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Exploring new cellular agriculture-based value chains via an analysis on potential feedstock sources in Finland

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ABSTRACT

The aim of this study was to examine cellular agriculture-based value chains in Finland with two specific objectives: 1) to estimate the potential of selected Finnish agri-food industry side streams and agri-biomasses as the source of carbon for microbial protein production and 2) to identify the barriers and enabling factors related to four cellular agriculture-based value chains based on the Finnish feedstocks sources for fermentation. By evaluating the carbohydrate content of 13 plant-based biomass streams (molasses, brewers spent grain, distillers spent grain, sugar beet stalk, sugar beet pulp, oat husk, wheat bran, rapeseed cake, potato cell juice, potato peels and residues, potato tops, straw, surplus grass) as a sugar source for fermentation, the total microbial protein production potential was calculated annually at ca. 290 000 and 360 000 tons for precision and biomass fermentation, respectively. Among the agricultural and food industry streams, straw and oat husk biomass could theoretically supply feedstock for 211 000 and 22 000 tons of protein per year by biomass fermentation, respectively. This is a substantial amount, e.g. when considering 120 000 tons of protein needed annual by Finnish population. The qualitative part of the study elaborated barriers and opportunities of the biotechnology-based production processes using four value chain concepts with distinct feedstock source (grass, bran/husk, sawdust and greenhouse residues) as case examples. The qualitative analysis concluded that, in addition to bioprocess development for reducing production costs, key factors for ensuring well-functioning cellular agriculture business models include resolving agricultural feedstock pre-processing and logistics, optimized facility location, and access to renewable energy.

1. Introduction

Climate change is posing substantial societal and environmental challenges to the current food production systems. As the food system is a significant source of the greenhouse gas emissions, including substantial land use with related environmental consequences, it is important to aim at reducing the global warming potential of the food system. While European Union has set the carbon neutrality target to 2050 (European Parliament and the Council, 2021), Finland, for example, aims at achieving carbon neutrality already by year 2035, especially through land use changes (Huttunen et al., 2022).

Cellular agriculture is a new way of producing food with minimal use of land (Tuomisto, 2022). Cellular agriculture refers to the utilization of microbial, animal, plant and algae cells for food and feed production. Instead of arable farming and animal production, it is possible to produce feed and food ingredients in bioreactors that resemble brewery tanks. Using this cell-based technology, industrial enzymes and mycoprotein Quorn are currently produced by microbes for the use by the food industry, for example. Companies called Solar Foods (microbial biomass production from CO2), Enifer (microbial biomass production from food industry side-stream), and Onego Bio (precision fermentation for egg protein production) are the first industrial players working with scaling up fermentation-based food protein production in Finland,

Because cellular agriculture is not directly dependent on weather and climate conditions, the technology is expected to enable efficient, year-round food and feed production also in regions typically not suitable for year-round, or even at all for food production. The first calculations suggest that, for example, the production of egg protein by microbes, instead of growing chickens, greenhouse gas emissions can be reduced by up to 72% and land use by 90% (Järviö et al., 2021a). Production of

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edible microbial protein has been calculated to reduce land use 99% and to have 53–100% lower environmental impacts than animal-based food protein sources (Järviö et al., 2021b). However, because most of the production processes are not yet developed to full industrial scale, there are uncertainties about the ultimate sustainability impacts, and which process and value chain factors mostly influence the sustainability indicators.

The sources of feedstock (nutrients for cell cultures), energy and water in the production processes are noted as important factors for the development of sustainable cellular agriculture processes both from economic and environmental viewpoints. Especially the source of carbon is an important component for building a sustainable process, and thus, searching for low-cost and environmentally sustainable carbon sources for fermentation, for example, from agri-food and forest industries is topical. Effective utilization of side streams has already been shown to affect the profitability of microbial fermentation processes both for single cell protein and precision fermentation (Voutilainen et al., 2021). An important aspect to consider is the availability of the feedstocks in the different regions and countries. While there has been a systematic global-level analysis of waste to protein systems (Piercy et al., 2023), it is similarly important to deep-dive into country-specific conditions for scaling up cellular agriculture technologies, as reported for Finland (Seisto et al., 2025).

Besides the feedstock availability, energy infrastructure has a fundamental role in cellular agriculture development. Based on the global dynamic model and life-cycle assessment by El Wali et al. (2024), replacing traditional livestock products with cellular agriculture from 2020 to 2050 can be achieved with environmental benefits, but it will require 33% of the global green energy capacities in 2050. Fasihi et al. (2025) estimated microbial protein production using hydrogen oxidizing bacteria based on variable renewable electricity. They included Finland as one of the study countries noting that when considering the electricity costs only, production in the Nordics was more expensive than in sunny regions, such as Patagonia or Northern Australia.

As feedstock and energy supply are integral part of the cellular agriculture-based value chain development, synergistic solutions with existing industrial actors and infrastructure should be sought after. Development of integrated processes with existing agri-food-industry that eventually benefit both parties should be considered. Currently many agri-food sector's side streams are used as animal feed, bioenergy or composted. The same is valid also to forestry side streams and energy. However, taking into account the required transformation of the food system towards more sustainable and also circular economy-based solutions, planned regulations for biomass use (for example, possible EU bans of the burning of lignocellulosic biomass for bioenergy or input imports from Brazil) and push for cascaded biomass utilization, it should be explored whether the cellular agriculture-based processes would add value to the utilization of different side streams.

Because cellular agriculture is still an emerging sector, the value chains are underdeveloped, and the key value propositions of cellular agriculture need to be improved. Therefore, the aim of this study was to examine distinct feedstock-specific cellular agriculture-based value chains and investigate their potential in food and feed production in Finland. This included two specific objectives, namely i) to estimate the potential of selected Finnish agri-food and forestry industry side streams as a carbon source for microbial protein production (tons per year) and ii) to identify the barriers and enabling factors related to four cellular agriculture-based value chains that were identified based on the availability of the feedstocks and previous stakeholder work (Niemi et al., 2022). The potential of side streams was estimated by using a theoretical calculation that utilised data from various studies and statistics, whereas four value chain concepts were explored in a qualitative business model workshop with Finnish stakeholders and experts, focusing on the barriers of production processes and opportunities for different actors. Three of the value chains were defined around the existing feedstocks and side streams (grass, bran and sawdust) in Finland, and one value chain was a prospective integrated factory of a protein crop-producing greenhouse and a microbial fermentation process.

2. Materials and methods

2.1. Raw materials from agri-food supply chain

Data on the availability of agri-food biomasses were extracted from various sources shown in Table 1. Based on their relevance for Finland, following agri-food biomass streams were included in the analysis: molasses, brewers' spent grain (BSG), distillers' spent grain (DSG), oat bran, wheat bran, barley bran, rapeseed cake, potato tops, food potato peels and screening residue, potato cell juice, sugar beet stalk, sugar beet pulp, straw, and grass (surplus from feed production) (Table 1). The annual volumes and carbohydrate contents of these biomass streams were collected based on the literature (Table 1) with assumptions and information presented below.

Molasses is a sugar-containing by-product from sugar production. Processing 100 tons of sugar beet yields 4-6 tons molasses. Sugar beet production in 2021 in Finland was 403 000 tons (Luke, 2024). Dry matter content in sugar beet molasses is on average 77 %, of which 62% is sugar. Therefore, in 2021, approximately 20 000 wet tons and 16 000 dry tons of molasses containing 9 600 tons of sugars was produced.

BSG, a byproduct of brewing industry, is a carbohydrate-rich raw material, and about half of the dry mass is carbohydrates. In 2020, the production of beer in Finland was 3.7 million hectoliters. With an average value of 17.5 kg of BSG formed per hectoliter of beer, about 65 000 tons of wet BSG is generated per year in Finland. As moisture content in BSG is on average 75 %, the dry mass of BSG was 18 000 tons (Metcalfe et al., 2019). According to Ikram et al. (2017), BSG contains 60-73% lignin, cellulose and hemicellulose from dry basis. DSG is produced as a side stream from ethanol distillation. According to Altia (2021) company, 214 million tons of Finnish barley was used in year 2021, of which 34% was used in feed production. This equals 73 000 tons of dry product. According to Nigam (2017), barley DSG contains about 70% fibres, consisting of cellulose (15–25%), hemicellulose (28–35%) and some lignin.

Sugar beet stalk amount is about 40% of total biomass, thus being roughly 67% of sugar beet mass. Dry matter in sugar beet stalk is about 20 %. In 2021, 403 000 tons of sugar beet was produced in Finland (Luke, 2024). Thus, stalk amount was 270 000 tons and dry mass 54 000 tons in 2021. Sugar beet leaves are composed mainly of cellulose (13% - 18%), hemicellulose (11% - 17%), and pectin (14% - 18%) with small amount of lignin (5% - 6%) (Aramrueang et al., 2017). Thus, carbohydrates count for 29% when excluding lignin and pectin. Sugar beet pulp is a by-product remaining after sucrose extraction from sugar beets yielding about 70 kg dry matter (DM) of pulp from 1 ton DM of sugar beets (Ziemiński et al., 2012). Sugar beet production in 2021 in Finland was 403 000 tons (Luke, 2024) and the dry matter content 23% (Starke and Hoffmann, 2014). Thus, the sugar beet pulp production was 7000 tons dry matter. Sugar beet pulp contains about 30% cellulose, 26,8% hemicellulose, 24.2% pectin and 4.1% lignin and 10.3% protein on dry matter basis. When lignin is ignored, carbohydrate content is 81% and when lignin and pectin are ignored it is 57% (Ziemiński et al., 2012).

Bran is a byproduct of the milling industry in production of cereal flours. In wheat, bran counts typically for 15% of the grain. In 2022, altogether 810 000 tons of wheat was used, of which food use was 362 000 tons. With an assumption that 50% of the wheat used for food would be refined wheat flour (i.e., bran separated), about 30 000 tons bran would be available. Oat husks are the biggest by-product of the oat-milling, and their average share is 25% of the grain (Girardet and Webster, 2011). Based on the total annual oat use in Finland, 669 000 tons (of which food use was 101 000 tons in 2022), it was estimated that 165 000 tons of oat husk are available annually. For this study, 65% carbohydrate content was used for both wheat bran (Sharanappa et al.,

Table 1

Agri-food biomass sources in Finland with information on their annual production quantities and carbohydrate content (dm).

Raw material from agri-food supply chain	Production ton/year (dry)	Carbohydrate content %	Carbohydrates (dry ton)	References for the data sources
Molasses	15 400	62	9 548	Dellait (2024); Luke (2024)
Brewers spent grain (BSG)	16 250	68	11 050	Ikram et al. (2017); Metcalfe et al. (2019); Statista (2024)
Distillers spent grain (DSG)	73 000	70	51 100	Altia (2021, 2024); Nigam (2017)
Sugar beet stalk	54 000	29	15 660	Aramrueang et al. (2017); Luke (2023, 2024)
Sugar beet pulp	2 100	57	1 197	Luke (2024); Starke and Hoffmann (2014); Ziemiński et al. (2012)
Oat husk	165 000	65	96 525	Luke (2024); Welch et al. (1983)
Wheat bran	30 000	65	17 550	Luke (2024); Onipe et al. (2015); Sharanappa et al. (2016)
Rapeseed cake	21 060	51	10 741	Canola Council of Canada (2024); Feedipedia (2024); Luke (2024)
Potato cell juice	4 623	33	1 526	Luke (2024); Pääkkönen et al. (2004)
Potato peels and screening residue	24 750	85	21 038	Luke (2024); Tuomisto and Huitu (2016),
Potato tops	140 000	50	70 000	Hakala et al. (2009); Luke (2024)
Straw	1 462 000	64	935 680	Alakangas et al. (2016); Luke (2023, 2024)
Grass, surplus	678 000	54	366 120	Meyer et al. (2016)
Grass (based on total grassland)	3 840 000	52	1 996 800	Luke (2024); Pihlajaniemi et al. (2020)
Feed crop yield [1]	1 800 000	60	1 080 000	Luke (2024)

[1] Crop yield that is used as feed according to the balance sheet for food commodities (Luke, 2024), including cereals and excluding grass yield.

2016) and oat husk (Welch et al., 1983).

Rapeseed cake is produced when oil is extracted from the seeds. While oil yield is 40-45% of the seed, 55-60% is processed residue in form of rapeseed cake. The dry matter content of rapeseed cake is 89%. In 2021, 30 300 tons turnip rape and 10 900 tons rape were produced in Finland (Luke, 2024). If all rapeseeds were processed and 57.5% residue formed, 23 690 tons of rapeseed cake would be generated. In 2021, the amount of dry rapeseed cake produced was 21 000 tons. Rapeseed cake contains 23% cellulose and non-celullosic polysaccharides and 11% non-fibre carbohydrates. Thus, carbohydrate content is 34% (dry weight basis).

Potato production and processing generates substantial amount of carbohydrate rich streams. Based on statistics (Luke, 2024), the production of potato tops in Finland in 2022 was roughly 140 000 tons (dry matter). With estimate of 50% carbohydrate content, the total available carbohydrates could be 70 000 tons. In the production of potato starch, substantial amount of cell juice is obtained. The amount of used starch potato in Finland has been reported at 174 000 tons per year, of which on average 79.5% is potato cell juice, giving 138 000 tons potato juice annually (Luke, 2024; Pääkkönen, et al. 2004). Potato juice is estimated to contain 105-110 g/L sugar in roughly 10 times concentrated solution, while the dry content is 3.3-3.6%. Thus, one litre of potato cell juice contains about 11 g sugars, which is 33% of the total dry matter, resulting in total to 1526 tons of sugars (dry matter) in 138 000 tons of juice. In potato processing, it is estimated that up to 50% of food potato and food industry potato is peeling or screening residue (Tuomisto and Huitu, 2016). When calculating with a potato (tuber) amount of 330 000 tons in 2021 (Luke, 2024), the residue accounts for 165 000 tons. Dry weight of the peeling residue is estimated to be (15%) and the carbohydrate content 85% from dry weight (Tuomisto and Huitu, 2016).

According to the Natural Resources Institute Finland (Luke, 2023), straw yield is close to the grain yield. However, only 65% of the straw can be harvested from field. In 2021, the production of grains (wheat, barley, oat, rye, ryewheat, mixed) in Finland was 2.6 million tons and thus the estimate for straw production is 1.7 million tons. As the dry matter of straw is 86 %, the annual dry straw yield is 1.4 million tons. Wheat straw contains 37% cellulose, 23-30% hemicellulose (dry weight basis), remaining 30-33% being lignin and ash. (Alakangas et al., 2016). In 2021, 802 000 ha of grassland, including hay, silage, pasture and other grassland were cultivated in Finland. The average silage yield in 2021 was 15.91 ton/ha. Hence, the potential amount of gras was estimated at 12.8 million tons. (Luke, 2024). Dry matter of grass silage was estimated at 30%, and it contains about 52% carbohydrates (Pihlajaniemi et al., 2020). According to Meyer et al. (2016), excess production of grass (grass that is not consumed by the animals) in Denmark is on average 12% of the produced amount. In this study, surplus grassland was estimated at 15% of the total grassland yield. Therefore, the amount of surplus grass in 2021 in Finland was estimated at 2.3 million tons.

2.2. Production potential of microbial protein based on feedstocks from agri-food industry

The potential to produce proteins with cellular agriculture by using side streams as feedstock identified in the previous section was evaluated. Table 1 reports side the availability and carbohydrate content of each side stream. These were used as a data source for sugar availability in the side streams. Moreover, the following estimates were considered in the evaluation: Pretreatment yield for sugars for liquid biomass and/or side streams was set at 100%, because it was assumed that in the liquid streams most of the sugars are or can be converted to be available for fermentation (Hyttinen et al., 2024). For solid biomass or side streams the pretreatment yield for sugars was assumed to be 90% (Niemi et al., 2017; Pihlajaniemi et al., 2020), because solid side streams require pre-treatment, for example by combining steam explosion with enzymatic hydrolysis with some losses during processing. The yield from sugar to protein for precision fermentation production was 0.2 g protein per g sugar, and the yield from sugar to protein for biomass fermentation, also called single cell protein (SCP), was 0.5 g microbial biomass per g sugar (Voutilainen et al., 2021). SCP microbial biomass protein content was estimated at 50% (Ritala et al., 2017), whereas the residual biomass after precision fermentation was assumed to be equal to protein amount (unpublished data of VTT).

2.3. Potential of integration of cell factories with other emerging protein production techniques

In addition to assessing the protein production potential by using industrial side streams as a source of carbon in a cell factory, there is a growing interest in integrating cellular agriculture with other emerging food production technologies such as new greenhouse technologies. Therefore, a scenario of integrating soyabean greenhouse cultivation with a cell factory producing food protein with precision fermentation was examined (Fig. 1). In this scenario, two different proteins are produced in an integrated protein production system. This system combines plant protein production in a greenhouse and protein production via precision fermentation in the cell factory into an integrated production system, and the two production units may utilize each other's side streams as the sources of energy, water and nutrient inputs. In this scenario, greenhouse production uses carbon dioxide from the cell

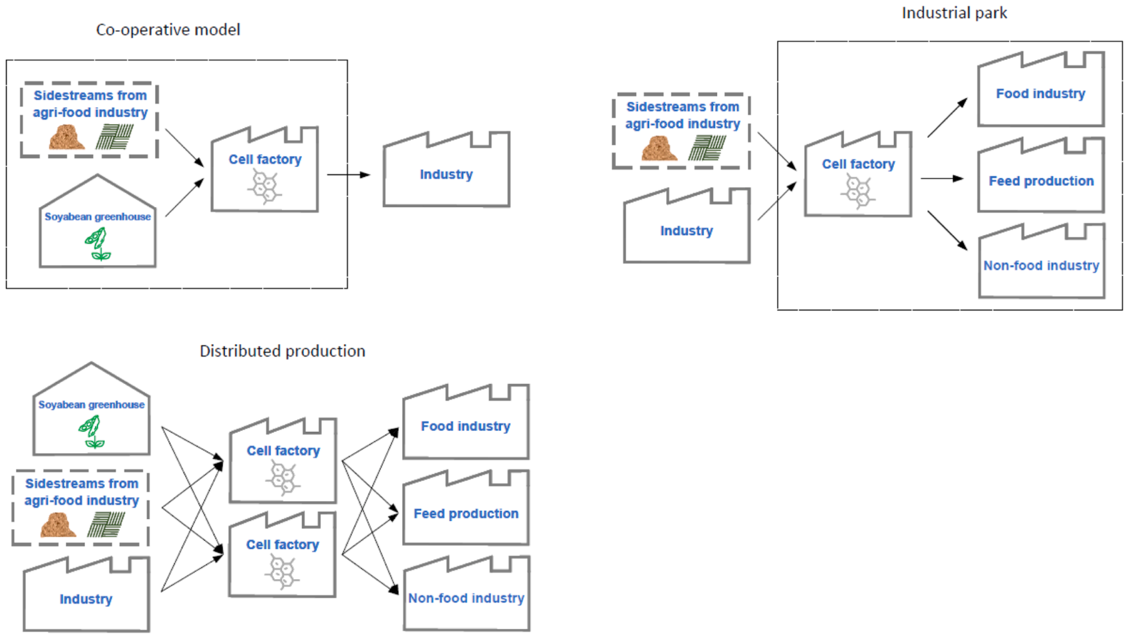

Fig. 1. Theoretical calculation for protein cultivation at greenhouse integrated with cellular agriculture process producing protein by precision fermentation.

factory to enhance the growth of soya beans. In addition, the wastewater containing still some nutrients and originating from cell factory, can be used in greenhouse cultivation. Vice versa, leaves, stems and hulls from soyabean production can be used as a sugar and nutrient source in cell factory after proper pretreatment process. Evaluation of protein production potential in the cell factory was based on the yield estimates given in previous sections. The potential of soyabean production was estimated based on data from an unpublished growing experiment conducted at Natural Resources Institute Finland (Luke) and consultation with a greenhouse expert (personal communication, Titta Kotilainen, Natural Resources Institute Finland (Luke), 13 March 2025).

The set target for the scenario was that the protein produced in the integrated factory should replace 10% of the animal-based protein used as food in Finland. Currently the majority (2/3) of dietary protein consumed in Finland is animal based (Valsta et al., 2018). Based on the recently adopted nutritional recommendations (Blomhoff et al., 2023), protein intake should be 0.83 g/kg for 18–64 years old people. Therefore, 70kg person needs 58.1g protein per day. Because the population of Finland is 5.6 million, the annual total protein need of Finns is 120 000 tons. With this amount, the annual target for the protein production from the integrated factory was set at about 12 000 tons.

2.4. *Conceptualization of the new value chains and business cases*

Based on earlier research and input obtained from a stakeholder workshop carried out by the research team (Niemi et al., 2022), four concepts of cellular agriculture value chains were developed. These concepts are illustrated in Fig. 2 and explained in this section. In general, each concept included a cell factory which input, output and other material streams were depicted. In addition, the concepts elaborated the source of inputs, especially feedstocks (nutrients) to the cell factory, as well as logistics and preprocessing needs related to the fermentation. Concepts 1 and 2 elaborated the supply of inputs to the greenhouse and agriculture, respectively, as well as how any outputs of the cell factory could be circulated back to the greenhouse or agriculture. Moreover, the concepts considered possible destinations of cell factory's outputs and the logistics of these outputs.

The first concept (Fig. 2A) focused on integrating a greenhouse that produces soybean with a cell factory that produced egg protein by precision fermentation. The integrated facility of greenhouse and cell factory requires nutrients, water and energy as inputs. Greenhouse's main outputs are soybean seeds, leaves, stems and used growth media. When the seeds are supplied to soybean refinery to produce plant protein, soy plant side streams are processed by the cell factory (precision

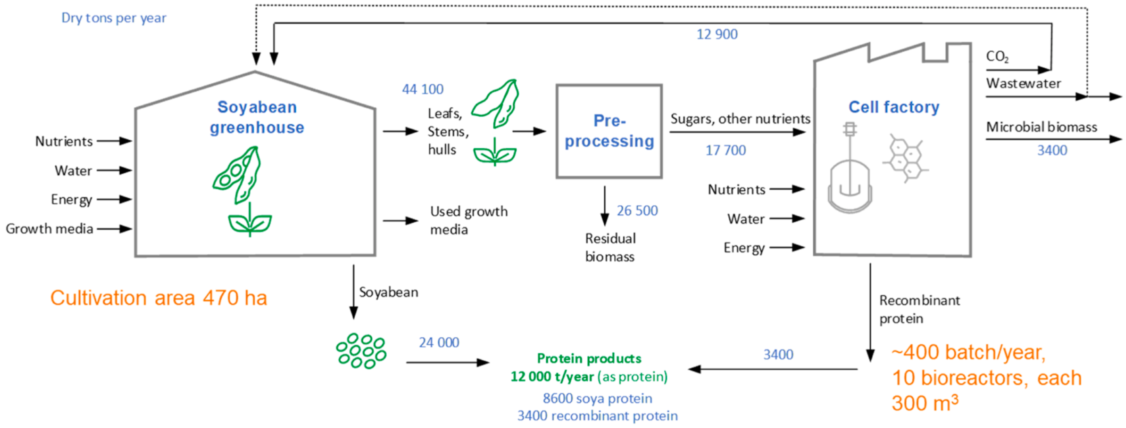

Fig. 2. Four cellular agriculture value chain concepts examined in this study.

fermentation) and growth media by a fertilizer factory. The cell factory could use sugars, but also other nutrients that are obtained after preprocessing the greenhouse's leaves and stems from soybean refinery's processes. An important step in this, and overall, in the concept, is the pre-processing that releases nutrients from the solid ligno-cellulosic biomass streams. The cell factory would produce egg protein for food industry as the main product. Residual microbial biomass after fermentation, produced CO_2 and sewage from the cell factory could be circulated back to the greenhouse, where they could be used as inputs. The residual microbial biomass could be also used as feed or bio-based material compound.

The second concept (Fig. 2B) focused on converting grass to microbial biomass (SCP) that can be used as food or feed. This concept includes the harvesting and supply of grass to the cell factory and it requires stabilization of grass (i.e. the first preprocessing step) before it is transported to further processing or the cell factory, while in other concepts (Figs. 2A, 2C, and 2D) the first preprocessing step is after transportation because the feedstocks are expected to be more stable than fresh grass. Therefore, this value chain would also require storage and preprocessing capacity on the farms. The value chain could be based on a decentralised sourcing of grass. After the stabilization and transportation, the grass is pre-processed to release the nutrients, and the cell factory will then utilize the nutrients of pre-processed grass to produce microbial biomass for food, feed or possibly also for non-food industries depending on the business case. CO_2 and sewage would be the main side streams of this cell factory concept. (Fig. 2B).

In the third concept (Fig. 2C), bran and husk are sourced from mills, transported to preprocessing to enable the use of nutrients in cell factory's process that targets to microbial lipid production. The outputs of a cell factory are fats and oils produced by microbes, which are supplied to food use, and the residual microbial biomass after fat/oil extraction, which is supplied to animal feed or biomaterial production, for example. CO_2 and sewage would be the byproducts of this cell factory as well. The main difference between concept 2 and 3 is that the feedstock of concept 3 is supplied constantly by the industrial actors, whereas in the grass-specific value chain the growth season will influence the feedstock supply and quality.

The fourth concept (Fig. 2D) was based on the exploitation of forest industry's outputs, namely sawdust and bark, which are widely available in Finland. To enable microbes to utilize nutrients from these products, preprocessing to breakdown and hydrolysis of the solid side streams would be required. This is relevant in the other concepts as well (Figs. 2A-C). In the 4th concept the cell factory produced microbial biomass, which is used by food, feed or non-food industries, and CO2 and sewage would be the main side streams. Other possible products of this cell factory concept were chemicals, extracted food ingredients and textile polymers produced by precision fermentation. Hence, the fourth concept was broader than three other concepts.

2.5. Business model workshop

The potential of four value chain concepts was examined qualitatively with stakeholders and experts in a business model workshop. A business model represents a structure that describes how and why the firm transacts with its customers, suppliers, partners, and vendors (Zott and Amit, 2008). Value proposition is the central element of a business model (Osterwalder et al., 2005). A workshop to analyse and develop the value chain concepts was organized on November 8th, 2022 in Espoo, Finland. The purpose of the workshop was to discuss in detail about the development of four proposed value chains related to cellular agriculture (Fig. 2), as well as to consider different business models and the structure of the operator network. Altogether 30 experts participated in the workshop. The participants included 16 experts of private companies, both small startups and well-established large enterprises, 13 experts from research institutes or universities and an expert from a public administration organisation. The participants represented a range of expertise, such as food science, biotechnology, technology, chemistry, biology and agricultural sciences. The participants were recruited by email invitations that were send to a stakeholder distribution lists in Southern and Western Finland as well as to persons who had attended an earlier project workshop (Niemi et al., 2022). The management of personal data was compliant with the European General Data Protection Regulation. The results of the workshop were recorded in an anonymous format so that the input provided by each participant was disassociated from his or her identity. The participants were asked a consent to participate in the study. No prior ethical review of the workshop protocol was needed, because no sensitive information was asked in the workshop (see TENK, 2019).

The workshop lasted half a day. It started with researchers' presentations that gave background information about the topic. Next, the participants were presented the guidelines of the group work. The participants were divided into four groups. Each group focused on one of the four case study concepts presented in the previous section (Fig. 2) by using a business model canvas (Supplementary Fig. S1). Each group was facilitated by a researcher working for the project by which the study was implemented. The facilitator recorded the input to the canvas that the participants provided either by post-it notes or by verbal communication Supplementary material, Fig. S1). After having discussed a concept for 60 minutes, the participants moved to discuss about another concept for 30 minutes. In the latter discussion, information provided by the previous group was summarised by the facilitator before the discussion was started. Finally, all participants gathered in a plenary session where the facilitators summarized input to each concept (15 minutes), and the participants had an option to provide their final remarks.

A modified business model canvas (modified from Osterwalder, 2004), was used to organize the discussion in the workshop. The canvas template is presented in Supplementary material, Fig. S1. Business models describe the company and how it captures and creates value (Zott et al., 2011). The building blocks of the business model canvas originate from the work of Osterwalder (2004). Each concept was examined by using a modified business model canvas (modified from Osterwalder, 2004) that examined seven questions. These questions were:

1. Concept idea: What is our hypothetical solution for?
2. Who will be the customers (buyers), end-users, beneficiaries and stakeholders of our concept?
3. What kind of enablers and capabilities do we need to develop to make the concept fly? How are we able to fill in the gaps on processes?
4. What kind of problems, challenges and user or business needs does the concept address?
5. Value propositions for customers, users and stakeholders: What kind of value does the solution idea create and for whom?
6. Future markets: To which customer segments will our idea be relevant for?
7. Novelty value: How is your solution idea exponentially better than the other alternatives?

Future markets and novelty value were discussed only briefly in each group. After the workshop the authors summarised the discussions, carried out a qualitative thematic analysis of each discussion group and compared the aspects raised by each group.

3. Results and discussion

3.1. Potential of agri-food feedstocks for production of protein by precision or biomass fermentation

In this study, the production potential and business prospects of four cellular agriculture-based value chains and related technologies in food and feed production in Finland were examined. Altogether 13 plant-based feedstocks from agri-food chain (i.e., molasses, brewers spent grain, distillers spent grain, sugar beet stalk, sugar beet pulp, oat husk, wheat bran, rapeseed cake, potato cell juice, potato peels and residues, potato tops, straw, and surplus grass (Table 1)) available in Finland were evaluated as feedstocks for fermentation processes. Table 2 summarizes the theoretical protein production potential from these feedstocks by precision or biomass fermentation technology. By combining the carbohydrate (and related theoretical available sugar) content of all the feedstocks, the total annual protein production was calculated to be about 290 000 tons and 360 000 tons for precision and biomass fermentation, respectively. In addition, a substantial amount of microbial cell biomass would be produced. Based on the expected conversion of sugar to protein (Voutilainen et al., 2021), the calculated protein production potential was lower for precision fermentation than for biomass fermentation. Because straw, surplus grass and oath husks had the largest annual production volumes in Finland, they also showed the highest potential for microbial protein production. Straw covered 59%, surplus grass 22% and oat husk 6% of the total production potential, whereas the ten other feedstock materials represented less than 13% of the production potential. The straw biomass available in Finland could theoretically supply sugar source for about 211 000 tons microbial biomass protein production. This is a substantial amount when considering that the population of Finland needs 120 000 tons protein annually. Regards to the studied food industry side streams, oat husks and distillers spent grain were the biggest streams enabling production of microbial biomass protein production of ca. 22 000 and 11 000 ton/a, respectively. For comparison, theoretical protein production using current Finnish feed crops and total grassland biomass was calculated, and as expected, especially the potential for grass biomass is huge, suggesting annually 450 000 tons microbial biomass-based protein production using grass as a feedstock in fermentation (Table 2).

Table 2
The theoretical production potential (ton/year) of microbial protein production in Finland by precision or biomass fermentation processes. Losses due to downstream processing are not considered in these values.

Agri-food biomass, i.e., the feedstock for fermentation	Protein by precision fermentation	Cell biomass byproduct from precision fermentation	Protein by biomass fermentation	Cell biomass by biomass fermentation
Molasses	1 910	1 910	2 387	4 774
Brewers spent grain	1 989	1 989	2 486	4 973
Distillers spent grain	9 198	9 198	11 498	22 995
Sugar beet stalk	2 819	2 819	3 524	7 047
Sugar beet pulp	215	215	269	539
Oat husk	17 375	17 375	21 718	43 436
Wheat bran	3 159	3 159	3 949	7 898
Rapeseed cake	1 933	1 933	2 417	4 833
Potato cell juice	305	305	381	763
Potato peels, residues	3 787	3 787	4 733	9 467
Potato tops	12 600	12 600	15 750	31 500
Straw	168 422	168 422	210 528	421 056
Grass, surplus	63 461	63 461	79 326	158 652
Total	287 173	287 173	358 966	717 932
Other agriculture feedstocks for comparison				
Feed crops produced in Finland	194 400	194 400	243 000	486 000
Grass, based on the total grassland area in Finland	359 424	359 424	449 280	898 560

As suggested by the theoretical calculations, there is a substantial potential in using grasslands and grass harvest for protein production via fermentation processes. Permanent and temporary grasslands cover about 45 million hectares (Mha) of the EU's agricultural land area. This includes Boreal regions where cereal yields are low and grain legumes do not grow (Huyghe et al., 2014; Peltonen-Sainio and Niemi, 2012; Schils et al., 2022). According to the EU agricultural outlook (EC, 2023), the EU ruminant herd is forecast to shrink by 9-13% by 2035 especially because of environmental policies and growing animal welfare concerns. Such a change would release about 10% of the EU's grassland (4.5 Mha) to other uses, corresponding annually to 37 Mt (dry weight) of grass, e.g. for alternative uses such as food use. From this amount of grass, theoretically almost 9 Mt of mycoprotein (by biomass fermentation) could be produced annually.

Besides the microbial protein production using agri-food feedstocks, two other cases were calculated as they were included in the study as specific value chain concepts (Fig. 2). First, production of microbial lipids was estimated, because it represented one of the value chain concepts in "Concept 3: From bran/husks to food fat/lipids" (Fig. 2C). Regards to this concept, the production potential (ton/a) of microbial lipids was calculated similarly to protein production (Table 2) by using conversion factor of 0.32 from sugars to lipids and production of lipids and microbial biomass 1:1 (w/w) (Ratledge and Wynn, 2002). With these assumptions it was estimated to be possible to produce 5 000 tons or 45 000 tons of microbial lipids from wheat bran and oat husks in Finland, respectively. When compared to for example 41 000 tons of rapeseed produced in Finland in 2021 that results in about 16 400 tons rapeseed oil, the production potential of microbial lipids from individual side streams is substantial, but focussing on speciality lipids might be justified considering the estimated production costs (Bonatsos et al., 2020). Second, the production potential of "Concept 4: From sawdust to food/feed/non-food" (Fig. 2D) was assessed. Although the focus on this study was in agri-food feedstocks, one of the investigated value chain concepts was based on forest-based side stream, mainly because of the substantial amount of forest-based industry in Finland. Finnish forest industry produces annually about 460 000 tons saw dust dry matter. Based on this Fig., the annual microbial protein production volume based on biomass fermentation of saw dust could reach 41 000 ton/a, which is a substantial amount when compared to the volumes and production potential of agri-food feedstocks (Table 2).

When evaluating the microbial protein or lipid production quantities, it is to be noted that the results represent a theoretical estimated maximum amount of ingredient production from the identified side streams. Hence, there are several aspects that must be considered. First, the same assumptions in pretreatment and yield from sugar to microbial biomass, protein and lipid were used for different feedstocks. This may under- or overestimate the production potential depending on the used feedstock. It is also known that preprocessing such as steam explosion can generate inhibitors that can reduce the efficacy of fermentation (Daza-Serna et al., 2023; Niemi et al., 2017). In the present study, the conversion factor of 0.5 g microbial biomass per g sugar was based on the grass silage study using *Paecilomyces variotii* that is a strain known to grow well on lignocellulosic side streams (Pihlajaniemi et al., 2020). The more sensitive strains such as *Trichoderma reesei* can have substantially lower conversion rates (Daza-Serna et al., 2023; Haajanen et al., 2025). Hence, if the conversion factor would be around 0.1 that would result in five times less product when compared to the values of Table 2. Another critical step in the production process is the downstream processing (DSP) that can further reduce the yield of the target compounds. Depending on the end product and production process, DSP can include various unit operations (Li et al., 2024; Shanu et al., 2024). The critical steps in the downstream process include harvesting, washing and separation of the cells from the culture media, cell lysis for the intracellular products (e.g. relevant for lipid production), and the purification of the end product. Besides the end product quantity, also the quality of the product can be influenced by the DSP as reported for lipid production (Gorte et al., 2020). For biomass fermentation products, heat treatment steps for biomass stabilization and nucleotide removal can also cause solid matter and protein loss in the microbial biomass. Regards to precision fermentation for protein production, strains that are capable of secreting proteins extracellularly are beneficial for the recovery of the protein as a simpler process can be applied when compared to the intracellular protein production (Aro et al., 2023).

In the present study, the product yield calculations focused on the sugar content of the feedstocks and neglected the other nutrients required for fermentation, and that would require additional consideration. However, sugar as a carbon source is the critical element in the fermentation process and also the key factor for techno-economic and environmental impacts of the microbial production processes (Järviö et al., 2021a; Voutilainen et al., 2021). A recent LCA study of ovalbumin produced by precision fermentation reported that when compared to a chicken-based egg white powder climate impact for microbially produced ovalbumin was 52–74 % smaller, and land occupation 88–93 % smaller, and the best results for the microbially produced ovalbumin were obtained with a carbon source from a side stream such as straw (Leino et al., 2025). When Voutilainen et al. (2021) estimated the sugar production prices for the side stream based raw materials, the costs were ca. 500 €/ton and higher than other reports around 300–400 €/ton. As the sugar market price has been varying around 300-400 €/ton, the side

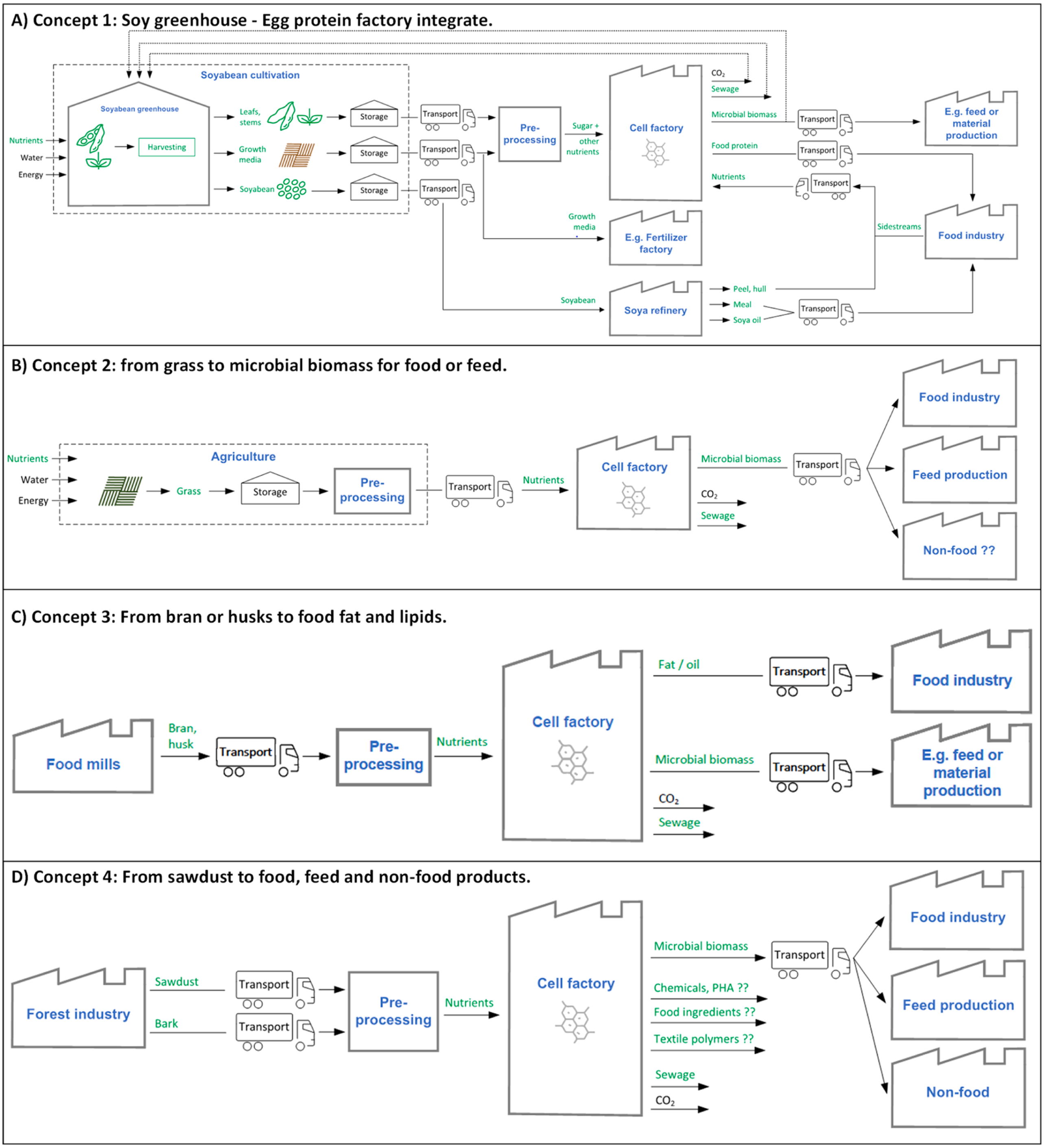

Fig. 3. Theoretical calculations for protein cultivation at greenhouse integrated with cell factory process producing protein by precision fermentation.

stream-based sugar production process would need optimization to reduce the production cost. Besides the feedstock nutrient composition, storage and feasible preprocessing solutions, logistics play a critical role in building a value chain based on the agri-food feedstocks. Especially in relation to the agricultural feedstocks, cost-efficient transportation is essential, as discussed further in the following sections.

3.2. Theoretical calculations for soybean cultivation in greenhouse integrated with cell factory process producing protein by microbes by precision fermentation

In addition to the volumetric potential calculations presented in the previous section, the production potential of the integrated greenhouse-cell factory, i.e. the concept 1 (Fig. 1, Fig. 2A) was assessed. The aim was to assess how large facilities would be required if the protein production by the integrated production concept would replace 10 % of the current animal protein consumption of Finnish population (ca. 12 000 ton/a). The production volumes were estimated based on the side stream yield of soybean cultivation, i.e. how much sugar source soy plant's byproducts would supply to the fermentation process. Thus, the integrated greenhouse-cell factory was estimated to produce 8600 ton/a soybean protein in greenhouses and 3400 ton/a egg protein by precision fermentation. The mass flows are illustrated in Fig. 3. The results showed that 470 ha of greenhouse area and 10 bioreactors of 300 m^3 processing ca. 400 batch/a would be required to reach these production levels. Over the past few years, egg production in Finland has been between 75 000 and 79 000 ton/a (Luke, 2024), which is equivalent to about 10 000 tons egg protein/year. Therefore, a greenhouse-integrated cell factory producing egg protein could cover about one third of the current egg protein production in Finland. The current greenhouse area in Finland is about 340 ha. Therefore, a new factory for soybean protein production would require substantial increase in the amount of greenhouse facilities in Finland. Regards to the bioreactors required for the cell factory producing egg protein, the comparison could be made to existing beer and cider production in Finland, which is about 380 000 m^3/a (Hakkarainen, 2023; The Federation of the Brewing and Soft Drinks Industry, 2024). This would in theory mean about 1500 batches produced in 25-35 bioreactors each having the volume of 300 m^3. Compared to this scale, the new protein production in bioreactors would require infrastructure that equals approximately one third of the existing amount in Finland. Naturally this would mean mostly building new infrastructure, because the beer and cider production facilities are in use and not directly adaptable to precision fermentation.

3.3. Development needs and prospects of the four evaluated value chain concepts

The four different feedstock-specific cellular agriculture concepts (Fig. 2) were assessed by qualitative study using a canvas template (Supplementary Fig. S1) in a stakeholder workshop. The outputs of the group discussions for the different value chain concepts are presented below concept by concept. The canvas template was not strictly followed during the discussions, and thus, the results report the narrative and content of specific group discussions. The main discussion topics are summarised in Table 3, and the detailed results of the group discussions in the Supplementary Table S1

3.3.1. Concept 1: Soy greenhouse– Integrated egg protein cell factory

Although several challenges on the integrated greenhouse-cell factory concept were noted, the group discussion identified also positive viewpoints. One identified challenge of concept 1 was that there may be competing markets for both inputs and outputs of the integrated factory. For example, soya side streams could be used as animal feed. Production methods of concept 1 can also be costly meaning the end products of the integrated factory become too expensive for the customers, hence leading to low competitiveness of the integrated factory. Moreover, it

Table 3
Summary of the main features of the value chain concepts that were discussed in the four groups.

Topic discussed	Concept 1	Concept 2	Concept 3	Concept 4
Key problems, challenges and needs				
Economic challenges, e.g. high production costs, product price, profitability	✓	✓		
High energy use	✓			
Competition with existing use of side streams, justification of use	✓	✓		
Sensitive to terroristic acts	✓			
Sufficiency of quality and quantity of output	✓			
Input supply (safety, quality, quantity or constancy of supply), including side streams	✓	✓	✓	✓
Logistics and storage issues, incl. Location of the facility	✓	✓		
Uncertainty of environmental benefits		✓		
Need to develop or improve (pre-)processing		✓	✓	✓
Better understanding of the business case needed		✓		✓
New technical expertise needed		✓	✓	
Possible use of GMO organisms in cell factories			✓	
Scalability and production capacity issues	✓		✓	
Key enablers and capabilities				
Integration with vertical farming	✓			
Impacts on biodiversity	✓			
Environmental sustainability	✓	✓		
Renewable energy	✓	✓		
Circularity, zero-waste	✓	✓		
Affordable or underexploited inputs		✓	✓	
GMO inputs or outputs	✓		✓	
New or alternative raw materials	✓	✓		
New or alternative outputs	✓	✓		
New business and co-operative models		✓		
Development of processing or preservation techniques		✓		
Integration with a new biobased industry, e.g. textile				✓
Improvements in the current processes		✓		
Water availability in Finland		✓		
Resolved logistic and locational issues		✓	✓	✓
Innovations		✓	✓	
New or revised policies		✓		
Taxation			✓	
Validated processes for quality			✓	
Constant supply of feedstock				✓
Key customers, users, beneficiaries or stakeholders				
Consumers	✓	✓		
Food industry	✓		✓	✓
Farmers (integrate)	✓		✓	
Contract manufacturers globally			✓	
Equipment manufacturers			✓	
Forestry industry, including packaging operators		✓	✓	✓
Feed industry		✓		✓
New sectors: chemicals, medicines, textile, cosmetics etc.		✓		✓
Government, policy makers		✓		
Investors		✓		

(*continued on next page*)

Table 3 (*continued*)

Topic discussed	Concept 1	Concept 2	Concept 3	Concept 4
Value proposition of Customers, Users and stakeholders				
Enhanced environmental sustainability, e.g. zero waste	✓	✓	✓	✓
The product is domestic or local	✓	✓		
Reduced costs			✓	
Tailored product composition, e. g. fatty acids, functional properties		✓	✓	
Adds value, even to all fractions				✓
More from forest				✓
Substituting animal products		✓		
Exiting product from old materials		✓		
Self-sufficiency		✓		
Technology export			✓	✓

✓= topic was discussed in the group.

should be ensured that the carbohydrates and nutrients from soya side streams would be suitable for the fermentation process and that there is sufficient cooling capacity. Energy use was also considered being a key challenge for the integrated factory. Sensitivity to external disruptions was mentioned as a risk in the group discussions, if the production was concentrated in a few large facilities in the country. The value proposition of concept 1 was suggested to be the promise of improved sustainability and domestic protein production. Regarding the key enabling factors for concept 1, vertical farming was mentioned as a possible complementary solution. Possible beneficial effects on biodiversity were suggested as well as that GMO species can offer higher yields than non-GMO.

Synergetic benefits could be identified: when the cell factory and greenhouses are located near each other, for example, heat recovery from cooling of the cell factory could be passed to greenhouses, and also municipal sector could provide food waste as nutrient input to the cell factory. The discussion noted skepticism about soybean production in greenhouse, although soybean was selected as an example for this concept because of its high nutritional value, superior performance in food processing and significant limitations to cultivate soy at open fields in Finland. The workshop participants recommended alternative plants to soybean like fava beans and chickpea. Although fava beans can be produced at open fields in Finland, yield and quality problems were mentioned as challenges of fava beans. In addition, a new flow was suggested. It would include protein extraction from leaves and other by-products of soybean cultivation before utilizing the residues as nutrient source in the cell factory.

3.3.2. *Concept 2: From grass to microbial biomass for Food/ Feed*

In the group discussion of concept 2 “From grass to microbial biomass”, it was noted that opportunities to apply this concept exist especially if there is excess grass or wild grass that can be used as feedstock. The input would be inexpensive and have high protein and sugar content. The key enabling factors to implement the solution that converts grass to feedstock for a cell factory included finding for grass as feedstock an “owner”, who manages logistics, invests in the value chain, and has access to clean energy. This could involve, for example, a co-operative, logistically smart and sufficiently large farmer network, development of harvesting and storage practices, and additional innovations to process the residue after feedstock preparation to energy or fertilizer and that way recycle all nutrients and carbon back to the process. The participants concluded that the costs of grass-based sugar and logistics must be low enough, and supply of grass should be continuous highlighting the need for storage. Environmental impacts of grass cultivation, land use, competition on grass for feed use, and the need to identify the most suitable fractions for fermentation were discussed. Possible regulatory barriers, the concerns regarding low production efficiency, stable product quality, and energy consumption of cell factory were also discussed. The participants pondered whether this concept will reduce land use in a feasible manner; however, environmental sustainability was still viewed as the main benefit. This case was suggested to provide means for carbon sequestration and carbon storage as well as a “domestic ecological plant protein (with reference to grass protein) to replace animal-based proteins”. The environmental benefits were noted to help to reach the set climate neutrality goals. Regards to the value chain model, the outputs of this case were considered relevant mainly for business-to-business trade. The key customers having the potential to use the outputs included food, feed, pet food manufacturers, pharmaceutical and cosmetic industries as well as bioenergy and recycled fertilizer manufacturers, highlighting the broad applicability potential based on this group discussion. Farmers were perceived as one of the key potential beneficiaries of this new farm-centric value chain case, and also consumers would benefit from environmental amenities and new products.

3.3.3. *Concept 3: From bran/husks to food fat/lipids*

Key challenges that arose in the discussion related to the concept 3 “From bran/husk to food fat/lipids” were related to feedstock logistics, meaning that bran and husks are raw material for mills, and currently e. g. oats grains are often transported without milling to central Europe for further use. Thus, to function well, the concept would require that the milling industry exists in Finland. Therefore, the availability of side streams, together with the microbial quality of side streams, were noted as challenges. Moreover, scalability and production capacity of cell factories, and the production process itself raised questions, for example, possible use of genetically modified organisms in cell factories. Efficiency and the costs of both pretreatment of side streams and fat/oil extraction that is required in microbial lipid production, as well as required bioprocess expertise were noted as potentially hindering factors for the concept to realize. At the same time, potential cost reductions, tailored fatty acid composition and healthiness of the produced lipids as well as environmental sustainability (zero-waste) were mentioned as possible selling points of the concept 3. Key enabling factors suggested by the discussion group participants included the location of mills (e.g. centralized pre-treatment, preprocessing facilities and cell factories in a same location, and also collaboration with Estonia), creation of co-operatives that eliminate long supply chains, involving farmers in the value chain, and changes in taxation. In addition, re-thinking existing value chains, and e.g. finding better use for oat side streams, finding applications for GMO microbial cell biomass side streams, and in general additional research funding for increasing the technology readiness level of the processes would facilitate realizing this concept. The discussion group pointed out that brans and husks could also be used for plant protein isolation before feeding to fermentation. However, new byproducts can be generated during processing, and thus, it would be important to Fig. out the end-use for new side streams generated in the new value chains. The identified customers of the microbial lipid production were food industry using emulsifiers, palm oil or cocoa butter, pulp and textile industry using e.g. surfactants, and packaging operators.

3.3.4. *Concept 4: from sawdust to food/feed/non-food*

Group discussion about the concept 4 “From sawdust to food/feed/non-food” concluded possible challenges in food production and suggested more potential for the concept 4 in non-food applications. The concept “from wood to food” raised questions especially from regulatory viewpoint because it may require the novel foods acceptance process. Thus, food was seen rather as a long-term solution than as a short-term business case. The identified future markets for the end-products included applications in packaging, chemical, textile and cosmetic industries. Concept 4 was proposed to offer opportunities for small and medium-sized timbers who have not yet optimized their processes and would benefit from new biorefinery concepts. Enabling zero-waste process and generating value for all streams were suggested as key features that add value to concept 4. A big potential for Finnish forest, food and technology industry was anticipated, because Finland has much forest biomass and related side streams, and the concept was considered as an opportunity to build integrates with the new biobased industry, for instance with new textile fibre production processes. The potential for technology export was also foreseen, and this was considered as a benefit for business generation. Clarification of how the actors obtain added value from new products via fermentation when compared to the current bioenergy use of wood was a noted to be a critical success factors for concept 4. The requirement of pre-processing and pre-separation of added value components before bioconversion, and availability of sawdust stream would be needed to understand the true business potential of this new value chain. An example of a company separating added-value components from sawdust was presented, and this stimulated discussion that value chain development could be started from the perspective of side streams generated in the separation process. The suggested key enabling factors included that sawdust production is constant around the year, which is important for fermentation process, and that logistics systems already exist due to existing forest industry supply chains, although additional infrastructure must be established for collecting and pre-processing (stabilization) of the side streams. The discussion on concept 4 mainly focused on sawdust, whereas bark as a feedstock was discussed only briefly.

3.3.5. General considerations on the studied the value chain concepts

The group discussions indicated similar findings for the four cellular agriculture concepts. However, as already noted, some of the topics raised in the group discussions for the specific concepts (Fig. 2) may be valid for all the cellular agriculture processes and value chains, although they might have been taken up only by some of the discussion groups (Table 3). Therefore, some aspects are further discussed in the following paragraphs to emphasize key elements relevant for the cellular agriculture value chains.

The challenges and potential solutions concerning side stream-based feedstocks for fermentation were thoroughly examined in all four groups. The need to improve feedstock pre-processing and the relevance of feasible logistics were noted important aspects to be solved. As many of the agri- or forest-based feedstocks, including wood-based side streams, are scattered around the countryside, harvesting and stable and standardized supply of feedstocks to the fermentation processes is a key challenge to be resolved. The questions concerning logistics of either inputs or outputs or the location of the facility were also pondered by all the four discussion groups. Another important point related to the feedstock supply that was not much discussed among the stakeholders is the seasonality of the feedstocks. Especially, the production of agricultural feedstocks is highly seasonable, and thus, e.g. for straw and grass feedstocks, year around supply for fermentation needs to be resolved. Pre-processing, stabilization and storage of the stabilized and/or pretreated feedstock close to either a farm or a fermentation factory needs to be optimized to ensure operation of the fermentation factory at maximum capacity.

The cost of production was expectedly noted as a critical point for the business success. Voutilainen et al. (2021) concluded that the production cost of Pekilo protein, that has cellular agriculture origin, should have been on average €5160 per ton, Fusarium protein €6549, Torula protein €7311 and protein by precision fermentation (e.g. egg or dairy) €9007 per ton to make the production of these test cases profitable. In their study, capital costs accounted for 39-46% of the production cost, other fixed costs accounted for about one fifth and other costs for 31-41% of the total production cost, highlighting the importance of capital investments to build the new value chains. Reducing the production cost by strain and bioprocess development and using the side stream-based feedstocks are potential development targets that can improve both the economic and environmental sustainability (Järviö et al., 2021b; Voutilainen et al., 2021).

High energy use was specifically discussed only the group that focused on concept 1, but the issue of energy use is considered relevant also for three other concepts. In general, energy use is important in all cellular agriculture processes, as the production systems are rather energy intensive (Tuomisto et al., 2022), and thus, low-emission cellular agriculture requires ensuring green energy supply. Besides energy and electricity, water is also an important input for the process. A recent report (Välisalo et al., 2025) studied the main risks of cell factories operating in the future and concluded that freshwater shortages, power outages, and scarcity of chemicals and other input materials were potential causes for production interruptions, and also for impairments to occupational health, product safety, and environmental safety.

Also, domestic or local origin of product or the intention of substituting animal products for the outputs of each concept may be relevant for all four concepts. Regarding the beneficiaries, key customers and stakeholders, farmers and food industry were explicitly discussed only for concepts 1 and 2 but they are relevant stakeholders in all four concepts. For example, food industry is the key user of outputs of each concept. Moreover, enterprises and developers would need funding in all four concepts, and they would be affected by policies even if these aspects did not gain major attention during the discussions in all four groups. Indeed, societal and consumer acceptance are important for the market entry of the new food ingredients produced by the cellular agriculture technologies. The availability of cellular agriculture-based products is still limited because of low technology readiness level and pending selling permits, an aspect that is associated with complicated regulatory processes. Hence, also the consumer studies are rare. Public awareness, perceived naturalness, and understanding of food-related risks have been noted as the key aspects to focus when considering the consumer acceptance of cultured meat (Pakseresht et al., 2022). Also Banovic and Grunert (2023) noted naturalness, and concluded that emphasizing similarities to traditional fermentation positively affected the public's perception of precision fermentation. In the EU, a key hurdle for building new value chains is the lengthy novel foods regulatory approval process. Policy support can be a critical element to facilitate the regulatory landscape and market uptake and is a key aspect to consider, although it was not comprehensively discussed by the stakeholder and expert groups in this study.

3.3.6. Business model and value chain structure

Based on the group discussions and previous research (Niemi et al., 2022; Rønning et al., 2024), the cellular agriculture value chains need further development although some parts of the value chains already exist. Building up new value chains that hardly exist now is an opportunity to design a value chain that has a fresh start. Actors can choose the location of their operations and select the most appropriate partners, there is minimal historical burden of structures. Material and energy flows and accumulation of knowledge are important when setting up cellular agriculture value chain. Therefore, an interesting opportunity is to develop an ecosystem where cellular agriculture plant is integrated in terms of material flows, energy and value creation with other production system and industrial parks. Energy infrastructure is indeed an integral part of the new value chains. El Wali et al. (2024), for example, assessed that replacing traditional livestock products with cellular agriculture by 2050 would require 33% of the global green energy capacities. In general, securing investments in building the infrastructure for the new value chain is a critical aspect that has been addressed also in several policy reports. On another note, government support can be essential for the new value chains targeting for alternative protein production (e.g. Rønning et al., 2024).

One of the most critical elements of a business model is the value proposition. It is essential for cellular agriculture business as well. Despite the heterogeneity of business models and industries, there are common elements in different business models, as summarized by Hamwi and Lizarralde (2019). They are narratives that tell the story of businesses by considering the value proposition, value creation and value capture (McGrath, 2010; Osterwalder, 2004), and they can be regarded as ways to unlock the latent value of technologies or commercialize an early-stage technology (Chesbrough and Rosenbloom, 2002). In this respect, four cellular agriculture concepts had both differences and similarities. All four concepts and discussion groups emphasised expected environmental benefits of proposed solutions. Expected environmental benefits were related especially to reducing carbon footprint and to the zero-waste concept. Moreover, concept 2 elaborated enhanced land use and exploitation of already existing infrastructures, making “boring and traditional to something that is new and exciting”. Concepts 3 and 4 by contrast were elaborated also functional properties of outputs of the process. Hence, all concepts tended to emphasize the potential of adding value to the value chain through innovative and sustainable attributes of the output.

Different collaboration models for the cellular agriculture value chains should be explored and developed. Depending on the local and regional infrastructure and available inputs and feedstocks and their competitive advantages and disadvantages, different business models can be applied. Fig. 4 illustrates three options developed by using insights from the workshop. The first option is a co-operative model where greenhouses, side stream suppliers from the agri-food sector and cell factory establish a co-operative and operate the ecosystem jointly. The second option represents an industrial park type collaboration model, where the business entities are separate business operators, but the cell factory and its customers are located geographically close to each other, for example in an industrial park. Third option represented in Fig. 4 is a production ecosystem, where cell factories, its input suppliers and customers are distributed across different geographical locations and the business units may be many but small. Each of these collaboration models have their advantages and disadvantages, as pointed out by workshop discussions. Moreover, different concepts may require different collaboration models. Distributed production, or at least distributed input supply may be the first step model for concepts 2 and 4, because grass and wood are scattered around the country. Co-operative by contrast might be suitable for all concepts and industrial park might be suitable for concepts 1 and 3, because the units may be larger than in concepts 2 and 4. However, if sawdust is sourced from the large factories of timber industry. In general, the local and regional capabilities can influence substantially on what would be the most feasible business model. As discussed by Piercy et al. (2023), more developed regions, with established centralized waste management infrastructure, are better-suited for efficient centralized bioconversion systems, while less developed regions with more dispersed byproduct streams and limited infrastructure presumably benefit more from decentralized solutions. Hence, a systemic optimization approach that integrates both centralized and decentralized technologies, tailored to the regional side stream status, local conditions and industrial capacities, is needed.

A limitation of the current study is that the workshop discussion may not have covered all relevant aspects of each concept. As it was focused on Finnish conditions, comparing to other countries in Europe and globally would also be beneficial. Further research on how to advance cellular agriculture-based business models in different regions is therefore needed. Glaros et al. (2023) noted three key considerations for cellular agriculture futures, namely, to understand the places and scales across which cellular agriculture ‘happens’, to balance competitive industry interests with public-private collaboration, and to navigate the extent to which cellular agriculture interfaces with traditional agriculture. Fairness considerations are also important in the context of cellular agriculture because a transition can have societal consequences (Moritz et al., 2024). As an emerging industry it may not have similar position as traditional agriculture. It may also benefit if its rival position, for example in terms of attracting investors’ funding. Key just aspects include the need for fair distribution of benefits along the value chain, global access to cellular agriculture benefits, and the recognition of social transformations in technological solutions. Additionally, transparent decision-making, open data access, and capacity building for stakeholders are critical elements for fostering equitable and sustainable development in cellular agriculture, as pointed out by Moritz et al. (2024). As presented in this study, cellular agriculture value chains tend to depend on the existing agriculture and food industry. Thus, developing integrated and joint value chains seems a desirable and plausible target that may benefit both existing and new actors.

4. Conclusion

The theoretical calculations and qualitative work conducted in this study suggest that there is a substantial potential in using agri-food feedstocks in cellular agriculture for protein production. With the major side streams and agricultural biomass produced in Finland microbial protein production could, in theory, easily cover the annual dietary protein need of Finnish population. The gaps in feedstock logistics and preprocessing requirements call for development activities to build feasible value chains on the agricultural feedstocks. In the future, feedstock composition would require more attention as only the sugar content was addressed in this study. The findings of this study are to be supported by the real-life technical studies, testing and piloting to confirm the sugar yields and cultivations with different microbial strains to validate the conversion from sugar to the end product, as well as the potential loss during downstream processing. Besides the bioprocess development for the reduction of production costs, value chain structure, optimal location of the facilities, and availability of renewable energy are among the key aspects to be examined in order to ensure a well-functioning cellular agriculture business model. Although this study focused on Finnish conditions, the findings are expected to be mostly valid globally. However, regional capabilities and possible barriers have to be taken into account when adapting the solutions to different continents and countries.

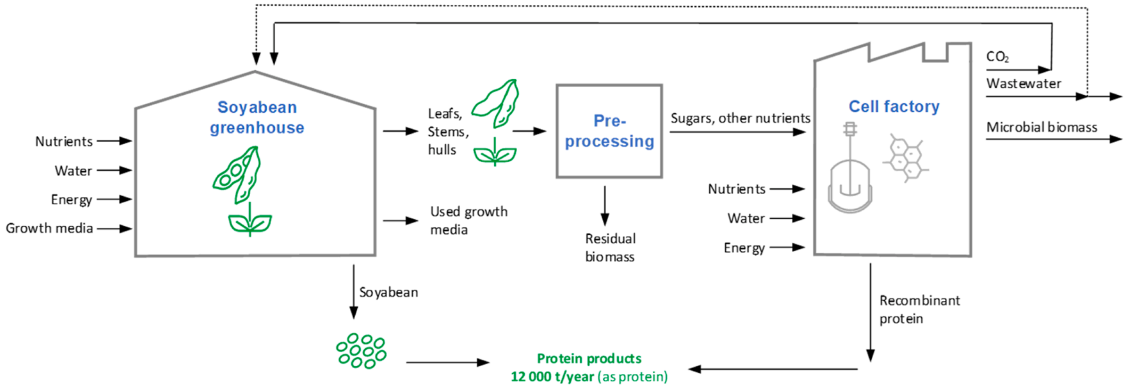

Fig. 4. An outline of three possible collaboration models for the cellular agriculture value chains.

Ethical Statement

All procedures were performed in compliance with relevant laws, institutional guidelines and the Finnish National Board on Research Integrity (TENK, 2019) guidelines and ethical principles of research with human participants.

When conducting the research and data analysis presented in the manuscript, the privacy rights of human subjects was observed. No sensitive information on study participants was collected.

An informed consent was obtained from the participants of the workshop.

Generative AI was not used in this study.

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CRediT authorship contribution statement

Jarkko K. Niemi: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Marja Nappa:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation. **Anneli Ritala:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation. **Emilia Nordlund:** Writing – review & editing, Writing – original draft, Validation, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

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

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.fufo.2026.100951.

Data availability

Data will be made available on request.

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