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A Qualitative Comparative Analysis of cross-sectoral bioresource residue flows from agriculture, forestry, and aquaculture: the crucial role of non-biobased sectors in the development of the circular bioeconomy

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Introduction: Primary production sectors of the bioeconomy—agriculture, forestry, and aquaculture (AFA)—have a significant role in the transition towards the circular economy (CE). Their generated residues can be transformed into renewable biomass resources that serve as an input in the production processes within AFA and other sectors. Valorization of residues in new value-added products and development of new value chains often require cross-sectoral collaboration. In this paper, we use the conceptual framework of industrial symbiosis and identify patterns and test selected influencing factors of cross-sectoral flows of bioresource residues generated in AFA.

Methods: We apply a Qualitative Comparative Analysis (QCA) to perform a comparative analysis of 107 circular initiatives in the biobased sectors in five countries—Estonia, Latvia, Lithuania, Norway, and Ukraine. We focus on the (i) sectors involved in the flow of bioresource residues, (ii) companies' motivation to initiate circular flows, and (iii) type of bioresource residues used.

Results: The analysis of these factors reveals three pathways leading to cross-sectoral flow of bioresource residues: a combination of agriculture with a non-AFA sector (such as energy, food, and feed industries); a combination of aquaculture with the absence of forestry; and a combination of forestry with the absence of aquaculture. Motivational factors such as revenues and legal requirements were not confirmed as decisive for cross-sectoral resource flows.

Discussion: The results show that non-AFA sectors appear central in the development of industrial symbiosis for the circular bioeconomy, and collaboration between AFA and non-AFA sectors needs to be expanded for a better valorization of bioresource residues.

KEYWORDS

circular economy, industrial symbiosis, Qualitative Comparative Analysis, bioeconomy, agriculture, aquaculture, forestry

1 Introduction

The circular economy (CE) is gaining increasing attention as an approach for enabling the transition toward more sustainable production and consumption (Dace et al., 2024). The concept moves away from the linear economy model of 'take-make-consume-dispose' (Domenech et al., 2019, p. 76) toward closing loop economy in which resources are being regenerated, reused, or reduced. Among others, the aim of the CE is to enable the transformation of waste of different production processes and industries to become new feedstock in new production processes leading to a closed loop system (Domenech et al., 2019; Muñoz et al., 2024; Wouterszoon Jansen et al., 2022). The literature highlights that a variety of pathways in CE exists where one of the distinctions is based on the type of material—biological vs. technical—flow (Wouterszoon Jansen et al., 2022). Since organic waste and byproducts are increasingly seen as valuable resources in producing new value-added products and energy, not least through cross-sectoral interactions and cooperation (Mahjoub and Domscheit, 2020), biobased sectors such as agriculture, forestry, and aquaculture (AFA) become key for the transition toward CE due to the diversity and volumes of their residues (Leipold and Petit-Boix, 2018).

In this paper we use the term 'residue' as this does not define the quality of the leftovers. By using 'residue', we do not define if it is classified as waste or a byproduct. We are using the terms 'waste' and 'byproduct' when we need to make a distinction between these two categories and when these terms are used in previous scientific papers that we refer to.

Key strategies used to transition to CE in the bioeconomy include residue valorization and cascading technologies (Egelyng et al., 2018; Donner et al., 2021; Santagata et al., 2021; Zabaniotou and Kamaterou, 2019), as well as application of life cycle and cost assessment tools (De Laurentiis et al., 2024; Santagata et al., 2021). Implemented across supply chains, circular approaches have led to a significant reduction in greenhouse gas (GHG) emissions (Abbate et al., 2023) and opened opportunities for making economic development carbon neutral (Möslinger et al., 2023; Salvador et al., 2022).

The development of new circular products requires expertise from different fields and cross-sectoral collaboration among stakeholders from different industries who have not collaborated before. Hence, a key prerequisite for implementing CE is collaboration between sectors for enabling a circular flow of bioresources across those (Danvers et al., 2023). However, it is contended that there is a lack of research on collaborative processes and structures that can advance circularity and enable cross-sectoral collaboration (ibid.). Research on CE has been focused more on barriers for adopting circular practices (Bittner et al., 2024), including challenges of integrating consumers (Vidal-Ayuso et al., 2023), policy analysis (Chenavaz and Dimitrov, 2024), logistics management (Ding et al., 2023), and various technological solutions such as new approaches to cascading (Campbell-Johnston et al., 2020).

A potentially useful framework for looking specifically at circular use of bioresource residues across different sectors is provided by the concept of industrial symbiosis (IS), which is closely associated with CE. The concept has attracted a rapidly growing global interest in the scientific community, particularly with regards to cleaner production through value chain management (Morales et al., 2022), policymaking (Lybæk et al., 2021), institutional capacity building (Lindfors et al., 2020; Lybæk et al., 2021), and business model innovations (Corsini et al., 2024), among other approaches. However, there are still comparatively few studies that analyze CE and IS in the bioeconomy sector considering its particularities (Velasco-Muñoz et al., 2021), and more comparative studies and exploration of the social aspects of CE and IS initiatives are expected (Neves et al., 2020).

This present paper contributes to this gap in research by conducting a comparative analysis of circular initiatives in five Northern and Eastern European countries to identify selected factors enabling cross-sectoral flows of bioresource residues. The main research objective is to identify important factors whose combined effect enables such flows. This can help gain more information on the design of circular initiatives in the biobased sectors and the role of IS within them. It also allows us to identify whether there are any common bioresource flow patterns across selected countries. This study builds on a comprehensive empirical data collection of initiatives involving circular use of bioresource resides within, between, and beyond AFA sectors from the five countries. Our study therefore examines AFA sectors that are playing an increasingly important role in national economies of the analyzed countries and addresses the lack of a comprehensive overview of specific characteristics of bioresource flows in the region. Moreover, forestry is an important sector across the region, potentially creating an opportunity to contribute to debates of the current state-of-the-art scholarship on the flows of residues generated in this sector. We apply a method of Qualitative Comparative Analysis (QCA), which has not been applied in related thematic studies yet.

We analyze intra- and cross-sectoral initiatives with regards to important factors such as sectors involved in the flow of bioresource residues, companies' motivation to initiate circular flows of bioresources, and types of bioresource residues used. Based on a thorough QCA study, we provide insights into the nature and enabling factors of cross-sectoral circular flows of bioresource residues originating from or utilized in the AFA sectors and their relevance for IS.

The remaining paper is structured as follows: Section 2 provides the theoretical framework of this study by presenting a background on IS literature and the factors identified as relevant for the cross-sectoral flow of bioresource residues. Section 3 describes the research design and methodology applied in this study. Sections 4 and 5 present and discuss the combined effect of factors identified for enabling the cross-sectoral flow of bioresource residues, as well as identify the limitations of the study and recommendations for future research. Section 6 provides the main conclusions including stakeholder recommendations.

2 Literature review

In reviewing the relevant literature, we first focus on Industrial Symbiosis as an important form for collaboration between companies for the CE and a key concept in this study, followed by an overview of the selected factors—relevant biobased sectors involved, companies' motivation, and types of bioresource residues—we assume to enable a cross-sectoral flow of bioresource residues explored in this study.

2.1 Collaboration for circularity—industrial symbiosis

Collaboration that aims at advancing circularity involves complex processes, which is due to the required systematic changes in business

processes, practices, and norms that embody a shift from linear to circular and more sustainable economic models (Danvers et al., 2023). To explore this type of collaboration, over the last decades there has been a growing body of literature tackling the concept and practices of Industrial Symbiosis (IS) that is viewed as an important tool to realize a CE (Schlüter et al., 2022). It generally refers to collaboration between industrial entities in the "physical exchange of materials, energy, water, and byproduct" to create mutual economic, environmental, and social benefits (Chertow, 2000, p. 314). As defined by Domenech et al. (2019, p. 76), IS "involves organizations operating in different sectors of activity that engage in mutually beneficial transactions to reuse waste and byproduct, finding innovative ways to source inputs and optimizing the value of the residues of their processes." This form of inter-firm resource sharing among diversified clusters of firms is considered a practice that brings about a range of environmentally and economically desirable symbiotic exchanges and thus needs to be fostered (Chertow, 2007; Neves et al., 2020).

Nowadays there is a large variety of IS practices both in terms of the activity size and types as well as industries and sectors involved in such arrangements (Neves et al., 2020). Emphasizing the role such collaboration between economic actors can play in reducing the consumption of raw non-renewable resources, Bijon et al. (2022) have specifically looked at the interrelations between the concepts of IS and bioeconomy through exploration of initiatives, which involve an exchange of one or several organic byproducts. While they recognize that IS pertains to any type of byproduct, the specific focus on bioeconomy highlights the use of organic matter in such collaborative arrangements. As defined by the European Commission, "the bioeconomy covers all sectors and systems that rely on biological resources (animals, plants, micro-organisms and derived biomass, including organic waste), their functions and principles. It includes and interlinks: land and marine ecosystems and the services they provide; all primary production sectors that use and produce biological resources (agriculture, forestry, fisheries, and aquaculture); and all economic and industrial sectors that use biological resources and processes to produce food, feed, bio-based products, energy, and services" (European Commission, 2018, p. 4). This, however, does not limit collaboration between agri-food companies in biobased AFA sectors, but also actively involves participation of other companies and sectors beyond these three on the way toward innovation development in the bioeconomy (Lancker et al., 2016).

While the most frequently studied industries in the context of IS are chemical, cement, paper, steel and iron industries, as well as refineries, Neves et al. (2020) acknowledge that there is also a handful of IS studies focusing on primary production in relation to agriculture-related activities (incl. crop production and animal husbandry). This does not, however, imply that IS is limited to segregated intra-sectoral arrangements (i.e., featuring the use of a residue for a different purpose in the same sector), as in many, if not the majority of, cases of IS this collaboration is developed across different industries in a cross-sectoral manner, be it between AFA sectors or between AFA and non-AFA sectors. While we acknowledge that also intra-business arrangements can enable cross-sectoral circularity of bioresources, this is a less frequent case than inter-firm cross-sectorality due to a less common combination of different sectors within a single company.

As proposed by Chertow (2007), the three core opportunities for inter-firm resource exchange include (1) byproduct reuse, (2) utility/infrastructure sharing, and (3) joint provision of services. Regarding the first one, which is of primary interest in this paper, there are several studies in Europe and beyond looking into IS involving one or several of the AFA sectors as suppliers or users of biobased residues. These include, for instance, the use of byproducts from food and fish processing as organic waste for local farms and pet food production, as well as the potential use of organic waste from farms as an input for a gasifier in the United Kingdom (Mirata, 2004: Figure 2), the reuse of brewers' grain as animal feed in Latvia (Rosa and Beloborodko, 2015) and Sweden (Patricio et al., 2018), as well as the use of manure and corn sourced from farms by a biogas cogeneration firm to generate electricity, with the heat going to manure-drying and a greenhouse in Belgium (Verguts et al., 2016). Other examples include the use of straw from local farms by bioethanol manufacturing plant and yeast slurry from production processes as a substitute for fertilizer in agricultural settings in Denmark (Valentine, 2016), and farms distributing, exchanging or selling side streams generated in their production for off-farm use and used as bedding, fertilizer, feed, soil conditioning, growing mediums, or ground cover in Finland (Hynni et al., 2025).

It is emphasized that IS can be both planned and spontaneous (Chertow, 2007). Scholars, looking at the development of eco-industrial parks, put an emphasis on the geographic proximity or co-location of businesses as a key factor enabling such symbiotic inter-firm relationships (Chertow, 2000). Yet, more recent studies acknowledge that the underlying synergies can as well occur between more distant entities (Neves et al., 2020), and thus proximity does not act as a mandatory precondition. Other factors fostering IS, as identified by Valentine (2016), include a pragmatic environmental spirit, opportunities to explore new possibilities, initiatives that provide mutual benefit, and dominant needs stimulating proactive search for solutions.

Besides the facilitating factors, there are inevitably many difficulties and failures in pursuing this type of inter-organizational collaborative arrangements. As highlighted by Neves et al. (2020), this is not least due to the receiving company's dependence on the quality and quantity of the externally supplied waste, with a failure in this supply bearing the risk of compromising the whole business model. Mahjoub and Domscheit (2020) also emphasize challenges faced on the way toward the organic waste-based bioeconomy that are related to the physical and chemical variability of waste streams, the required scope of changes in technologies, production modes, services, infrastructures, pre-existing habits, as well as high level of investments, and sometimes limited governmental initiatives. It is also acknowledged that the degree of coordination and integration required by IS can be difficult to both start and maintain (Bansal and Mcknight, 2009).

While there are multitude of factors that can and do play a role in enabling or hampering IS, our particular interest in this paper lies in looking at a specified set of factors determining the circular use of bioresource residues in the biobased sectors of agriculture, forestry, and aquaculture. In the following sections we look more specifically into (1) the role these three sectors play in such use of biobased resources, also (2) looking into the companies' basic motivational factors, and (3) distinguishing between plant- and animal-based residues.

2.2 Factors relevant for cross-sectoral flow of bioresource residues

Establishing residue valorization flows within a company or between several companies depends on a variety of factors at the

organizational level (such as available financial resources, presence of research and development, technologies already in place, production efficiency, managers' knowledge and behavior regarding circularity and waste management) as well as at the macro-level (such as existing policy regulations and environmental context) (Vamza et al., 2021). Due to limited technological capabilities and knowledge, companies often treat residues as waste or input for less sustainable and low value streams such as biogas and solid fuel production (ibid.). One way to create increased value of residues is to collaborate with companies from other relevant sectors where biobased residues can find a new value or integrate other sectors into the company's own activities. Hence, to increase the circularity of residues from biobased sectors a cross-sectoral flow of these resources is needed.

To gain more insights into the characteristics of existing biobased residue flows involving AFA sectors, we deem it relevant to distinguish between three categories of relevant factors. The first one is related to mapping the sectors involved. Individual primary production sectors for bioresources are agriculture, forestry, and aquaculture. In addition, bioresource residues can also flow to non-AFA sectors, or these sectors can serve as a bridge sector in this flow. The second category pertains to the type of motivation companies (where the bioresource residues emerge) follow when a sectoral flow of bioresource residues takes place. Here we divide between legal requirements, on the one hand, and interest in increased revenues, on the other. The third category includes the type of bioresource residue. Here we make a distinction between plant-based and animal-based bioresource residues. Figure 1 shows an overview of the selected factors we assume to enable a cross-sectoral flow of bioresource residues explored in this study. These will be explained in more detail in the following sub-sections.

2.2.1 Relevant biobased sectors

We focus on three primary production sectors—agriculture, forestry, and aquaculture (AFA)—that generate and make use of biobased resources in the circular bioeconomy and have the potential for developing relations of industrial symbiosis. We consider other sectors (non-AFA sectors), such as food, energy, feed industries, pharmaceutics, construction, etc., when their engagement is necessary for the establishment of a circular resource flow.

Agriculture (AGRICUL). Agriculture has a significant role in transitioning toward the CE. On the one hand, agricultural production has a considerable negative environmental impact [it contributes to 24 percent of global GHG emissions (Barros et al., 2020)] that need to be reduced. On the other hand, it generates huge amounts of biobased residues [from 2010 to 2016, in EU28, the estimated quantity of the agricultural waste and byproduct were around 18.4 billion tons (Bedoić et al., 2019)] and bears high potential of providing resource-efficient and regenerative solutions to establish closed loops. In the context of IS, agriculture becomes a key actor both as the producer and receiver of byproduct and residual organic matter (Bijon et al., 2022). The use of agricultural residues can considerably reduce the volumes of agricultural waste and the extraction of virgin raw materials. These residues have a broad application to produce energy, food, animal feed, medicines, high-value-added chemicals, fertilizers, various biobased materials, such as bioplastics, biofibers, and biomaterials, etc. (Bedoić et al., 2019; Bijon et al., 2022; Martínez-Moreno et al., 2024). Adding value to agricultural byproducts has an additional benefit for farmers in terms of cost reduction and establishing new revenue streams, and it can act as a springboard for the local economy (Donner et al., 2021). Yet, Bijon et al. (2022) and Martínez-Moreno et al. (2024) argue that the role of this sector has not been well investigated in current IS initiatives.

Forestry (FORESTRY). In the context of the CE, forests represent circular ecosystems that help absorb carbon dioxide. Forests are also the main source of non-food bioresources, and woody biomass is a key source of renewable energy (Gregg et al., 2020). Forest operations generate large amounts of residues, which can be transformed for further use to produce biomaterials, such as wood-based composite panels, wood-plastic composites, wood pellets, and biofuels, such as biochar, bio-oil, syngas, and biogas (Braghiroli and Passarini, 2020). Valorization of forestry residues provides important business opportunities in this sector. However, it is undermined by their technical characteristics (such as non-uniform physical properties, soil and other contaminants) and economic costs of collection and transformation (ibid.; Gregg et al., 2020; Jarre et al., 2020). In the meantime, there is a trend toward a more integrated IS in the sector with collaboration between forestry and related sectors, such as energy and chemical industry, to pool resources for a more effective use of forestry residues (Gregg et al., 2020).

Aquaculture (AQUACUL). For the development of CE, aquaculture is an important sector generating animal protein with lower GHG emissions. Aquaculture residues contain ingredients with high economic value for other industries—they can become a source of minerals, vitamins, proteins, and lipids for their further use in the food and feed industries, production of cosmetics and pharmaceuticals (Coppola et al., 2021; Fraga-Corral et al., 2022). There are also applications of aquaculture residues in construction

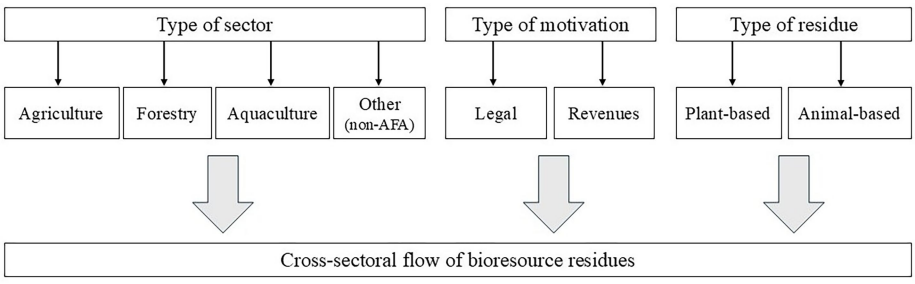

FIGURE 1
Factors characterizing cross-sectoral flow of bioresource residues included in the study.

and energy sectors (Fraga-Corral et al., 2022). Aquaculture, in turn, absorbs residues from other sectors, such as manure, pig slurry, food waste, etc. (ibid.; Sampathkumar et al., 2023). Aquaponics or combination of aquaculture with hydroponics or cultivating plants in water without soil represent examples of symbiotic closed-loop circular systems that reduce resource consumption and waste disposal (de Korte et al., 2024). Again, IS creates new revenue streams and reduces costs for the companies and generates broader economic and environmental benefits.

Non-AFA (NONAFA). Connection to and collaboration with other sectors outside the AFA sectors can be necessary for valorizing or/and using bioresource residues generated in these primary production sectors. Such collaborations facilitate the development of new residue-based products and value chains. As noted above, there are existing solutions and a huge potential of using AFA residues in such industries as food, feed, construction, energy, chemistry, and others (Barros et al., 2020; Ding et al., 2024; Migliore et al., 2020; Stegmann et al., 2020). Extension of the use of renewable residue-based materials with longer-term life cycles beyond the AFA sectors can reduce depletion of non-renewable resources and GHG emissions (Hanssen et al., 2020).

2.2.2 Companies' motivation

Companies might engage in circular initiatives due to different types of internal and external motivations. On the basis of previous studies and considering the binding legal framework of business operations, we have selected the willingness to increase revenues and to meet legal requirements as two principal motivational factors of companies to adopt circular solutions. In addition, these criteria (legal requirements and increased revenues) were part of the STEEP (Social, Technological, Environmental, Economic, and Political) approach applied in the overall research design of the project this study relates to Circle (2023). Furthermore, the methodological specifics of QCA requires us to limit the number of sub-conditions. QCA is based on Boolean algebra. Conditions are represented with binary values meaning that the more conditions we include in the dataset the more theoretical possible configurations we obtain but without more empirical evidence.

Increased revenues (REVENUES). Neves et al. (2020) refer to obtaining economic benefits as one of the key factors that foster IS relationships. Similarly, economic prosperity is featured also as one of the dominant aims or motivations for the CE (Kirchherr et al., 2017; Salvador et al., 2022). This aim may be achieved in various ways such as more efficient use of the resources that reduces costs or by increasing competitive advantage and profits (Salvador et al., 2022). Revenues are crucial for circular business models to operate, hence increased revenues present an important factor for the financial feasibility of circular businesses and streams (ibid.) and can be regarded as a relevant motivational factor for cross-sectoral circular flow of bioresource residues.

Legal requirements (LEGAL). The circular initiative cases in our dataset consists of plant and animal-based residue flows, which have strict legal requirements. Hence, we added legal considerations to test how much they influence the circular flow of bioresource residues. EU and national legislation of the Member States regulate waste management with much detail, along with polices regulating fisheries management, food and feed safety, renewable energy production, etc., with these regulations having a notable impact on the development of the bioeconomy and handling of biowaste streams (Kardung et al., 2021). Our aim was to understand if these legal requirements act as motivational triggers and are presented by the AFA companies as their primary motivation. This interest is in line with our findings from a recent literature review which suggest that legal requirements are rarely highlighted as the driving factor for CE (Salvador et al., 2022). At the same time the incentivizing role of regulatory or permitting pressure is listed among the motivations underlying IS Chertow (2007). Findings from a study on critical success and risk factors for circular business models valorizing agricultural waste and byproducts (Donner et al., 2021) states that successful circular business models in agriculture depend also on external local and (inter)national factors and changes, such as legislative measures and restrictions.

2.2.3 Types of bioresource residues

At a more general level we can differentiate between two types of bioresource residues in the AFA sectors. These are plant-based and animal-based residues. We are interested in exploring whether one type of bioresource residue enables a cross-sectoral flow of these resources more than the other. While there is a certain variability between the AFA sectors in the relative shares of biobased residue types, with aquaculture dominated by animal-based ones, forestry—by plant-based ones, and agriculture featuring a more balanced ratio of the two, both types are present to some extent in each of the three sectors.

Plant-based residues (PLANT). Plant-based residues have great potential to be part of cross-sectoral circular flows for the creation of new value-added products. There is a wide spectrum of plant-based residues that are used to create high-value bio-based products—including food, animal feed, pharmaceuticals, biochemistry and energy production. The inclusion of these products in the CE can significantly increase the economic efficiency of the bioeconomy chain (Salvador et al., 2022). There are different examples such as the use of lignocellulose in agriculture or forestry to produce cheaper bioplastics (Ding et al., 2024; Mujtaba et al., 2023) or protein recovery from non-traditional feedstocks, including crops (soy and wheat proteins) in agriculture (Mahjoub and Domscheit, 2020). One popular way to add new value is by producing bio-humus and selling this to customers (De Nijs et al., 2023).

Animal-based residues (ANIMAL). Animal-based residues are often more difficult to recycle and potentially pose a greater threat to the environment. There is high potential from the agricultural livestock sector for cross-sectoral circular collaborations. Inclusion of animal residues into CE is also particularly important from an environmental point of view (Ampese et al., 2022). Livestock residues such as manure can be transformed to create high value-added products (Ren et al., 2022). We can also find the use of animal-based residues from aquaculture, such as for the production of fish oil or animal feed (Lange, 2022). At the present stage, the most common examples of the circulation of animal-based residues are linked with processing of manure, which is returned to agriculture as well as used for energy production for further application in both AFA and non-AFA sectors (Ramirez et al., 2021; Kanani et al., 2020). New materials for specific applications can also be produced from animal-based residues (Ramirez et al., 2021). Mahjoub and Domscheit (2020) describe recovery of proteins from nonconventional feedstock including cattle byproducts (casein, collagen) and microorganisms.

3 Materials and methods

The following section presents the methodological approach underlying this study. We first provide a short background on QCA followed by a description of the cases included in this study, and the calibration of conditions and outcome.

3.1 Qualitative comparative analysis

We apply a comparative research design called QCA in this study. This method originated in the field of political science, developed by Charles Ragin and has gained a wide interest among scholars in different fields in recent years. QCA has also been applied in the field of sustainable production and consumption (Bai et al., 2021). QCA is a comparative method based on Boolean algebra and set theory (Berg-Schlosser et al., 2009). It bridges case-oriented and variable-oriented approaches (Rihoux et al., 2021). QCA uses specific terminology. The assumption is that cases show a complex combination of different attributes called conditions that imply a certain outcome. It is based on three important concepts, which are (1) conjunctural causation, (2) multifinality, and (3) equifinality (Berg-Schlosser et al., 2009). Conjunctural causation means that not a single condition causes an outcome but that the combination of different conditions leads to a certain outcome. Multifinality means that the same condition can imply a different outcome depending on its combination with other conditions that are present or absent. Finally, QCA assumes that there is not one combination of conditions leading to a certain outcome but there can be different explanatory non-exclusive combination paths (equifinality).

In our case we assume that the combination of certain conditions enables a cross-sectoral flow of bioresource residues. We conducted a crisp set QCA, which means that conditions and the outcome (cross-sectoral circular flow of a bioresource residue) were operationalized in a binary way (Otte and Maehle, 2022). We decided to apply a crisp set QCA due to the exploratory nature of this research and a strong focus on the qualitative meaning of the conditions without quantitative measurements like the use of interval data where a fuzzy set approach would have been more appropriate (De Meur et al., 2009).

3.2 Case selection

The empirical material of our study consists of 107 cases of bioresource residue flows within, between and beyond AFA sectors in Estonia, Latvia, Lithuania, Norway, and Ukraine (see Table 1 for summary and Table A1 for the full list of analyzed cases). The data collection of these intra- and cross-sectoral circularity initiatives was implemented in the Baltic countries and Norway between May and September 2022, and in Ukraine—between April and June 2023. Altogether we collected 150 cases of bioresource residue flows.

The original methodology of data collection envisaged to capture a diversity of bioresource residue flows in AFA sectors, to grasp a variety of bioresources, types of circular use, value chains, collaborations, and motivations. The unit of analysis was the flow of a single bioresource, either directly or through a bridge sector. This means, if a company had a complex business structure that involved the flow of several bioresource residues or several flows of the same residue, each of them was considered separately. The collected cases have started at different times during the last 15 years. The cases included well-established initiatives in the company or innovative ones that proved their viability. All cases included in the original study were operating at the time of data collection. We applied various sources for the information gathering ranging from prior knowledge of the research team, previous research in the region, consultations with stakeholders, search by relevant keywords in printed and online media. The data were collected in an Excel data sheet and described in a systematic way, using a common template. This included both the description of the essence of bioresource residue flow and primary driving factors as qualitative information, and the coding of the information against the domains of the analysis (conditions) used in this article.

For this article, the data on collected cases were examined in the working group of authors, to determine whether they met all the criteria set forth in the methodology. Cases that were at a research and development (R&D) level were excluded since our interest lies in established bioresource residue flows and relations of IS between operating business entities. In addition, we excluded cases where we lacked information on some conditions or where the company acted as an intermediary in the bioresource flow, i.e., no bioresource residues were created in the process of its own operation. Hence of the 150 originally collected cases we were left with 107 cases.

3.3 Calibration of conditions and outcome

We applied a collective calibration process meaning that a core group of co-authors met together to discuss the calibrations of each condition and outcome for all 107 cases. We calibrated the outcome [1] as a cross-sectoral circular flow of the bioresource residue, and outcome [0] as not a

TABLE 1 Summary of the analyzed cases per country, condition and outcome.

Country	Number of cases	Type of sector				Type of motivation		Type of residue		Cross-sectoral flow of bioresource residues
		Agri-culture	Forestry	Aqua-culture	Non-AFA	Revenues	Legal	Plant-based	Animal-based	
Estonia	22	17	3	2	15	19	3	9	15	15
Latvia	19	16	5	4	10	15	1	16	11	13
Lithuania	21	18	2	5	14	19	0	19	9	16
Norway	16	12	7	6	11	16	0	13	9	14
Ukraine	29	28	3	4	20	23	0	20	14	23
Total	107	91	20	21	70	92	4	77	58	81

cross-sectoral circular flow of the bioresource residue. The end of the flow was defined as when the bioresource residue gains value and the bioresource residue is either used by these companies or a third party.

We calibrated the total of eight pre-identified conditions as follows. Regarding the sector conditions, we calibrated initiatives with a circular flow of a bioresource residue involving the presence of the relevant (AFA) sector with [1]. Initiatives with a circular flow of a bioresource residue without involving the relevant (AFA) sector were calibrated with [0]. As for the company's motivation, initiatives with a circular flow of a bioresource residue showing increased revenues as a motivation were calibrated [1]. Initiatives with a circular flow of a bioresource residue without showing increasing revenues as a motivation were calibrated [0]. Furthermore, initiatives with a circular flow of a bioresource residue showing legal requirements as a motivation were calibrated [1], while initiatives with a circular flow of a bioresource residue not expressing legal requirements as a motivation were calibrated [0]. Regarding the types of bioresource residues, initiatives with a circular flow of an animal-based bioresource residue were calibrated with [1], while those with a circular flow not including an animal-based bioresource residue were calibrated with [0]. Accordingly, initiatives with a circular flow of a plant-based bioresource residue were calibrated with [1], while those with a circular flow not including a plant-based bioresource residue were calibrated as [0].

Table 2 shows how we operationalized the three categories of relevant factors for fostering cross-sectoral bioresource residue flow (see Figure 1) into the QCA terminology. We included the three categories as macro-conditions and the eight identified factors as sub-conditions, which will be included in our analysis. The table illustrates how we calibrated each sub-condition based on its theoretical assumption on the cross-sectoral flow of bioresource residues derived from the literature review outlined in section 2. We followed the same table design applied by Otte and Maehle (2022). We propose that each sub-condition is a potentially necessary condition but that alone cannot produce the outcome (i.e., cross-sectoral flow of bioresource residues) and will have to be combined with other conditions. Hence, each condition may operate in conjunction with other enablers (conditions). In the QCA software, conditions are included in capital letters and abbreviated when necessary. Table 2 shows the abbreviated conditions in capital letters followed by an explanation of its meaning for our analysis. We followed the same presentation style applied by Pagliarin et al. (2019).

4 Results

This section presents the main results of this study. It starts with providing a dichotomized data matrix and truth table of the data set, followed by the main results in form of interpreting the most parsimonious solution of the standard analysis with fsQCA 3.0.

4.1 Dichotomized data matrix and truth table

In our analysis we focus on the (i) sectors involved in the flow of bioresource residues, (ii) companies' motivation to initiate circular flows, and (iii) type of bioresource residues used. Based on the operationalization criteria presented in section 3.3, Table A1 in the appendix illustrates the dichotomized data matrix of selected circular initiatives in the AFA sector. The table indicates that the condition LEGAL shows very little variation. In only four out of 107 cases the condition is present [1]. Hence, we can consider the condition as close to constant and omit it from further analysis. We include it in a separate analysis that is discussed in section 5.3.

The first step in QCA after designing a dichotomized data matrix is to conduct a test of necessity for [1] outcome (cross-sectoral flow of bioresource residues). According to Schneider and Wagemann (2012), necessary conditions show high consistency values of 0.9 or more. We conducted a test of necessity with the fsQCA 3.0 software presented in Table 3. We can see that none of the eight conditions is necessary but three conditions including AGRICUL, NONAFA, and REVENUES are close to be necessary.

We then designed a truth table (Table 4), which sorts cases from the dichotomized raw data table (Table A1) with the same configurations of conditions into one row. We assigned for each configuration a value of [1] (presence) or [0] (absence) based on the consistency values. The threshold was set to 0.75, as recommended in the literature (Schneider and Wagemann, 2012), meaning that all configurations with a consistency of 0.75 or higher were calibrated as [1] outcome (cross-sectoral flow of bioresource residues). This results in the truth table that shows 28 different configurations with empirical evidence information and diversity. Two configurations (see rows 1 and 3) indicate a lower consistency value (0.9). These configurations present a contradictory configuration indicating that all cases included show the same combination of conditions that lead to a [1] or [0] outcome except for one case. The configuration in row 1 was configurated as [1] due to its high consistency values (Schneider and Wagemann, 2012). The same was undertaken with the second contradictory configuration in row 3 implying [0] outcome.

The truth table indicates that we have 21 configurations leading to the outcome [1]. We can see that 22 cases cluster into configuration in row 1, and 11 in row 2. Many of the other configurations are often represented by fewer cases indicating that our dataset includes a potentially high diversity among cases (Otte and Maehle, 2022).

4.2 Most parsimonious solution

We conducted a standard analysis with fsQCA 3.0 for the outcome [1] (a cross-sectoral flow of a bioresource residue), and outcome [0] (not a cross-sectoral flow of a bioresource residue). QCA is based on set theory, which means we cannot logically derive the negative [0] outcome from the [1] outcome (Rubinson et al., 2019). The standard analysis in fsQCA will provide us with three different solution paths (complex, intermediate, and most parsimonious) that differ in their use of logical remainders (logically possible configurations without empirical data). Due to the explorative nature of our study and insufficient theoretical knowledge, which provides us with limited information on logical remainders, we chose to interpret the most parsimonious solution (Schneider and Wagemann, 2012). The most parsimonious solution helps us identify the core conditions for the cross-sectoral flow of bioresource residues. The results from the most parsimonious solution are included in Table 5.

We present the other two solution paths (complex and intermediate) for the [1] and [0] outcome in the appendices

TABLE 2 Calibration of the eight sub-conditions based on theoretical assumptions.

Macro-condition	Sub-condition	Proposition	Calibration	Literature reference(s)
Type of sector	AGRICUL. Role of agriculture	The inclusion of AGRICULTURE enables cross-sectoral circular flow of the bioresource residue	Initiatives with a circular flow of a bioresource residue involving agriculture were calibrated [1]. Initiatives with a circular flow of a bioresource residue without involving agriculture were calibrated [0].	Bijon et al. (2022), Barros et al. (2020), Donner et al. (2021) and Bedoić et al. (2019)
	FORESTRY. Role of forestry	The inclusion of FORESTRY enables cross-sectoral circular flow of the bioresource residue	Initiatives with a circular flow of a bioresource residue involving forestry were calibrated [1]. Initiatives with a circular flow of a bioresource residue without involving forestry were calibrated [0].	Braghiroli and Passarini (2020), Gregg et al. (2020) and Jarre et al. (2020)
	AQUACUL. Role of aquaculture	The inclusion of AQUACULTURE enables cross-sectoral circular flow of the bioresource residue	Initiatives with a circular flow of a bioresource residue involving aquaculture were calibrated [1]. Initiatives with a circular flow of a bioresource residue without involving aquaculture were calibrated [0].	Coppola et al. (2021), Fraga-Corral et al. (2022), Sampathkumar et al. (2023) and de Korte et al. (2024)
	NONAFA. Role of non-AFA sector	The inclusion of NONAFA enables cross-sectoral circular flow of the bioresource residue	Initiatives with a circular flow of a bioresource residue involving NONAFA sectors were calibrated [1]. Initiatives with a circular flow of a bioresource residue without involving NONAFA sectors were calibrated [0].	Ding et al. (2024), Migliore et al. (2020), Barros et al. (2020), Stegmann et al. (2020), Hanssen et al. (2020) and Fraga-Corral et al. (2022)
Type of motivation	REVENUES. Role of increasing revenues	The inclusion of REVENUES enables cross-sectoral circular flow of the bioresource residue	Initiatives with a circular flow of a bioresource residue showing increasing revenues as a motivation were calibrated [1]. Initiatives with a circular flow of a bioresource residue without showing increasing revenues as a motivation were calibrated [0].	Kirchherr et al. (2017), Neves et al. (2020) and Salvador et al. (2022)
	LEGAL. Role of legal requirements	The inclusion of LEGAL enables cross-sectoral circular flow of the bioresource residue	Initiatives with a circular flow of a bioresource residue showing legal requirements as a motivation were calibrated [1] Initiatives with a circular flow of a bioresource residue without showing legal requirements as a motivation were calibrated [0].	Mahjoub and Domscheit (2020), Lestari and Sunyoto (2023), Salvador et al. (2022) and Chertow (2007)
Type of bioresource residue	PLANT. Role of plant-based bioresources	The inclusion of PLANT-BASED enables cross-sectoral circular flow of the bioresource residue	Initiatives with a circular flow of a plant-based bioresource residue were calibrated [1]. Initiatives with a circular flow not including a plant-based bioresource residue were calibrated [0].	Lange (2022), De Nijs et al. (2023), Mujtaba et al. (2023), Mahjoub and Domscheit (2020), and Ding et al. (2024)
	ANIMAL. Role of animal-based bioresources	The inclusion of ANIMAL-BASED enables cross-sectoral circular flow of the bioresource residue	Initiatives with a circular flow of an animal-based bioresource residue were calibrated [1]. Initiatives with a circular flow not including an animal-based bioresource residue were calibrated [0].	Lange (2022), Ramirez et al. (2021), Ren et al. (2022), Ampese et al. (2022), Kanani et al. (2020) and Mahjoub and Domscheit (2020)

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TABLE 3 Analysis of necessary condition with fsQCA 3.0.

Outcome: CROSSFLOW		
Conditions tested	Consistency	Coverage
AGRICUL (Role of agriculture)	0.814815	0.725275
FORESTRY (Role of forestry)	0.234568	0.950000
AQUACUL (Role of aquaculture)	0.246914	0.952381
NONAFA (Role of Non-AFA sector)	0.814815	0.942857
REVENUES (Role of increasing revenues)	0.864198	0.760870
PLANT (Role of plant-based bioresources)	0.765432	0.805195
ANIMAL (Role of animal-based bioresources)	0.506173	0.706897

(Tables A2–A5). In the most parsimonious solution, we can identify three sufficient configurations for a cross-sectoral flow of bioresource residues and two for a not cross-sectoral flow of bioresource residues. We represent these in Table 5 in the form of a configuration chart originally developed by Fiss (2011) and also applied by Otte and Maehle (2022). Filled circles indicate the presence of the condition, and blank circles show the absence of a condition. Blank cells indicate that the presence or absence of the condition is not relevant. The table also includes three parameters of fit, which are raw coverage, unique coverage, and consistency.

Based on the QCA applied in this study, we can identify three combinations of conditions associated with a cross-sectoral flow of bioresource residues. The analysis of the negative [0] outcome reveals two solution paths. For the [1] outcome, configuration 3 including the presence of agriculture combined with Non-AFA sectors shows the majority of cases (50%) with a minimal lower consistency due to two contradictory cases (101LT, 140UA). Interestingly, none of the configurations for the positive [1] or negative [0] outcome include increased revenues as a motivational type, or any type of bioresource residue conditions (plant and animal based residues). This indicates that increased revenues and types of bioresource residues are no core conditions for the presence or absence of a cross-sectoral flow of bioresource residues.

The core combinations of conditions include the sector conditions whereby most cases implying the [1] outcome (cross-sectoral flow) combine agriculture and non-AFA sectors. Hence, for this configuration the revenue motivation and the type of bioresource are not determining conditions enabling a cross-sectoral flow of bioresource residues. The importance thus lies in the sectors involved, which are agriculture and non-AFA sectors. Namely, the cross-sectoral flow of bioresource residues takes place where residues are generated by agricultural production and then used in sectors that go beyond biobased ones, notably broadening opportunities for industrial symbiosis. This combination is followed by cases that either take place in forestry or aquaculture and include the absence of the other. These two paths combined cover 36% of the cases.

5 Discussion

This section discusses the interrelations of the conditions in the three mutually exclusive solution paths important for the [1] outcome (cross-sectoral flow). As QCA takes a qualitative cross-comparative approach, it is important to return to the cases and interpret these (Rihoux et al., 2021). We will describe some of the cases included in each of the three configurations for the [1] outcome (cross-sectoral flow). We chose cases according to the following two criteria (Pagliarin et al., 2019): (1) cases that present good examples of a path; and (2) cases that are uniquely covered by a solution path. Furthermore, this section discusses the role of legal requirements in our analysis and provides contextual information on AFA sectors and bioresource flow specifics across the selected countries. Finally, this section addresses the limitations of this study.

5.1 The combination of agriculture and non-AFA sectors

We can see that solution path 3, which shows the frequent flow of bioresource residues from agriculture to sectors other than forestry and aquaculture, includes examples from all five countries but the majority of cases ($n = 19$) are from Ukraine. We assume that this is due to the importance of agriculture for the Ukraine's economy and less prominent presence of forestry compared to the other four countries. This solution path generally reflects the important role of agriculture as a crucial sector for IS in providing and applying bioresource residues (Bijon et al., 2022). In the analyzed cases bioresource residues emerge in agriculture but then either flow directly to a non-AFA sector, or a non-AFA sector becomes a bridge sector. This aligns with previous research by Ramirez et al. (2021) who illustrate in their work a circular economy approach to livestock industries, where waste materials from livestock industries can be converted into high value products in non-AFA-sectors.

We provide one example from each country included in this solution path in Table 6 to demonstrate the different internal variations. We can see that the cases include a variety of bioresource residues (e.g., organic residuals from plant and seedling production, waste sheep wool) and involve non-AFA sector actors such as food retailer chains, e-shops, and energy suppliers. The frequent use of bioresource residues in non-AFA sectors aligns with results from previous research emphasizing the relevance of agricultural biomass to be converted into different types of bio-based products (Gontard et al., 2018) and serving as a feedstock in particular the energy sector to replace fossil fuels or other non-renewable energy sources (Swaminaathan et al., 2024; Szarka et al., 2021).

The first solution path, represented by configuration 3, provides more empirical evidence to previous claims in IS research arguing for the relevance of non-AFA sectors for fostering circular flows of bioresource residues among the biobased sectors (Lancker et al., 2016). It shows the importance of thinking outside the confines of related sectors and the use of bioresource residues for new applications that provide these resources with a type of "after life" or "new life" to enable a more sustainable production and consumption.

5.2 The combination of aquaculture and forestry

We discuss the second and third solution paths (configuration 1, 2) jointly since they show that aquaculture and forestry are implying a cross-sectoral flow of bioresource residues only if one of them is present and the other absent (see Table 7). The second solution path,

TABLE 4 Truth table with case configurations ([1] = cross-sectoral circular flow of a bioresource residue; [0] = not cross-sectoral circular flow of a bioresource residue).

Row	AGRICUL	FORESTRY	AQUACUL	NONAFA	RE-VENUES	PLANT	ANIMAL	Outcome: CROSS FLOW	Number of cases	Raw consistency	Cases
1	1	0	0	1	1	1	0	1	22	0.9	016LV [1], 029LV [1], 038EE [1], 053EE [1], 066NO [1], 069NO [1], 099LT [1], 101LT [1], 117LT [1], 118LT [1], 119LT [1], 120LT [1], 129UA [1], 131UA [1], 133UA [1], 136UA [1], 140UA [0], 141UA [1], 144UA [1], 145UA [1], 146UA [1], 148UA [1]
2	0	1	0	1	1	1	0	1	11	1	021LV [1], 024LV [1], 035EE [1], 036EE [1], 039EE [1], 076NO [1], 077NO [1], 088NO [1], 108LT [1], 109LT [1], 135UA [1]
3	1	0	0	1	1	0	1	0	10	0.9	003LV [0]; 033EE [1], 043EE [1], 045EE [1], 046EE [1], 047EE [1], 060EE [1], 124UA [1], 127UA [1], 143UA [1]
4	1	0	0	0	1	0	1	0	9	0	004LV [0], 031EE [0], 040EE [0], 042EE [0], 075NO [0], 095LT [0], 098LT [0], 123UA [0], 126UA [0]
5	1	0	0	1	1	1	1	1	8	1	007LV [1], 017LV [1], 034EE [1], 063NO [1], 092LT [1], 097LT [1], 132UA [1], 134UA [1]
6	1	0	0	0	1	1	0	0	7	0	012LV [0], 027LV [0], 044EE [0], 050EE [0], 100LT [0], 128UA [0], 151UA [0]
7	1	0	1	0	1	1	1	1	5	1	064NO [1], 102LT [1], 103LT [1], 103LT [1], 106LT [1], 139UA [1]
8	1	0	0	1	0	1	0	1	3	1	112LT [1], 114LT [1], 149UA [1]
9	1	0	1	0	0	0	1	1	3	1	121UA [1], 138UA [1], 142UA [1]
10	1	0	0	0	0	1	1	0	3	0	022LV [0], 049EE [0], 125UA [0]

(Continued)

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TABLE 4 (Continued)

Row	AGRICUL	FORESTRY	AQUACUL	NONAFA	RE-VENUES	PLANT	ANIMAL	Outcome: CROSS FLOW	Number of cases	Raw consistency	Cases
11	1	1	0	0	1	1	0	1	2	1	005LV [1], 083NO [1]
12	1	1	0	1	1	1	0	1	2	1	078NO [1], 150UA [1]
13	1	0	1	0	1	0	1	1	2	1	008LV [1], 071NO [1]
14	0	0	1	1	1	0	1	1	2	1	041EE [1], 058EE [1]
15	1	0	0	0	1	1	1	0	2	0	025LV [0], 096LT [0]
16	1	1	0	0	1	1	1	1	2	1	010LV [1], 090NO [1]
17	0	0	1	1	1	1	1	1	2	1	026LV [1], 105LT [1]
18	1	0	1	1	1	1	1	1	2	1	061NO [1], 080NO [1]
19	1	1	0	1	0	1	0	1	1	1	018LV [1]
20	1	0	1	1	1	1	0	1	1	1	115LT [1]
21	1	0	0	0	0	0	1	0	1	0	048EE [0]
22	1	0	0	1	0	0	1	1	1	1	032EE [1]
23	1	1	0	1	1	0	1	1	1	1	122UA [1]
24	1	0	1	1	1	0	1	1	1	1	082NO [1]
25	1	0	1	0	0	1	1	1	1	1	013LV [1]
26	1	0	0	1	0	1	1	1	1	1	137UA [1]
27	1	0	1	1	0	1	1	1	1	1	009LV [1]
28	0	1	1	1	1	1	1	0	1	0	065NO [0]

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TABLE 5 Analysis of sufficient conditions for cross-sectoral [1] and not cross-sectoral [0] circular flows of bioresource residues [design adapted from Fiss (2011) and Otte and Maehle (2022)].

Solution path information	Cross-sectoral flow of bioresource residues			Not cross-sectoral flow of bioresource residues	
Configuration number	1	2	3	4	5
AGRICUL			●		
FORESTRY	●	○		○	●
AQUACUL	○	●		○	●
NONAFA			●	○	
REVENUES					
PLANT					
ANIMAL					
Raw coverage	0.234	0.246	0.630	0.846	0.038
Unique coverage	0.185	0.185	0.518	0.846	0.038
Consistency	1	1	0.944	1	1
Solution coverage	1			0.884	
Solution consistency	0.964			1	
Cases with membership	005LV [1], 010LV [1], 018LV [1], 021LV [1], 024LV [1], 035EE [1], 036EE [1], 039EE [1], 076NO [1], 077NO [1], 078NO [1], 083NO [1], 088NO [1], 090NO [1], 108LT [1], 109LT [1], 122UA [1], 135UA [1], 150UA [1]	008LV [1], 009LV [1], 013LV [1], 026LV [1], 041EE [1], 058EE [1], 061NO [1], 064NO [1], 071NO [1], 080NO [1], 082NO [1], 102LT [1], 103LT [1], 105LT [1], 106LT [1], 115LT [1], 121UA [1], 138UA [1], 139UA [1], 142UA [1]	003LV, [1], 007LV [1], 009LV [1], 016LV [1], 017LV [1], 018LV [1], 029LV [1], 032EE [1], 033EE [1], 034EE [1], 038EE [1], 043EE [1], 045EE [1], 046EE [1], 047EE [1], 053EE [1], 060EE [1], 061NO [1], 063NO [1], 066NO [1], 069NO [1], 078NO [1], 080NO [1], 082NO [1], 092LT [1], 097LT [1], 099LT [1], 101LT [1], 112LT [1], 114LT [1], 115LT [1], 117LT [1], 118LT [1], 119LT [1], 120LT [1], 122UA [1], 124UA [1], 127UA [1], 129UA [1], 131UA [1], 132UA [1], 133UA [1], 134UA [1], 136UA [1], 137UA [1], 140UA [1], 141UA [1], 143UA [1], 144UA [1], 145UA [1], 146UA [1], 148UA [1], 149UA [1], 150UA [1]	004LV [1], 012LV [1], 022LV [1], 025LV [1], 027LV [1], 031EE [1], 040EE [1], 042EE [1], 044EE [1], 048EE [1], 049EE [1], 050EE [1], 075NO [1], 095LT [1], 096LT [1], 098LT [1], 100LT [1], 123UA [1], 125UA [1], 126UA [1], 128UA [1], 151UA [1]	065NO [1]

● Indicates presence of a condition, ○ indicates absence of a condition, blank spaces indicate "do not care" [presentation format adapted from Fiss (2011) and Otte and Maehle (2022)].

where bioresource residues from forestry are used in sectors other than aquaculture, includes mostly cases where these residues go to bioenergy production to meet electricity demand. Here the non-AFA sector in terms of energy becomes relevant. The third solution path, where aquaculture is part of a cross-sectoral flow of bioresource residues while not engaging with forestry, includes many cases where residues from fish farms are sold as fertilizer to agriculture but also outside AFA sectors as pet food. This aligns with previous research that has shown that byproducts from aquaculture are widely used in non-AFA sectors, especially as animal and pet food due to their high protein and energy content (Campanati et al., 2021). Furthermore, by being used in the pet food industry they can replace other higher grade products that can be used for human consumption (Stevens et al., 2018, p. 7).

TABLE 6 Example cases from all five countries included in the solution path AGRICUL*NONAFA for the [1] outcome cross-sectoral circular flow of a bioresource residue.

Case	Description of circular initiative
017LV [1]	Using manure and biomass of agricultural origin to produce biogas and make use of the generated heat for farm operations.
043EE [1]	Using sheep wool as a replacement for bubble wrap in packaging.
066NO [1]	Using vegetables otherwise discarded to produce vegetarian ready-made meals.
099LT [1]	Using residues from buckwheat processing to produce biogas used for powering the equipment and heating the plant.
140UA [1]	Using sunflower oil residues to produce animal feed and phosphatide concentrate.

TABLE 7 Example cases from all five countries included in solution paths FORESTRY*aquacul and AQUACUL*forestry. (Capital letters stand for the presence of a condition, lowercase letters the absence of a condition, "*" stands for "and").

Solution path	Case	Description of circular initiative
FORESTRY*aquacul	021LV [1]	Using forest residuals to produce energy in municipal heating.
	088NO [1]	Using wood based on residuals from forestry to produce bioethanol.
	035EE [1]	Using forestry residues to produce heating pellets.
	108LT [1]	Using sawdust and other lumber production residues to produce bioenergy.
	135UA [1]	Using wood residues to produce electricity.
AQUACUL*forestry	013LV [1]	Using lake sediment from fishponds as fertilizer in agriculture.
	041EE [1]	Using residues from the fish industry to produce fish meal and oil for fish feed and pet food.
	064NO [1]	Using animal manure and fish sludge to produce bioenergy and bio-fertilizer.
	103LT [1]	Using residues from pisciculture to produce agricultural fertilizer.
	121UA [1]	Using residues from fish farm to grow tomatoes and greens in an aquaponic system.

It should be noted that the full initial set of 150 cases included also research and development projects from Norway where residues from forestry were used to produce feed for aquaculture thus seemingly counteracting the two identified configurations. However, we excluded these cases from our analysis since they were not yet commercial practices. A business factor that needs to be considered here is that the fractions of forestry-based residues which can in principle be used as part of the fish feed are likely to have a higher commercial value if used in sectors other than aquaculture. Previous research from Norway has shown that yeast produced from wood chips from Norwegian trees can be used as high-quality proteins for farmed fish but the costs for these products are high. In addition, this type of production currently competes with the use of wood fiber for bioenergy production (Solberg et al., 2021). This shows that a cross-sectoral flow of bioresource residues within aquaculture and forestry is still at an experimental stage, but a possibility to be seized more actively in the future.

5.3 The role of legal requirements

The dichotomized raw data table (Table A1) showed that only four cases indicated the presence of legal requirements as motivational condition. One reason for this might be due to methodological limitations as the four cases were all part of a more limited set of cases selected for further in-depth analysis in the original study (not part of this paper) and thus featured a more comprehensive information than the other ones included in the present analysis. In interviews with the managers of these circular initiatives (three from Estonia and one from Latvia), legislative requirements were mentioned as an initial (early) motivational factor for choosing circular solutions. However, information on the majority of other cases beyond these four was mostly obtained from public sources (e.g., company records, websites and other public documents) and in these data sources legal requirements were not explicitly mentioned. Additional interviews with all these cases might have provided a different picture but this was beyond the scope of this study. Hence, our interpretation of the role of legal requirements must be viewed with caution. Furthermore, the utilization of bioresource residues depends on legislative restrictions, the technologies applied, and management decisions. It might be that the managers have not assessed the legislative risks. In a previous study it was found that no company perceived their residues as waste—most companies avoided any formal classification or, at most, considered them by-products (e.g., manure, which is by default defined as such under the EU Waste Framework Directive) (Kenk et al., 2024). The role of motivational factors, however, needs more in-depth future analyses as in this research we did not analyze companies' business models, only bioresource residue flows.

Despite this potential limitation, we provide insights into the legal requirements in the four cases that include the presence of this condition. All four were well-established farms having a long decision-making history on their business development solutions. All these cases were making use of animal-based resources related to manure, the further utilization of which is regulated on EU and/ or national levels. Thus, the Latvian case falls under the EU Waste framework directive (WFD 2008/98/EC) as the manure is used to produce biogas. In turn, the Estonian cases containing circular use of manure are not regulated by WFD, because two of those encompass residues in the form of manure that is distributed to farmers. In Estonia, the use of manure is regulated by the Water Act, and the company can have as many 'livestock units'—standard measurement units defined by WFD

2008/98/EC—as the amount of manure it can use according to the rules. Also, one case consists of a residue from a company's slaughterhouse and meets the four criteria set by WFD. This allows us to assume that regulations adopted long before are no longer explicitly highlighted by companies as important in the future development of certain practices.

5.4 Cross-country comparison of AFA sectors and bioresource flows

To the extent the present study allows drawing cross-country comparisons, from the analyzed non-representative sample of circular initiatives we can see some country-specific trends. These can be related to the unique crops and livestock that are particularly suited to their climate, soil, and farming practices and the specific biobased residues that are put to use (e.g., ones derived from sunflowers in Ukraine, barley in Norway, buckwheat in Lithuania, birch in Latvia). Likewise, there are some differences in the prevalence of specific sectors in these economies—such as fish (salmon) farming in Norway, dairy farming in Latvia—that also bears a notable impact on the availability of specific bioresources for circular use. Note also must be taken of the differences in the prevalent types of production, farm size, their specialization and geographic spread that also can act as hindering or enabling factors of cross-sectoral bioresource residue flows, as, for instance, the presence of diversified farms might allow for more active in-house use of biobased residues, etc. Yet, generally, there are many commonalities between the five countries in terms of the crucial role of forestry, livestock farming, and cereal production in generating the key circular bioresource flows. In addition, in each country there are smaller-scale circular initiatives based on residues derived from more novel or niche crops or livestock production (like grapes in Latvia, insects in Norway, sheep in Estonia, or ostrich in Ukraine). The underlying study shows that the nature of bioresource flows depends on the size and specifics of the companies—while small agricultural or fish farms are locally oriented, sometimes organizing the flows within the same farm business, large multifunctional companies tend to create flows at regional or even national level.

5.5 Limitations

Although we focused on the collection of a variety of examples in AFA sectors, our sample is dominated by initiatives coming from agriculture, with a smaller number of cases related to forestry and aquaculture. These results are particularly surprising in the context of forestry, where the high level of development of this industry in the region would assumably feature a larger number of examples of circular use of the generated residues. The scope of our research does not allow us to explain whether this disbalance results from the specificities of these sectors or the degree of CE development in the selected Northern and Eastern European countries, but this may result in undervaluation of the importance of some conditions in enabling cross-sectoral flow of bioresource residues. It also may result from the obstacles to the use of residues such as wood quality and safety considerations arising from chemical additives (Jarre et al., 2020). Furthermore, in our analysis, we did not consider the 4R framework (reducing, reusing, recycling, recovering) or the waste hierarchy (cascading) as a condition for the QCA, which might be pursued in further studies of this kind to expand the scope of explored conditions of cross-sectoral flow of bioresource residues. Last, when collecting our examples, we did not focus on the distribution of the cases across time. Acknowledging that earlier solutions for bioresource residue flow may influence the expansion of certain approaches and hinder the entering of others in the given region, we recommend considering 'time' condition in future research (see Pagliarin and Gerrits, 2020).

6 Conclusion

This paper applied a comparative approach to circular initiatives from AFA sectors in selected Northern and Eastern European countries to identify patterns of cross-sectoral flow of bioresource residues. This study built on a comprehensive empirical data collection with 107 cases of circular initiatives in the biobased sectors from five countries (i.e., Latvia, Lithuania, Estonia, Norway, Ukraine). By applying the QCA methodology, we identified important factors for cross-sectoral flow of bioresource residues.

There are three main conclusions stemming from the analysis. Firstly, the results indicated that a combination of agriculture and non-AFA sectors is important for enabling a cross-sectoral flow of bioresource residues. This means that circular use of bioresources has a notable potential in cases where bioresource residues generated by agricultural production, such as leaves, overgrown shoots, fruit skins and husks of various grains, as well as skin and bones of animals, are made further use of in sectors that go beyond biobased ones and thus broaden the opportunities for industrial symbiosis. Secondly, the combination of aquaculture with the absence of forestry, or the presence of forestry combined with the absence of aquaculture serve as enablers of cross-sectoral flows of bioresource residues. This means that so far cross-sectoral arrangements between these two biobased sectors are quite limited and probably more difficult to develop due to sector-specific conditions such as limited amount and specificities of the residues not already used in more developed IS with agriculture. Thirdly, motivational factors such as increased revenues and legal requirements faced by companies did not appear as core conditions in the QCA, meaning that these two conditions are not determining factors for the cross-sectoral flow of bioresource residues.

While the present study focused on a limited set of countries in Northern and Eastern Europe, we believe that these insights also contribute to the broader regional and global debates on the potential pathways in the development of circular bioeconomy by promoting both conventional and innovative uses of biobased residues within and across various sectors. As a recommendation for stakeholders working with the CE, we can conclude that non-AFA sectors become central for developing relations of IS in the context of CE. They function either as a destination sector where the bioresource residue is applied (e.g., sheep wool for packaging), or they become a bridge sector in the residue flow from one AFA sector to another, as in the case when manure from agriculture is used for producing biogas (energy), which generates digestate, which is then returned as improved fertilizer to agricultural soils. Furthermore, the results provide additional empirical information on the design

of circular initiatives in the biobased sectors and the role of IS in pursuing cross-sectoral business collaborations. We could see that more R&D is needed for cross-sectoral collaborations between aquaculture and forestry. If the value of certain bioresource residues is not increased across sectors, as it is now with some types of fish feed, interactions between these sectors can be limited. Circular initiatives in the AFA sectors should envision a broader look and consider collaboration with non-AFA sectors to increase the value of their bioresource residues.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

Ethical approval was not required for the studies involving humans because according to EU regulations for ethical approval the procedure was not necessary. The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required from the participants or the participants' legal guardians/next of kin in accordance with the national legislation and institutional requirements because we asked for an oral permission in case of the 12 in-depth interviews. All other data was collected online (e.g., website information, company records). We use anonymised data, without linking our cases to specific companies or individuals.

Author contributions

PO: Conceptualization, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Methodology, Project administration, Software, Supervision, Validation, Visualization. AA-F: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing. OŽ: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. KK: Data curation, Formal analysis, Methodology, Writing – original draft, Writing – review & editing. SŠu: Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Writing – original draft, Writing – review & editing. SSh: Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. AV: Data curation, Investigation, Writing – original draft, Writing – review & editing. DM: Conceptualization, Methodology, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frsus.2025.1490685/full#supplementary-material

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