and ensure the feedstock quality. Knowing the resource flow then is crucial to build up the logistics and local recovery facilities, which can be supported by the digital application of resource mapping through e-marketplace.

The market is a positive driver for biogas and nutrient recovery as energy and resource security are threatened by Russia’s war on Ukraine. However, the dilemma is the constraint for finding investments to develop valorization practices. It leads to the discussion of policy, taxation, and incentive factors. From the questionnaire, 93% of respondents do not receive any incentives for BSWS recovery while the cost is high to handle BSWS, whether it is paying for waste management service, own recovery operation or selling. In addition, policy restrictions on manure and sludge recovery and utilization are also mentioned as challenges.

The social factors with customer adaption to BSWS derived product and job creation from BSWS recovery practices are highly positive from primary producer viewpoint. Considering e-marketplace adaption, interviewee 3 addressed the digital unfamiliarity, traditional working practices and change resistance as inhibitors with the recommendation to raise awareness and build capacity building.

Lastly, when it comes to environmental factors, the recovery of BSWS undoubtedly brings sustainable impact. For replacing and reducing virgin materials with BSWS alternative, interviewee 3 stated that it is potential, but the current law of mixed fertilizer market entry is still going on, so it is also another regulatory barrier to boost the environment and economic factors of utilizing BSWS as raw materials. Interviewee 3 added that there may be a concern about the overproduction of BSWS to supply market demand instead of preventing BSWS generation in the first place, which are also noticed before from questionnaire respondent that the BSWS trading and recovery practices can get wrong impression because of the economic benefit and competition.

Finding from this case, rural-urban symbiosis model of connecting stakeholders to create BSWS value chain are potential where self-sustaining practice is not feasible for all. The synergy in rural-urban collaboration then becomes the solution to uptake BSWS flow in optimal way. The critical challenges for this model are ensuring feedstock quality and quantity for market demand, logistics, policy restriction, lack of funding and incentives. Making the recovery practices economically viable is the key to the circularity transition. More opportunities lay in market demand and job creation.

6.3 Industrial ecosystem operational environment

The industrial ecosystem represents industrial synergy for BSWS treatment and recovery. While self-sustaining circularity is often home-based and small-scale solutions, rural-urban symbiosis stays in local decentralized solution, industrial ecosystem is the large-scale centralized solution to handle BSWS and produce circular products in large quantities. ECO3 industrial ecosystem case study is analyzed through 7 relevant stakeholder interviews within the development area. Their PESTLE impact assessment result is illustrated in figure 20.

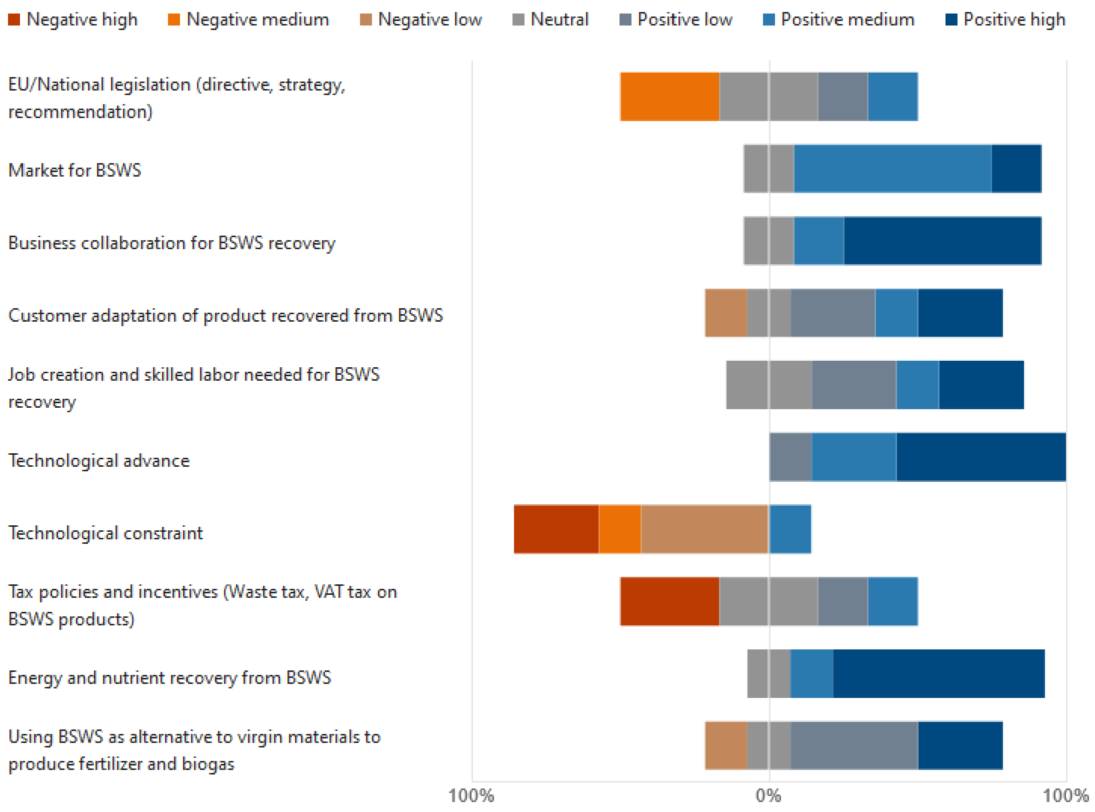


Figure 20. *Industrial ecosystem PESTLE impact assessment (n=7)*

The general PESTLE impact assessment based on the stakeholder rating proportion for this case is positive medium to high. The result shows positive high impacts in many factors, especially business collaboration, market, job creation, and energy nutrient recovery. The political and legal factors show more positive signs when compared with the two previous cases. On the other hand, technological constraint causes a significant negative impact.

Discussing about technological constraints, interviewee 8 from BSWS collection and treatment company stated that their technical challenge is to ensure product yield and quality. With composting they have extensive experience so there is not so much concern, however, for anaerobic digestion, they just adopted it for 2 years so there is a challenge to adjust the microbiological process with their feedstock. Interviewee 8 added that this yield constraint can be improved with better feedstock quality meaning better biowaste separation at source. According to the interviewee’s company statistics, there are still 37% of biowaste in mixed waste which implies better sorting is needed for BSWS value added recovery. Interviewee 10 from the research and education organization shared the same idea that the main technological challenge is product impurity (microplastic, heavy metal, pharmaceuticals) and upgrading and this challenge should be solved from the root cause which is feedstock quality with better separation and more sustainable product design. On the other perspective, interviewee 5 from the biogas buying, producing, and distributing company commented that the technical challenge is an economical challenge in their view. There is technological availability for biogas impurity removal and upgrading but it is the most expensive facility considering the whole recovery practices. Hence, the challenge within the industrial scale is then ensuring profitability and finding economically viable technical solutions.

The economic factor market is in favorable condition for biogas and organic fertilizer according to interviewee 5 – biogas producer and distributor, and interviewee 6 – fertilizer producer. Among the interviewees (7,9), there is a concern that electrical vehicles are more promoted than biogas vehicles. In corresponding to that, interviewee 5 stated that the heavy truck is the profitable market for biogas traffic fuel, and it is their focus while in passage car, the electrical vehicle dominates. When it comes to organic fertilizer produced from BSWS, interviewee 6 commented that the market sale for them is good and they export the organic fertilizer to several foreign countries. Their challenge is feedstock availability with high quality and quantity to produce more products and ensure the supply demand. According to interviewee 10, even though the market is in a good position for especially biogas production due to the war crisis, the energy price fluctuation causing market uncertainty can be a challenge for market development.

Business collaboration within ECO3 area is developing. Interviewee 9 stated that regular meetings for the industries within the area are held to define the feasible collaboration to improve the circularity. Interviewee 4, the ECO3 area developer commented that they will develop a digital platform to keep track of the innovation and share information to boost collaboration since industrial synergy is the key to the area development.

When it comes to political and legal factors, the industries rate it more positive than education and consultancy. Interviewee 5 stated biogas was introduced into the blending mandate of 12% biofuel for energy production in Finland, which has helped company to sell extra ticket of bioenergy to the other energy production and increase the profit. However, energy tax was added for biogas traffic fuel usage recently while it is still tax free for other industrial energy usage. For organic fertilizer, interviewee 6 stated that policies promote their production. On the other hand, their concern is the ununited regulations between European countries result to that they need permits, which have long permit application periods, in every country that they export their fertilizers to. From the consultancy side, interviewee 7 stated that BSWS permission process are long and strict that can inhibit technological innovation to some extent. Interviewee 9 recommended to add more end-of-waste status in legislation so that more BSWS are not categorized as waste and end up unrecovered.

Social factor job creation is highly positive in this case. Interviewee 4 stated that the ECO3 area operation has generated hundreds of new jobs and can contribute to local development. Social awareness needs to be raised more in media campaigns and education, especially in better biowaste separation knowledge according to interviewee 8. Circularity needs to be integrated more in every sector and education to boost the circular design and knowledge of sustainable material choice.

Considering environmental factors, interviewees 8 and 10 agreed that the BSWS recovery benefits can outweigh the environmental risks of methane leak, odor, and emission. Interviewee 8 added that CO_2 emission from the recovery can even be captured for added value with technological development.

Finding from this case, the critical technical constraint is to ensure product yield which can be traced back to the root cause of feedstock availability and quality, waste separation, and material design. Technological development generates a high positive impact, but the economic viability of the technology is a challenge for finding investment and ensuring sustainable business model. Technological innovation applying from the root cause of the problem such as waste separation and sustainable material design is better efficient and more cost effective. The changing in social factors such as better awareness raising for BSWS sorting and better integration of circularity in education to design and consume more sustainably can be the phenomenal solution for technical challenges. The political and legal factors are more positive for the industry. The industrial ecosystem operation generates a positive high impact on social, economic, and environmental factors in terms of job creation, and opening the market for BSWS products in large production while reducing the environmental footprint from BSWS treatment.

6.4 Overview of the challenges and opportunities

Through the stakeholder interview of 6 PESTLE operational perspectives in addition to the literature review of legislation and state-of-the-art technologies, the opportunities and challenges in CBE operational environment are identified as feedstock availability and quality, technical operation, financial viability, policy and legislation change, social acceptance, resource competition, and virgin material alternative.

Feedstock availability and quality: Withdrawing from the stakeholder interview and questionnaire results, ensuring consistent feedstock quality and quantity are challenging and may lead to significant costs for feedstock pre-treatment, logistics, and storage. It is the barrier to the material flow between BSWS producers and the industry while the BSWS producers are lack of buying demand and the industries are lack of quality feedstock. This challenge opens an opportunity for a business model to bridge this gap through buying BSWS from small producers, feedstock processing, and supplying to the industry.

Technical operation: The larger the operation scale, the more complex in technical and operational practices. Both literature review and stakeholder interview results show that the main technical issues are defined as low quality product that induces the need for a costly upgrading process. Tackling this technical challenge from the earlier cause of waste separation and material design is more efficient and cost-effective. The opportunities for future technical development then lay in upstream processes such as sustainable material innovation, product eco-design, waste separation, and feedstock pre-treatment. According to the literature review, the adaption of digital applications such as smart waste management, e-marketplace, AI, and blockchain-based value chain management system are accelerating factors for CBE transition. The valorization technology such as Black Soldier Fly Treatment is promising for industrial scale-up thanks to its product and production cost feasibility.

Financial viability: According to both the literature review and stakeholder interview, to make recovery practice economically viable is difficult with logistic challenges and high investment costs for facilities in addition to the energy price and market demand fluctuation. The key challenge for small operators is getting financial access to adopt recovery practices. As for technological innovation on large scale, sustaining the production until the market introduction and turning profitability is financially challenging. The opportunities for finance can open through regulations and funding schemes from Bioeconomy Strategy and Environmental Fiscal and Tax Reform.

Policy and legislation change: The regulatory environment has both challenges and opportunities. The legislation is changing to a more sustainable will, however, the challenges of unharmonized regulation between the new and existing regulations or between the countries are noticed. Through literature review and stakeholder interview, the restriction of BSWS product processing and utilization is noticed as a possible barrier to technological innovation in circulating BSWS. Furthermore, more political, and legal support for small BSWS recovery in self-sustaining and rural-urban symbiosis operations are needed since the earlier recovery practices can reduce much further treatment and logistic burdens. According to the stakeholder interview result, the industries rated the policy and legislation factors more positive than the other two smaller operations which may imply political supports focus more on the industrial sectors. Policies and legislations are agreed upon between stakeholders as the critical driver for BSWS market creation, consumption, and production behavior change. Fiscal instruments such as financing and tax incentive for BSWS recovery, reducing the subsidy for non-renewable practices, and the upcoming eco-design for sustainable product regulation will be significant CBE promotions. End-of-waste criteria expansion for BSWS is mentioned in both literature review and stakeholder interview to limit BSWS disposal as waste status and better uptake BSWS and place BSWS recovery products on the market. As technological challenges are recommended to be solved from the root cause of sustainable material design according to the stakeholder, the awaiting Eco-design for Sustainable Products Regulation in the literature review can be a great driver for upstream circularity.

Social acceptance: Consumer sustainable consumption is discussed in stakeholder interview as the driver for sustainable production. Consumer acceptance and demand are indeed an opportunity. Integration of sustainability into education in all sectors can foster social awareness and prepare sustainability workforce for the systemic multidisciplinary transition. However, change resistance and digitalization unfamiliarity can be barriers to adopting CBE technologies and digital management practices.

Competition with other resources: Organic fertilizer may compete with traditional fertilizer which is not favorable in terms of cost. Biogas traffic fuel may compete with electric vehicles as mentioned in the stakeholder interview, biogas energy may compete with other renewable energy sources, such as wind and solar power. The competitions are for investment capital and customer demand. Competition is a market challenge, and it can turn into favorable conditions through regulation support.

Virgin material alternative: The literature review concerns the challenge of decoupling raw material extraction from economic growth. The opportunities for using BSWS as an alternative to virgin material are high according to the stakeholder interview. BSWS as a virgin material alternative provides both environmental and economic benefits from saving raw material extraction and utilizing secondary material instead. The mixed production can also be a good chance to blend BSWS and ensure sufficient product quality. Nevertheless, the challenge lies in mixed production requirements and product entry permissions and regulations.

6.5 Circular operations and their interlinkage

Considering the connection between the 3 CBE operation models to view the circular bioeconomy transition in systemic way, circular operation interlinkage is discussed through the vision of small self-sustaining circle to medium rural-urban circle to the large industry circle (figure 21).

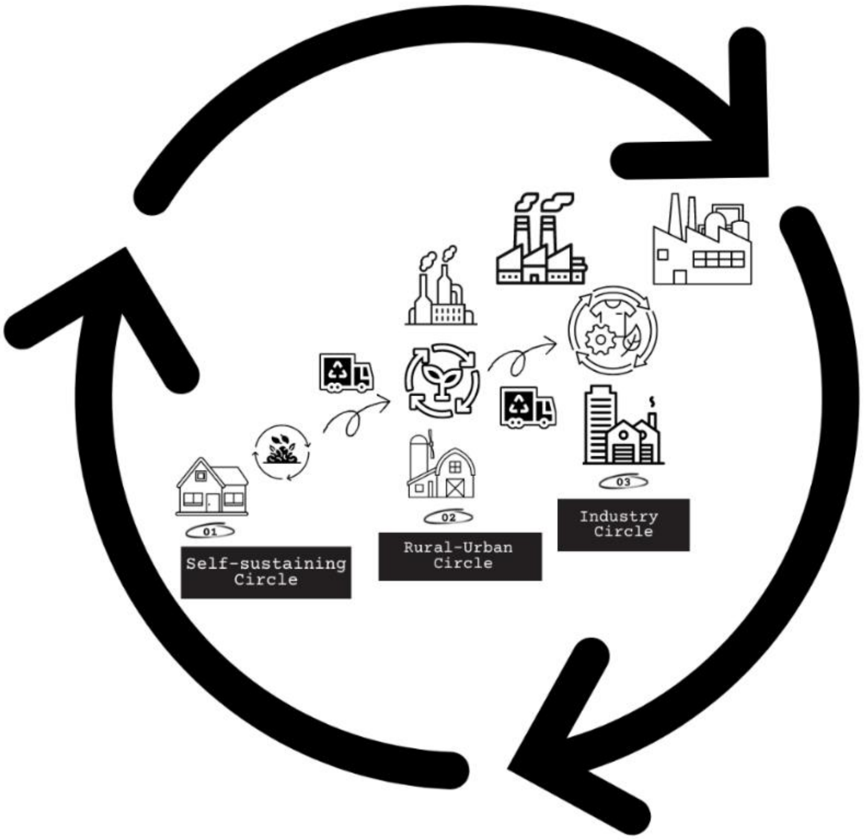


Figure 21. *Circular operation interlinkage*

As feedstock quality and logistics and its associated cost and environmental impacts are mentioned as the key challenges, the onsite technological innovation like ManPas device for self-sustaining practices or pre-treatment of BSWS should be in focused development as the fundamental circle of the circular bioeconomy loop. Where self-sustaining practices are not feasible, rural-urban symbiosis can optimize the circularity by gathering, trading, recovering BSWS in local facilities or mobile solutions, or by pre-processing feedstock for the industries. Following that, the centralized solution of the industry circle not only recirculates the industrial BSWS flow but also can uptake the feedstock processed from rural-urban symbiosis. By doing so, the feedstock quantity and quality gap between the primary producer and the industries can be bridged. Furthermore, the industrial synergies and large production can create a market for BSWS, generate demand and pull the smaller operations to grow circularity with it. The more circles and interlinkage created between the circular operation models, the larger the systemic circularity.

To make the systemic circular operation function requires multidisciplinary stakeholder engagement. Their roles and actions in the accelerating systemic CBE transition are illustrated in the figure 22.

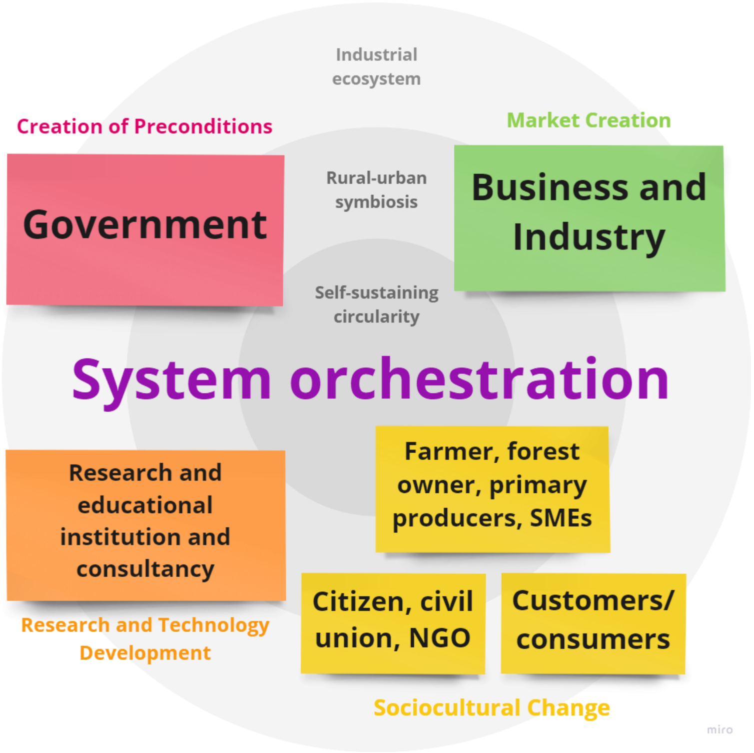


Figure 22. *Stakeholder engagement*

According to the network governance in circularity theory from Cramer (2020), there are 5 main actions for the stakeholder forces within the circular value chain development. They are market creation from business and industry forces, pre-condition creation from government forces, research and technology development from the research and consultancy force, sociocultural change from citizen and consumer forces, and system orchestration from the circularity platform developer or the transition coordinator. Promoting the systemic CBE transition from self-sustaining practices to industrial ecosystem requires the technological push of sustainable material design, BSWS separation and pre-treatment, BSWS valorization and digitalization in value chain management from research and education forces, market creation pull from business and industry to adopt circular technologies and business models to uptake BSWS and create value added products in conjunction with the pre-condition of political and legal supports in regulations, fundings, tax incentives from the administrative forces and sociocultural change to adopt circular BSWS products and services from the citizen and consumer forces. Out of that combination, the system orchestrator role and systemic operational management are crucial to engage the stakeholder in common goal actions to drive the circular initiatives forward, upscale, and replicate circular models.

7. CONCLUSION

Through the literature review of valorization technologies and digitalization adoption and stakeholder interviews, the main goal of the study is to create an overview of the CBE operational environment and identify the challenges and opportunities associated with the 3 CBE operation models and their interlinkage in CBE systemic transition.

Finding from the literature review and stakeholder interviews, the key elements impacting CBE operation are feedstock availability and quality, technical operation, financial viability, policy and legislation change, social acceptance, resource competition, and virgin material alternatives.

The common adopted technological solutions for BSWS are biological methods including composting and anaerobic digestion. The main technical challenge following it is to ensure product quality whose root causes are feedstock quality and availability and unsustainable material design. Technological development cures solving the problem from the earlier causes can bring more efficient and cost-effective effects. Data and digitalization technologies can foster the transition to CBE through e-marketplace, AI, and blockchain-based value chain management systems. The challenge for it remains in the high-tech adaption and digital infrastructure requirements.

The policies and regulations are moving towards CBE promotion through a biowaste separation mandate and renewable energy targets. However, unharmonized regulations, restrictions on BSWS product entry, taxation, and low circularity incentives are noticeable regulatory challenges. In addition, more financing and fiscal support for small operations are needed as developing a small self-sustaining circularity model can reduce the great burden of further logistics and treatment.

To initiate the systemic transition to circular economy requires the close interlinkage of small self-sustaining circularity, medium rural-urban symbiosis, and large industrial ecosystem operation models and stakeholder engagement. The driver for transition is the combination of technological push, market pull, political support, and sociocultural change to adopt circular products and services. While stakeholder engagement is a prerequisite to make that combination feasible, the role of the system orchestrator is crucial.

Future research can dig further into one specific BSWS such as wood waste and food waste to analyze the operational model in a more specific environment to define challenges, opportunities, and solutions more appropriate to that stream value chain.

REFERENCES

Ahmad, A. A., Zawawi, N. A., Kasim, F. H., Inayat, A., & Khasri, A. (2016). Assessing the gasification performance of biomass: A review on biomass gasification process conditions, optimization and economic evaluation. *Renewable and Sustainable Energy Reviews*, *53*, 1333–1347. https://doi.org/10.1016/J.RSER.2015.09.030

Alshehrei, F., & Ameen, F. (2021). Vermicomposting: A management tool to mitigate solid waste. *Saudi Journal of Biological Sciences*, *28*(6), 3284–3293. https://doi.org/10.1016/J.SJBS.2021.02.072

Arena, U. (2012). Process and technological aspects of municipal solid waste gasification. A review. *Waste Management*, *32*(4), 625–639. https://doi.org/10.1016/J.WASMAN.2011.09.025

Atfarm. (n.d.). *Atfarm*. Retrieved February 12, 2023, from https://www.at.farm/

Basu, P. (2013a). Pyrolysis. *Biomass Gasification, Pyrolysis and Torrefaction*, 147–176. https://doi.org/10.1016/B978-0-12-396488-5.00005-8

Basu, P. (2013b). Gasification Theory. *Biomass Gasification, Pyrolysis and Torrefaction*, 199–248. https://doi.org/10.1016/B978-0-12-396488-5.00007-1

Bin Dohaish, E. J. A. (2020). Vermicomposting of organic waste with Eisenia Fetida increases the content of exchangeable nutrients in soil. *Pakistan Journal of Biological Sciences*, *23*(4), 501–509. https://doi.org/10.3923/pjbs.2020.501.509

Bioeconomy. (2022). *Bioeconomy Strategy 2022–2035 – Sustainably towards higher value added*. https://www.bioeconomy.fi/bioeconomy-strategy-2022-2035-sustainably-towards-higher-value-added/

Biomass Atlas. (n.d.). *Biomasses*. Retrieved February 12, 2023, from https://projects.luke.fi/biomassa-atlas/en/

Center for Integrated Biowaste Research. (n.d.). *What is biowaste?*

Chauhan, C., Parida, V., & Dhir, A. (2022). Linking circular economy and digitalisation technologies: A systematic literature review of past achievements and future promises. *Technological Forecasting and Social Change*, *177*, 121508. https://doi.org/10.1016/J.TECHFORE.2022.121508

Circularise. (2022). *ISCC and Circularise pilot blockchain technology with 10 companies to complement mass balance certification*. https://www.circularise.com/press-release/iscc-and-circularise-pilot-blockchain-technology?hss_channel=lcp-7597126

Collacott, L. (n.d.). Success in managing complexity: the role of the Internet of Things in creating a circular economy. *Ellen MacArthur Foundation*.

ConnectedBin. (n.d.). *ConnectedBin*. Retrieved February 12, 2023, from https://www.connectedbin.eu/

D'Amato, D., Veijonaho, S., & Toppinen, A. (2020). Towards sustainability? Forest-based circular bioeconomy business models in Finnish SMEs. *Forest Policy and Economics*, *110*, 101848. https://doi.org/10.1016/J.FORPOL.2018.12.004

Deloitte. (n.d.). *Circular goes digital*.

Dou, Z., Toth, J. D., & Westendorf, M. L. (2018). Food waste for livestock feeding: Feasibility, safety, and sustainability implications. *Global Food Security*, *17*, 154–161. https://doi.org/10.1016/J.GFS.2017.12.003

ECO3. (n.d.). *ECO3*. Retrieved February 14, 2023, from https://eco3.fi/en/

Salah, M. E. H. (2005). Rural and Developing Country Solutions. *Environmental Solutions: Environmental Problems and the All-Inclusive Global, Scientific, Political, Legal, Economic, Medical, and Engineering Bases to Solve Them*, 313–400. https://doi.org/10.1016/B978-012088441-4/50015-0

Ellen MacArthur Foundation. (n.d.). *What is a circular economy?*

Ellen MacArthur Foundation, & Google. (n.d.). *Artificial intelligence and the circular economy: AI as a tool to accelerate the transition*.

Elyea, J. (2022). *Why You Need a Strategic Plan and an Action Plan*. https://envisio.com/blog/why-you-need-a-strategic-plan-and-an-action-plan/

Epstein, E. (2017). The science of composting. In *The Science of Composting*. https://doi.org/10.1201/9780203736005

European Biomass Industry Association. (n.d.). *Bio-Waste*.

European Commission. (n.d.-a). *A European Green Deal*. Retrieved November 2, 2022, from https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en

European Commission. (n.d.-b). *Eco-design for sustainable products*. Retrieved November 2, 2022, from https://ec.europa.eu/info/energy-climate-change-environment/standards-tools-and-labels/products-labelling-rules-and-requirements/sustainable-products/ecodesign-sustainable-products_en

European Commission. (n.d.-c). *Renewable energy directive*. Retrieved November 2, 2022, from https://energy.ec.europa.eu/topics/renewable-energy/renewable-energy-directive-targets-and-rules/renewable-energy-directive_en

European Commission. (n.d.-d). *Strategy and policy*. Retrieved March 6, 2023, from https://commission.europa.eu/strategy-and-policy_en

European Commission. (n.d.-e). *Waste Framework Directive*. https://environment.ec.europa.eu/topics/waste-and-recycling/waste-framework-directive_en

European Commission. (n.d.-f). *Waste Framework Directive*. Retrieved November 2, 2022, from https://environment.ec.europa.eu/topics/waste-and-recycling/waste-framework-directive_en

European Commission. (2018). *A new bioeconomy strategy for a sustainable European*.

European Commission. (2020a). *Circular economy action plan: for a cleaner and more competitive Europe*. Publications Office of the European Union. https://op.europa.eu/en/publication-detail/-/publication/45cc30f6-cd57-11ea-adf7-01aa75ed71a1/language-en

European Commission. (2020b). *From Farm to Fork: Our food, our health, our planet, our future*.

European Commission. (2022). *Infographics on biomass sources and uses in the EU-27 (2017 data)*. https://knowledge4policy.ec.europa.eu/publication/infographics-biomass-sources-uses-eu-27-2017-data_en

European Compost Network. (n.d.). *Bio-Waste in Europe*. Retrieved March 12, 2023, from https://www.compostnetwork.info/policy/biowaste-in-europe/

European Compost Network. (2022). COMPOST AND DIGESTATE FOR A CIRCULAR BIOECONOMY: Overview of Bio-Waste Collection, Treatment & Markets Across Europe. *ECN DATA REPORT 2022*.

European Environment Agency. (2013). *Green fiscal reform can create jobs and stimulate innovation across the EU*. https://www.eea.europa.eu/highlights/fiscal-reform-can-create-jobs

European Environment Agency. (2020). Biowaste in Europe – turning challenges into opportunities. *EEA Report No 4/2020*.

European Union. (n.d.). *Types of legislation*.

Favoino, E., Giavini, M., & Agraria del Parco di Monza, S. (2020). *Bio-waste generation in the EU: Current capture levels and future potential*.

Feleke, S., Cole, S. M., Sekabira, H., Djouaka, R., & Manyong, V. (2021). Circular bioeconomy research for development in sub-saharan africa: Innovations, gaps, and actions. *Sustainability (Switzerland)*, *13*(4). https://doi.org/10.3390/su13041926

Fertilizers Europe. (2022). *Fertilizing Product Regulation*. https://www.fertilizerseurope.com/agriculture-environment/fertilizing-products-regulation/

Finland Toolbox. (n.d.). *Circular Economy*. Retrieved March 13, 2023, from https://toolbox.finland.fi/circular-economy/

Finnish Ministry of the Environment. (n.d.). *Strategic programme to promote a circular economy*.

Fodor, Z., & Klemeš, J. J. (2012). Waste as alternative fuel – Minimising emissions and effluents by advanced design. *Process Safety and Environmental Protection*, *90*(3), 263–284. https://doi.org/10.1016/J.PSEP.2011.09.004

Garg, A. (2014). Mechanical biological treatment for municipal solid waste. *International Journal of Environmental Technology and Management*, *17*(2–4). https://doi.org/10.1504/IJETM.2014.061795

Gatto, F., & Re, I. (2021). Circular bioeconomy business models to overcome the valley of death. A systematic statistical analysis of studies and projects in emerging bio-based technologies and trends linked to the sme instrument support. *Sustainability (Switzerland)*, *13*(4). https://doi.org/10.3390/su13041899

George, T. (2022). *Semi-Structured Interview | Definition, Guide & Examples*. https://www.scribbr.com/methodology/semi-structured-interview/

HAMK. (n.d.). *Hygienized manure*. Retrieved February 14, 2023, from https://www.hamk.fi/projektit/hygienisoitu-lanta/#perustiedot

Hedberg, A., & Šipka, S. (2020). The circular economy: Going digital. *European Policy Centre*.

Huguier, P., Manier, N., Chabot, L., Bauda, P., & Pandard, P. (2014). Ecotoxicological assessment of organic wastes spread on land: Towards a proposal of a suitable test battery. *Ecotoxicology and Environmental Safety*, *113C*, 103–111. https://doi.org/10.1016/j.ecoenv.2014.11.017

Interreg Europe. (2021). *The biowaste management challenge*.

Isahak, W. N. R. W., Hisham, M. W. M., Yarmo, M. A., & Yun Hin, T. Y. (2012). A review on bio-oil production from biomass by using pyrolysis method. *Renewable and Sustainable Energy Reviews*, *16*(8), 5910–5923. https://doi.org/10.1016/J.RSER.2012.05.039

Jakobsen, S. T. (1994). Aerobic decomposition of organic wastes I. Stoichiometric calculation of air change. *Resources, Conservation and Recycling*, *12*(3–4), 165–175. https://doi.org/10.1016/0921-3449(94)90004-3

Johansson, N. (2021). Does the EU's Action Plan for a Circular Economy Challenge the Linear Economy? *Environmental Science & Technology*, *55*(22), 15001–15003. https://doi.org/10.1021/acs.est.1c06194

Kalundborg Symbiosis. (n.d.). *Surplus from circular production*.

Kan, T., Strezov, V., & Evans, T. J. (2016). Lignocellulosic biomass pyrolysis: A review of product properties and effects of pyrolysis parameters. *Renewable and Sustainable Energy Reviews*, *57*, 1126–1140. https://doi.org/10.1016/J.RSER.2015.12.185

KiertoaSuomesta. (n.d.). *KiertoaSuomesta*. Retrieved February 12, 2023, from https://kiertoasuomesta.fi/

Kirkels, A. F., & Verbong, G. P. J. (2011). Biomass gasification: Still promising? A 30-year global overview. *Renewable and Sustainable Energy Reviews*, *15*(1), 471–481. https://doi.org/10.1016/J.RSER.2010.09.046

Krueger, B. C., Fowler, G. D., Templeton, M. R., & Moya, B. (2020). Resource recovery and biochar characteristics from full-scale faecal sludge treatment and co-treatment with agricultural waste. *Water Research*, *169*, 115253. https://doi.org/10.1016/J.WATRES.2019.115253

Lardinois, I., & van de Klundert, A. (1993). *Organic Waste: Options for small-scale resource recovery.*

Law Insider. (n.d.). *Semi-quantitative methods definition*. Retrieved March 13, 2023, from https://www.lawinsider.com/dictionary/semi-quantitative-methods

Lohri, C., Diener, S., Zabaleta, I., Mertenat, A., & Zurbrügg, C. (2017). Treatment technologies for urban solid biowaste to create value products: a review with focus on low- and middle- income settings. *Reviews in Environmental Science and Bio/Technology*, *16*. https://doi.org/10.1007/s11157-017-9422-5

Lowe, E. A., & Evans, L. K. (1995). Industrial ecology and industrial ecosystems. *Journal of Cleaner Production*, *3*(1–2), 47–53. https://doi.org/10.1016/0959-6526(95)00045-G

Materiaalitori. (n.d.). *Material Market Services*. Retrieved November 2, 2022, from https://www.materiaalitori.fi/tietoa-palvelusta

Molino, A., Chianese, S., & Musmarra, D. (2016). Biomass gasification technology: The state-of-the-art overview. *Journal of Energy Chemistry*, *25*(1), 10–25. https://doi.org/10.1016/J.JECHEM.2015.11.005

Molino, A., Nanna, F., Ding, Y., Bikson, B., & Braccio, G. (2013). Biomethane production by anaerobic digestion of organic waste. *Fuel*, *103*, 1003–1009. https://doi.org/10.1016/J.FUEL.2012.07.070

MTK. (2020). *Symbiosis between rural & urban areas*.

Muralikrishna, I. v., & Manickam, V. (2017). Solid Waste Management. *Environmental Management*, 431–462. https://doi.org/10.1016/B978-0-12-811989-1.00016-6

Pantzar, M., & Suljada, T. (2020). Delivering a Circular Economy within the Planet's Boundaries: An Analysis of the new EU Circular Economy Action Plan. *Institute for European Environmental Policy and Stockholm Environment Institute*. https://ieep.eu/publications/an-analysis-of-the-new-eu-circular-economy-action-plan

PESTLE Analysis. (n.d.). *What is PESTLE Analysis? An Important Business Analysis Tool*. Retrieved February 14, 2023, from https://pestleanalysis.com/what-is-pestle-analysis/

Polprasert, C. (2007). Organic Waste Recycling Technology and Management. *International Water Association (IWA)*, *101*, 833–835.

Potting, J., Hekkert, M., Worrell, E., & Hanemaaijer, A. (2017). *Circular economy: Measuring innovation in the product chain*.

ProductPlan. (n.d.). *Roadmap Basics*.

Renewable Energy Magazine. (2020). *Filling Up with Biogas at the Dairy Farm*.

Rocamora, I., Wagland, S. T., Villa, R., Simpson, E. W., Fernández, O., & Bajón-Fernández, Y. (2020). Dry anaerobic digestion of organic waste: A review of operational parameters and their impact on process performance. *Bioresource Technology*, *299*, 122681. https://doi.org/10.1016/J.BIORTECH.2019.122681

Sayara, T., Basheer-Salimia, R., Hawamde, F., & Sánchez, A. (2020). Recycling of organic wastes through composting: Process performance and compost application in agriculture. In *Agronomy* (Vol. 10, Issue 11). https://doi.org/10.3390/agronomy10111838

SENSONEO. (n.d.). *3 smart waste solutions for making the waste collection an effective process*. Retrieved October 31, 2022, from https://sensoneo.com/smart-waste-solutions-making-collection-effective/

Singh, R. P., Singh, P., Araujo, A. S. F., Hakimi Ibrahim, M., & Sulaiman, O. (2011). Management of urban solid waste: Vermicomposting a sustainable option. *Resources, Conservation and Recycling*, *55*(7), 719–729. https://doi.org/10.1016/J.RESCONREC.2011.02.005

Sitra. (n.d.). *Leading the cycle – Finnish road map to a circular economy 2016-2025*.

Smith, J. U., Fischer, A., Hallett, P. D., Homans, H. Y., Smith, P., Abdul-Salam, Y., Emmerling, H. H., & Phimister, E. (2015). Sustainable use of organic resources for bioenergy, food and water provision in rural Sub-Saharan Africa. *Renewable and Sustainable Energy Reviews*, *50*, 903–917. https://doi.org/10.1016/J.RSER.2015.04.071

Snellman, H. (2020). *Reform of Waste Legislation in Finland – A Step Towards Circular Economy*. https://hannessnellman.com/news-views/blog/reform-of-waste-legislation-in-finland-a-step-towards-circular-economy/

Song, B., & Hall, P. (2020). Densification of Biomass and Waste Plastic Blends as a Solid Fuel: Hazards, Advantages, and Perspectives. *Frontiers in Energy Research*, *8*, 58. https://doi.org/10.3389/FENRG.2020.00058/BIBTEX

Stegmann, P., Londo, M., & Junginger, M. (2020). The circular bioeconomy: Its elements and role in European bioeconomy clusters. *Resources, Conservation & Recycling: X*, *6*, 100029. https://doi.org/10.1016/J.RCRX.2019.100029

United Nations. (2022). *The sustainable development goals report 2022*.

Urban Agenda for the EU. (2020). *Better Regulation for a Circular Economy*.

Vaneeckhaute, C., Meers, E., Michels, E., Ghekiere, G., Accoe, F., & Tack, F. M. G. (2013). Closing the nutrient cycle by using bio-digestion waste derivatives as synthetic fertilizer substitutes: A field experiment. *Biomass and Bioenergy*, *55*, 175–189. https://doi.org/10.1016/J.BIOMBIOE.2013.01.032

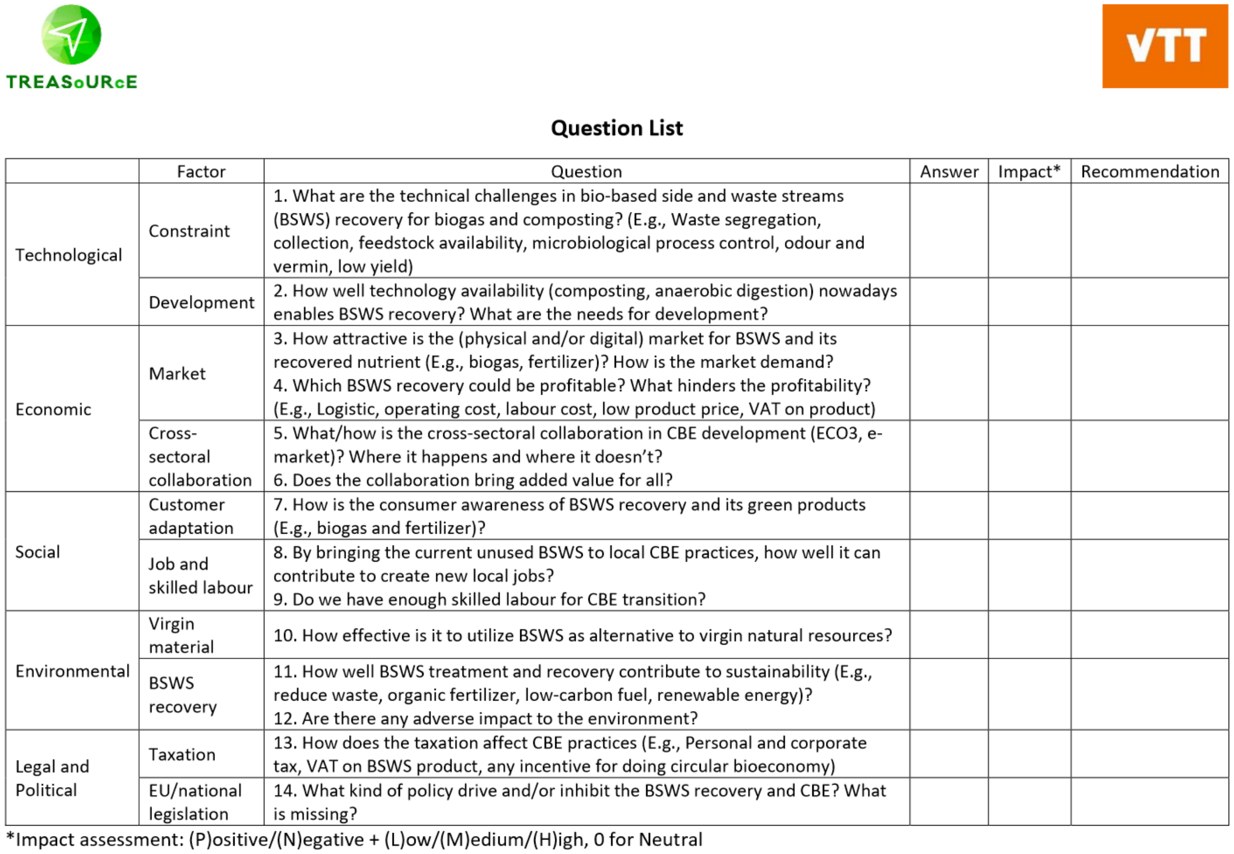
Watson, J., Zhang, Y., Si, B., Chen, W. T., & de Souza, R. (2018). Gasification of biowaste: A critical review and outlooks. *Renewable and Sustainable Energy Reviews*, *83*, 1–17. https://doi.org/10.1016/J.RSER.2017.10.003

World Economic Forum. (2020). *Why the world needs a “circular bioeconomy” - for jobs, biodiversity and prosperity*. https://www.weforum.org/agenda/2020/10/circular-bioeconomy-nature-reset/

Wynn, M., & Jones, P. (2022). Digital Technology Deployment and the Circular Economy. *Sustainability (Switzerland)*, *14*(15). https://doi.org/10.3390/SU14159077

Zero Waste Europe. (2016). *Press Release: EU Bioenergy – time to follow the Waste Hierarchy*. https://zerowasteeurope.eu/press-release/press-release-eu-bioenergy-time-to-follow-the-waste-hierarchy/

APPENDIX A: STAKEHOLDER INTERVIEW QUESTIONS

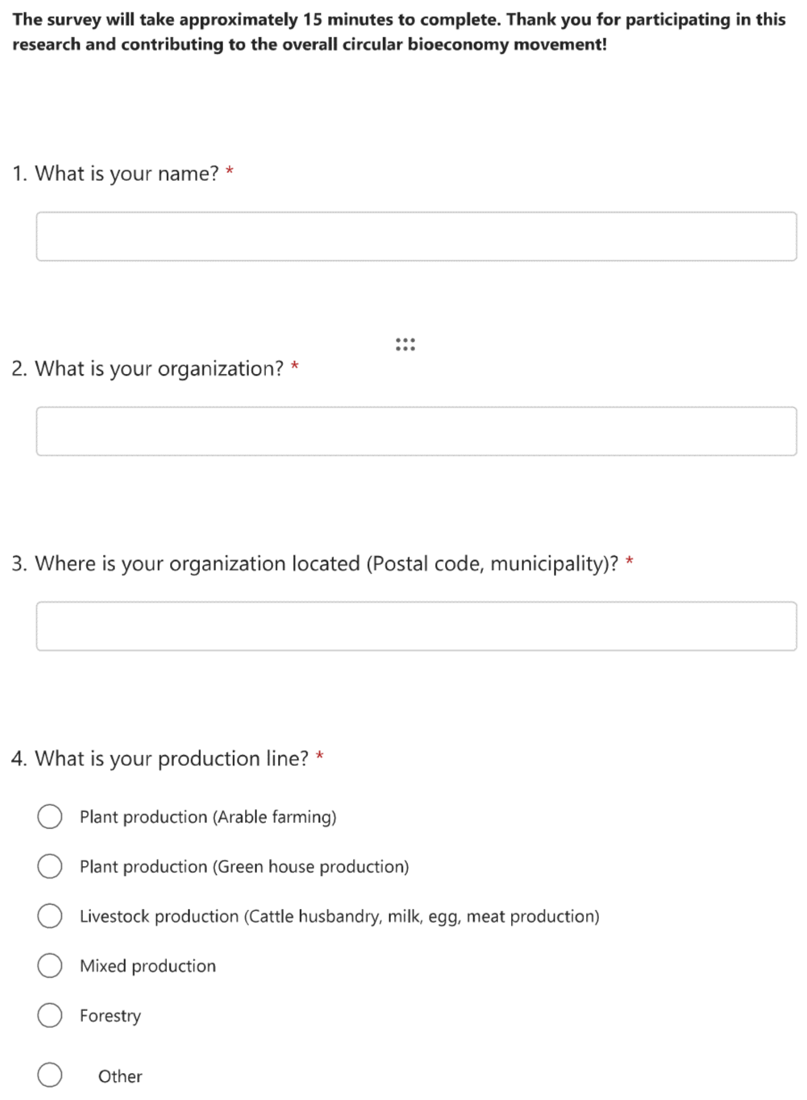


Question List

	Factor	Question	Answer	Impact*	Recommendation
Technological	Constraint	1. What are the technical challenges in bio-based side and waste streams (BSWS) recovery for biogas and composting? (E.g., Waste segregation, collection, feedstock availability, microbiological process control, odour and vermin, low yield)			
	Development	2. How well technology availability (composting, anaerobic digestion) nowadays enables BSWS recovery? What are the needs for development?			
Economic	Market	3. How attractive is the (physical and/or digital) market for BSWS and its recovered nutrient (E.g., biogas, fertilizer)? How is the market demand? 4. Which BSWS recovery could be profitable? What hinders the profitability? (E.g., Logistic, operating cost, labour cost, low product price, VAT on product)			
	Cross-sectoral collaboration	5. What/how is the cross-sectoral collaboration in CBE development (ECO3, e-market)? Where it happens and where it doesn't? 6. Does the collaboration bring added value for all?			
Social	Customer adaptation	7. How is the consumer awareness of BSWS recovery and its green products (E.g., biogas and fertilizer)?			
	Job and skilled labour	8. By bringing the current unused BSWS to local CBE practices, how well it can contribute to create new local jobs? 9. Do we have enough skilled labour for CBE transition?			
Environmental	Virgin material	10. How effective is it to utilize BSWS as alternative to virgin natural resources?			
	BSWS recovery	11. How well BSWS treatment and recovery contribute to sustainability (E.g., reduce waste, organic fertilizer, low-carbon fuel, renewable energy)? 12. Are there any adverse impact to the environment?			
Legal and Political	Taxation	13. How does the taxation affect CBE practices (E.g., Personal and corporate tax, VAT on BSWS product, any incentive for doing circular bioeconomy)			
	EU/national legislation	14. What kind of policy drive and/or inhibit the BSWS recovery and CBE? What is missing?			

*Impact assessment: (P)ositive/(N)egative + (L)ow/(M)edium/(H)igh, 0 for Neutral

APPENDIX B: PRIMARY PRODUCER OF BSWS QUESTIONNAIRE



The survey will take approximately 15 minutes to complete. Thank you for participating in this research and contributing to the overall circular bioeconomy movement!

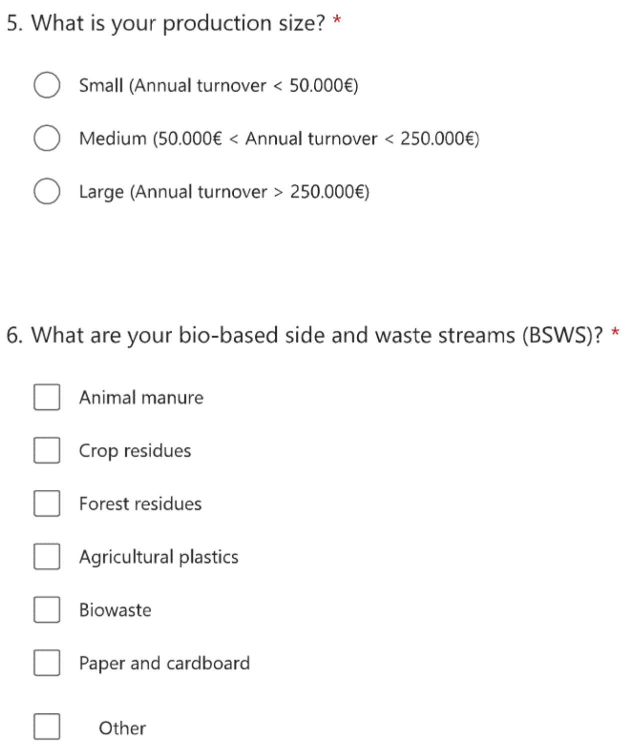
1. What is your name? *

2. What is your organization? *

3. Where is your organization located (Postal code, municipality)? *

4. What is your production line? *

○ Plant production (Arable farming)
○ Plant production (Green house production)
○ Livestock production (Cattle husbandry, milk, egg, meat production)
○ Mixed production
○ Forestry
○ Other



5. What is your production size? *

○ Small (Annual turnover < 50.000€)

○ Medium (50.000€ < Annual turnover < 250.000€)

○ Large (Annual turnover > 250.000€)

6. What are your bio-based side and waste streams (BSWS)? *

☐ Animal manure

☐ Crop residues

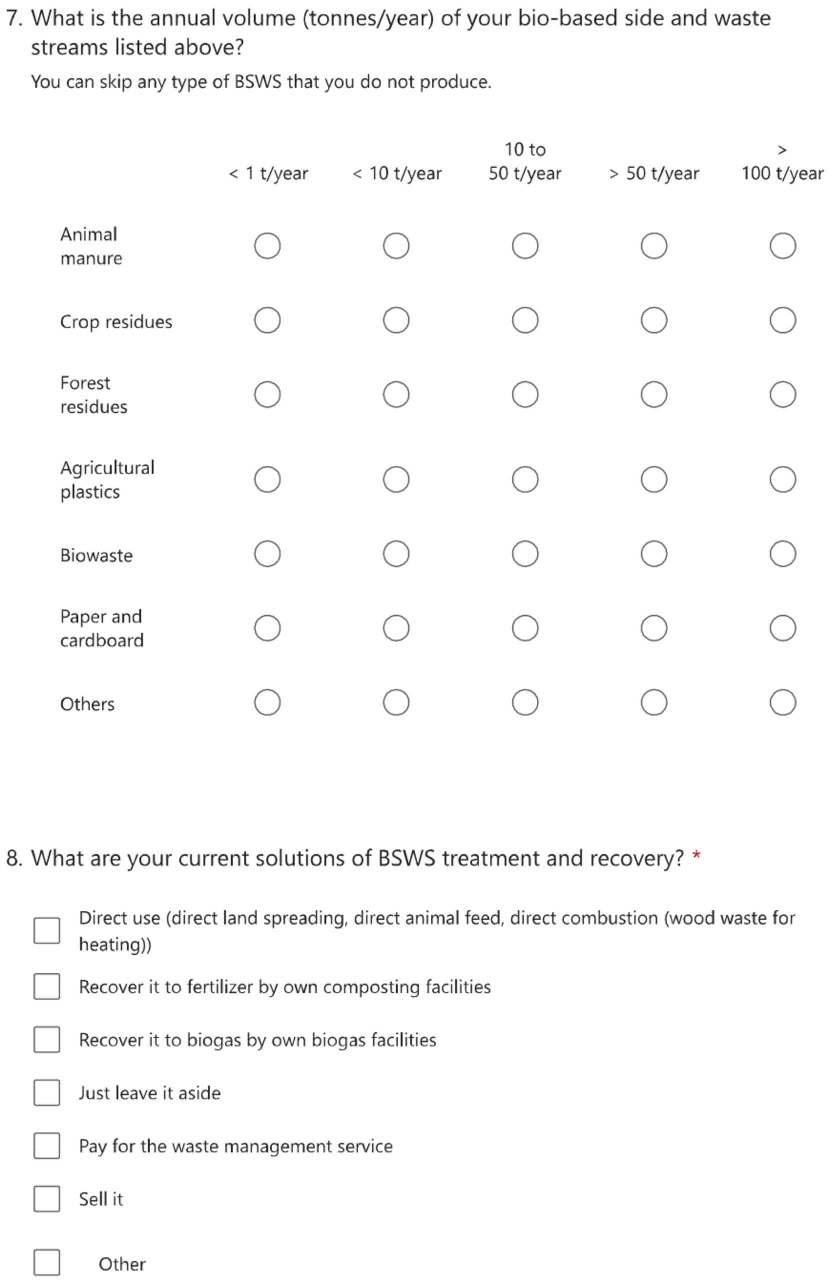
☐ Forest residues

☐ Agricultural plastics

☐ Biowaste

☐ Paper and cardboard

☐ Other



7. What is the annual volume (tonnes/year) of your bio-based side and waste streams listed above?

You can skip any type of BSWS that you do not produce.

	< 1 t/year	< 10 t/year	10 to 50 t/year	> 50 t/year	> 100 t/year
Animal manure	○	○	○	○	○
Crop residues	○	○	○	○	○
Forest residues	○	○	○	○	○
Agricultural plastics	○	○	○	○	○
Biowaste	○	○	○	○	○
Paper and cardboard	○	○	○	○	○
Others	○	○	○	○	○

8. What are your current solutions of BSWS treatment and recovery? *

☐ Direct use (direct land spreading, direct animal feed, direct combustion (wood waste for heating))

☐ Recover it to fertilizer by own composting facilities

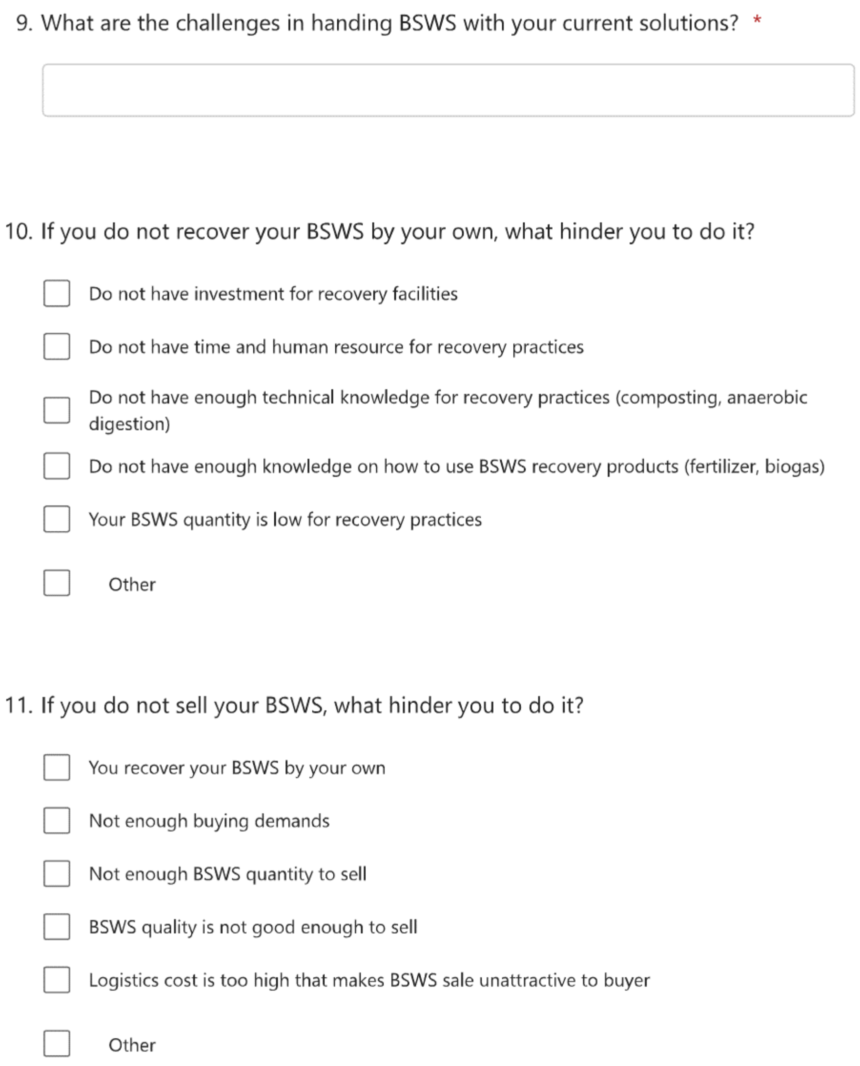
☐ Recover it to biogas by own biogas facilities

☐ Just leave it aside

☐ Pay for the waste management service

☐ Sell it

☐ Other



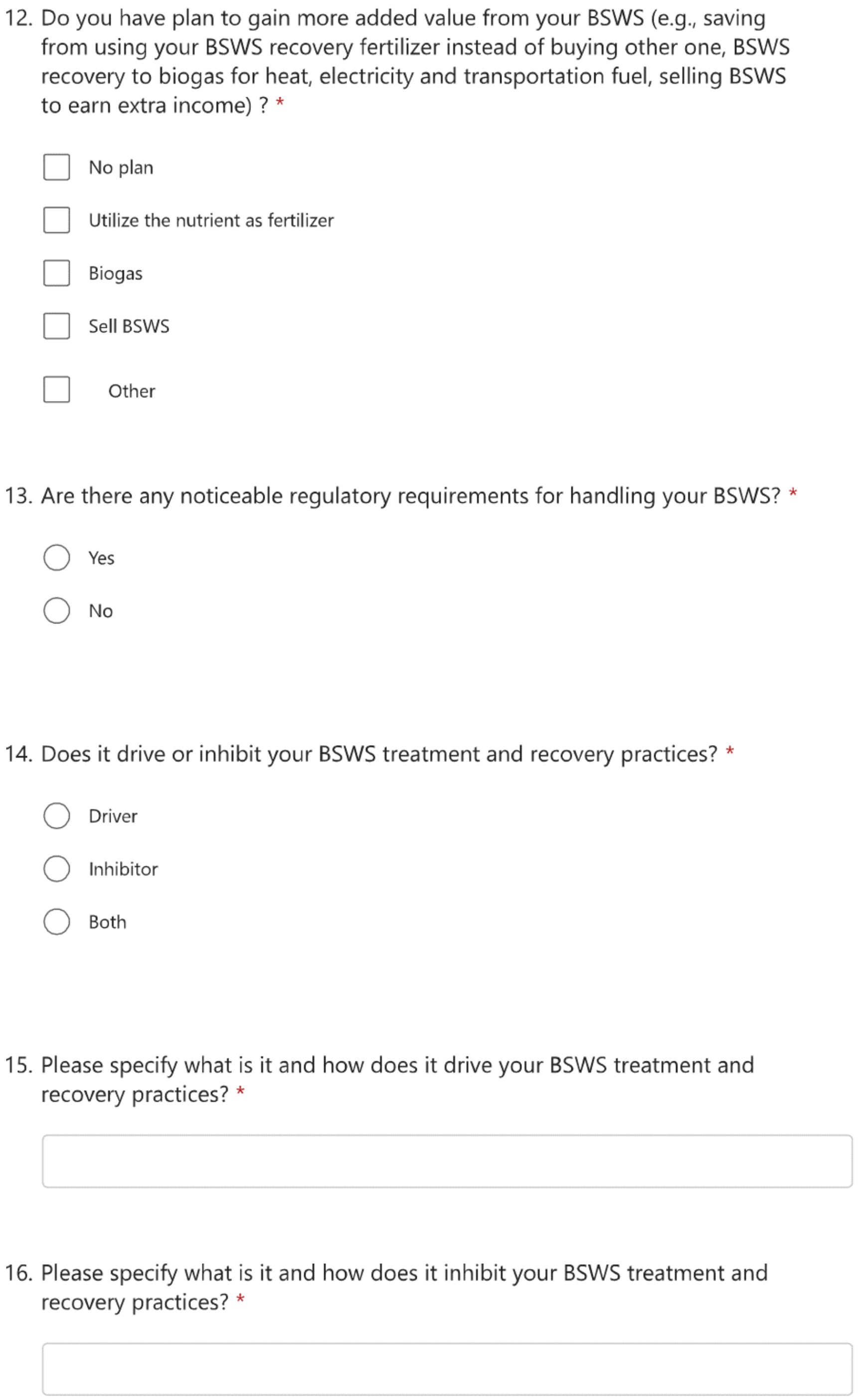
9. What are the challenges in handing BSWS with your current solutions? *

10. If you do not recover your BSWS by your own, what hinder you to do it?

- ☐ Do not have investment for recovery facilities
- ☐ Do not have time and human resource for recovery practices
- ☐ Do not have enough technical knowledge for recovery practices (composting, anaerobic digestion)
- ☐ Do not have enough knowledge on how to use BSWS recovery products (fertilizer, biogas)
- ☐ Your BSWS quantity is low for recovery practices
- ☐ Other

11. If you do not sell your BSWS, what hinder you to do it?

- ☐ You recover your BSWS by your own
- ☐ Not enough buying demands
- ☐ Not enough BSWS quantity to sell
- ☐ BSWS quality is not good enough to sell
- ☐ Logistics cost is too high that makes BSWS sale unattractive to buyer
- ☐ Other



12. Do you have plan to gain more added value from your BSWS (e.g., saving from using your BSWS recovery fertilizer instead of buying other one, BSWS recovery to biogas for heat, electricity and transportation fuel, selling BSWS to earn extra income) ? *

☐ No plan

☐ Utilize the nutrient as fertilizer

☐ Biogas

☐ Sell BSWS

☐ Other

13. Are there any noticeable regulatory requirements for handling your BSWS? *

○ Yes

○ No

14. Does it drive or inhibit your BSWS treatment and recovery practices? *

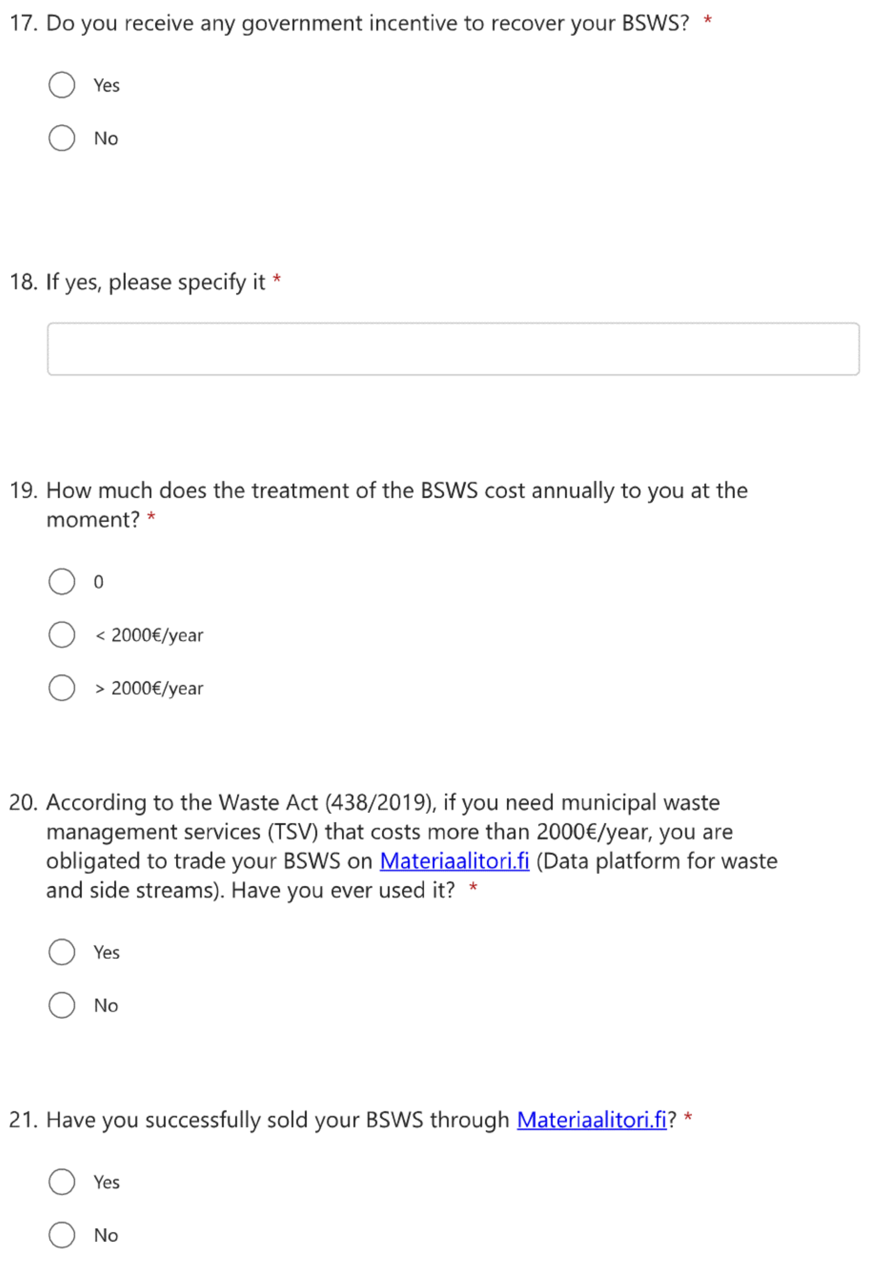
○ Driver

○ Inhibitor

○ Both

15. Please specify what is it and how does it drive your BSWS treatment and recovery practices? *

16. Please specify what is it and how does it inhibit your BSWS treatment and recovery practices? *



17. Do you receive any government incentive to recover your BSWS? *

○ Yes

○ No

18. If yes, please specify it *

19. How much does the treatment of the BSWS cost annually to you at the moment? *

○ 0

○ < 2000€/year

○ > 2000€/year

20. According to the Waste Act (438/2019), if you need municipal waste management services (TSV) that costs more than 2000€/year, you are obligated to trade your BSWS on Materiaalitori.fi (Data platform for waste and side streams). Have you ever used it? *

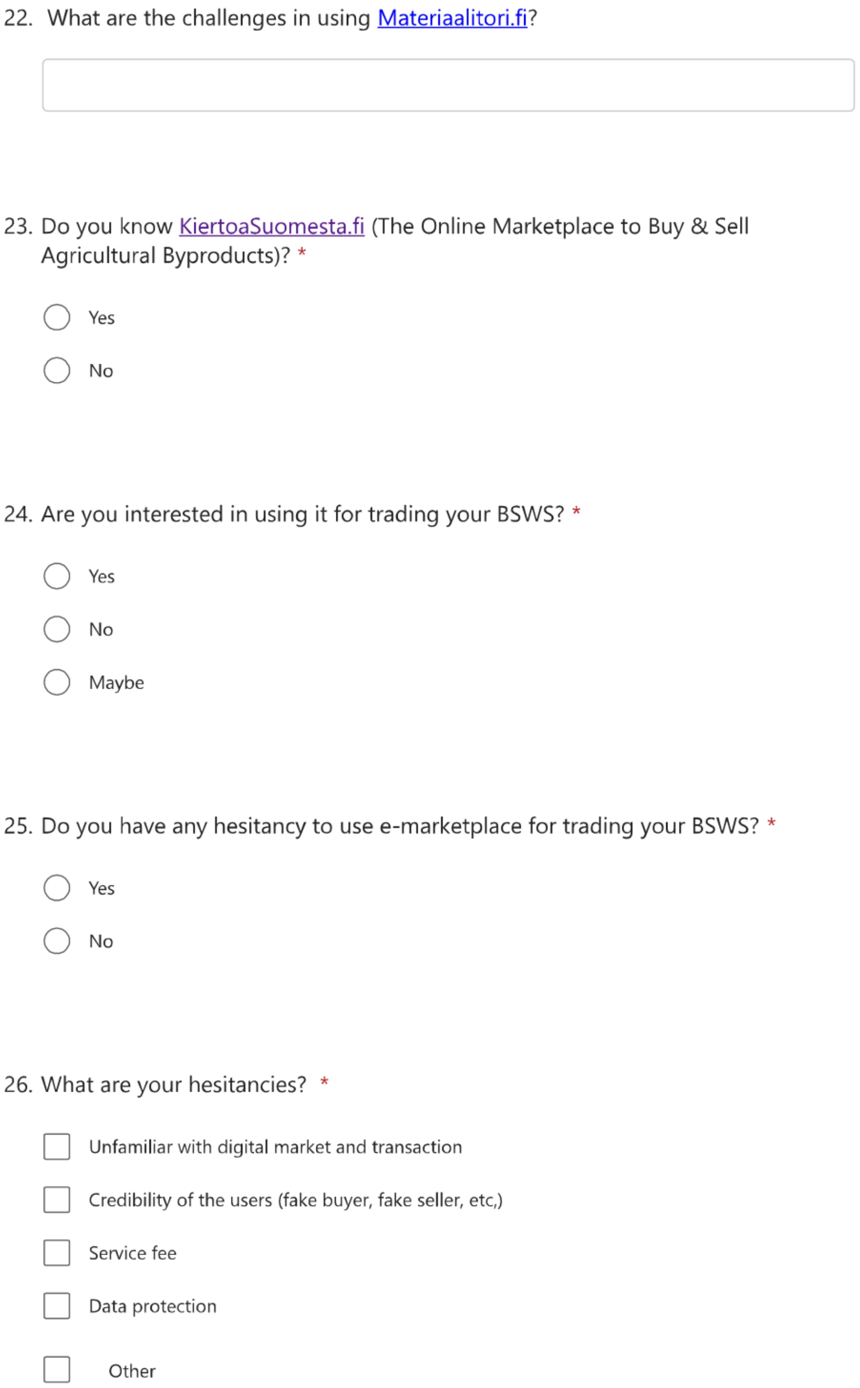
○ Yes

○ No

21. Have you successfully sold your BSWS through Materiaalitori.fi? *

○ Yes

○ No



22. What are the challenges in using Materiaalitori.fi?

23. Do you know KiertoaSuomesta.fi (The Online Marketplace to Buy & Sell Agricultural Byproducts)? *

○ Yes

○ No

24. Are you interested in using it for trading your BSWS? *

○ Yes

○ No

○ Maybe

25. Do you have any hesitancy to use e-marketplace for trading your BSWS? *

○ Yes

○ No

26. What are your hesitancies? *

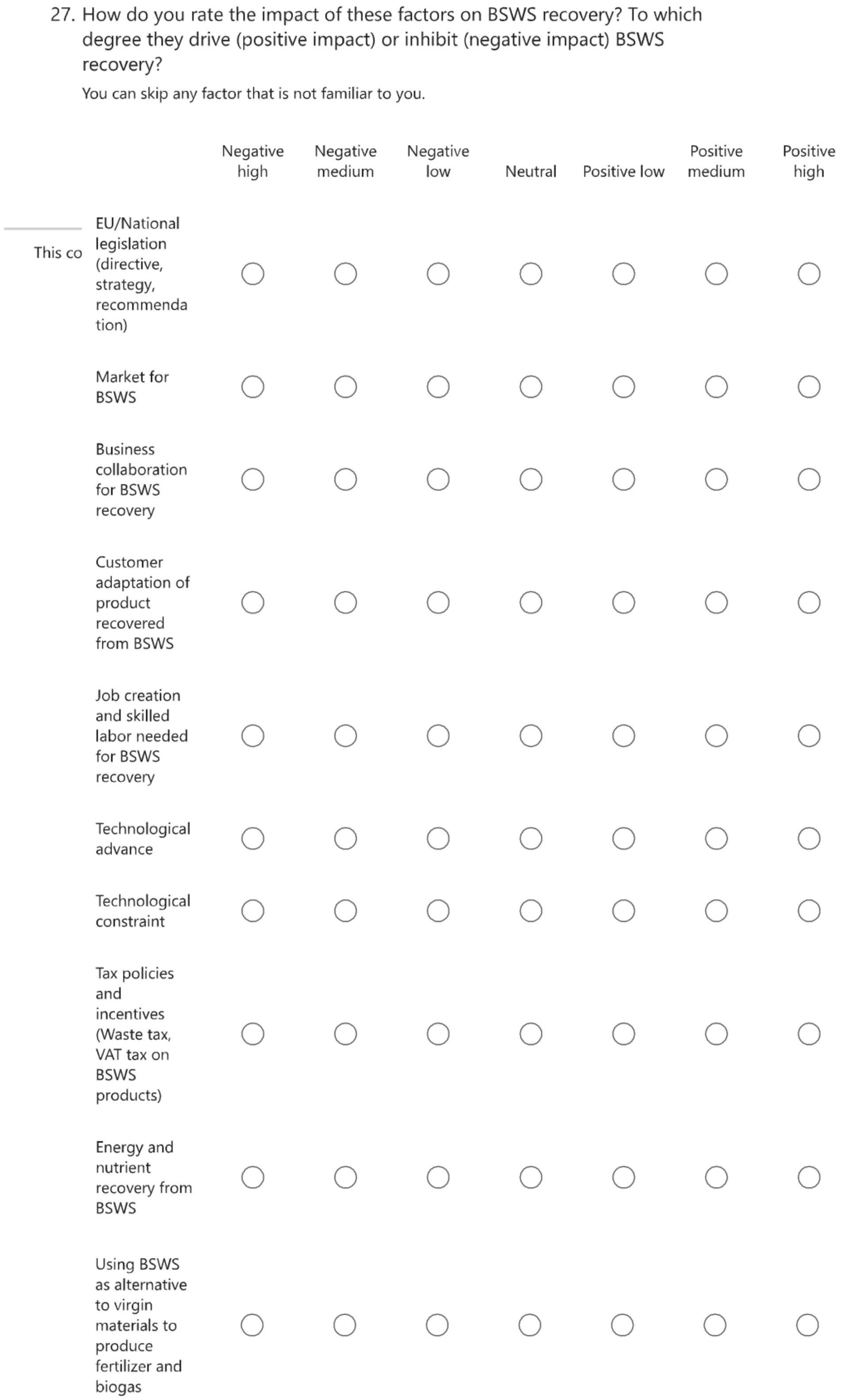
☐ Unfamiliar with digital market and transaction

☐ Credibility of the users (fake buyer, fake seller, etc,)

☐ Service fee

☐ Data protection

☐ Other



27. How do you rate the impact of these factors on BSWS recovery? To which degree they drive (positive impact) or inhibit (negative impact) BSWS recovery?

You can skip any factor that is not familiar to you.

This co

	Negative high	Negative medium	Negative low	Neutral	Positive low	Positive medium	Positive high
EU/National legislation (directive, strategy, recommendation)	○	○	○	○	○	○	○
Market for BSWS	○	○	○	○	○	○	○
Business collaboration for BSWS recovery	○	○	○	○	○	○	○
Customer adaptation of product recovered from BSWS	○	○	○	○	○	○	○
Job creation and skilled labor needed for BSWS recovery	○	○	○	○	○	○	○
Technological advance	○	○	○	○	○	○	○
Technological constraint	○	○	○	○	○	○	○
Tax policies and incentives (Waste tax, VAT tax on BSWS products)	○	○	○	○	○	○	○
Energy and nutrient recovery from BSWS	○	○	○	○	○	○	○
Using BSWS as alternative to virgin materials to produce fertilizer and biogas	○	○	○	○	○	○	○