8 Black is the new green

Sustainable diffusion of Innovation

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The Finnfjord algae project has been labelled a carbon capture and utilisation (CCU) project as it holds significant promise in converting CO_2 into biomass. Distinct from carbon capture and storage (CCS), which focuses solely on trapping and storing CO_2 in underground geological formations, CCU goes a step further, presenting an economic incentive through the potential monetisation of products, services, and technologies derived from CO_2 capture (Friedlingstein et al., 2020; Stocker, 2014; Styring et al., 2011). This approach not only helps reduce point source greenhouse gas emissions but also creates value by turning a harmful waste product into a resource. However, a pivotal concern about CCU is its potential to only delay the eventual CO_2 emission, rather than permanently sequestering it. This has raised questions from scholars in different fields about its long-term impact, with a common perspective that the broader environmental implications of deploying CCU at scale still require comprehensive scrutiny (Olfe-Kräutlein, 2020; Roy et al., 2023).

In the realm of CCU, carbon is captured from the end of one value chain and channelled to the beginning of another. In the context of Finnfjord, primarily a ferrosilicon manufacturer for the European market, the carbon is captured at the end of the ferrosilicon manufacturing value chain and then channelled to growing microalgae. In exploring innovations for sustainability transition, the transformation of CO_2 into diverse products via microalgae cultivation emerges (Mobin et al., 2019; Pulz & Gross, 2004). The dried biomass of these algae possesses intriguing potential. These single-celled algae, called diatoms, are unique for their ornate, glass-like silica-based cell walls, often called frustules. With their intricate patterns and uniformly spaced pores, they are suitable for various applications ranging from energy to aquaculture (Eilertsen et al., 2021). As a type of phytoplankton, diatoms not only play a critical role in carbon sequestration but also contribute to the world's oxygen production, underscoring their ecological importance (McQuatters-Gollop et al., 2011; Omar et al., 2023).

While the microalgae project at Finnfjord embodies sustainable innovation, a thorough examination of its broader implications is essential to label its widespread application as sustainable. However, some challenges remain: while microalgae cultivation offers a promising strategy to curb carbon emissions, utilizing the cultivated algae raises questions, particularly regarding its potential benefits and drawbacks, given

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various factors such as environmental impact and resource utilization. Therefore, by outlining the concepts of sustainable innovation and diffusion, this chapter delves deeper into how this innovative effort can be diffused into different products. It provides insights into whether diffusion is sustainable depending on the method through which the diatoms are utilised or rather, on the mitigation potential of the technology.

Sustainable innovation

An innovation is defined as "idea, practice or object that is perceived as new by an individual or other unit of adoption" (Rogers, 1983, p. 11). In today's rapidly evolving technological landscape, the acceleration of technological change has become a hallmark.

Over time, many forms of environmentally friendly behaviours came to be considered as innovations which in turn meant that they could be studied from a diffusion and adoption perspective (Darley & Beniger, 1981). The concept of sustainable innovation shares several terms with the phenomena, including many similarities and minor differences. Prevalent in the discourse, are concepts such as "environmental innovation," "eco-innovation," "circular economy," "sustainability-oriented innovation," and "green innovation" (Adams et al., 2016; Franceschini et al., 2016; Schiederig et al., 2012). These terms collectively represent a multidimensional approach to understanding innovation within the context of sustainability, offering a rich landscape for academic exploration.

For example, Zubeltzu-Jaka et al. (2018) refer to "green innovation," "environmental innovation," and "eco-innovation" as synonymous terms, insinuating that they include activities whose ultimate objective is environmental protection. One of the most referenced definitions of "eco-innovation" is provided by Kemp and Pearson (2007, p. 7) who define eco-innovation as

> the production, assimilation or exploitation of a product, production process, service or management or business method that is novel to the organisation (developing or adopting it) and which results, throughout its life cycle, in a reduction of environmental risk, pollution and other negative impacts of resources use (including energy use) compared to relevant alternatives.

This comprehensive definition, thus, places emphasis on not only the novelty of innovation but also particularly, the inputs, outputs, and life-cycle impacts of the innovation.

It should also be noted that sustainability-oriented innovation is often used synonymously with sustainable innovation (Hansen & Große-Dunker, 2013). Thus, according to Adams et al. (2016) and Hansen and Große-Dunker (2013), sustainability-oriented innovation is best known as the intentional creation or improvement of new products, services, processes, or practices that aim to enhance environmental and/or social benefits in addition to economic returns. In addition, Axtell et al. (2000, p. 266) acknowledge that sustainability-oriented innovation is therefore "a broader and more complex concept."

Furthermore, the concept of sustainable innovation includes ecological improvements but considers into account a firm's economic and social aspirations and goals.

This holistic perspective means that, rather than focusing on short-term profits, stakeholders place expectations on firms to convene at a triple bottom line of environmental, economic, and social value creation (Freudenreich et al., 2020). Fichter (2005, p. 138) provides a concrete definition of sustainable innovation, conceptualising it as:

> the development and implementation of a radically new or significantly improved technical, organisational, business-related, institutional, or social solution that meets a triple bottom line of economic, environmental and social value creation. Sustainable innovation contributes to production and consumption patterns that secure human activity within the earth's carrying capacities.

In addition, Kemp and Pearson (2007, p. 6) argue that the determinant of whether an innovation is an eco-innovation is: "that its use is less environmentally harmful than the use of relevant alternatives."

In conclusion, according to Halila (2007) and Kemp and Pearson (2007), the use of eco-innovation may or may not aim to reduce environmental harm, due to the fact that eco-innovations might be motivated to achieve business goals such as reducing costs or enhancing product quality. However, sustainable innovations have been challenged by greater financial risks, shareholder uncertainty, larger investments, and to have more regulations (Jinzhou, 2011). Most of these innovations also end up in small-market niches (Clausen & Fichter, 2019), therefore, creating additional barriers for consumers and companies to embrace such innovations (Karakaya et al., 2014). Nonetheless, there is more societal pressure on organisations to move in a sustainable direction, therefore, incentivising them to develop and adopt sustainable innovations as a basic requirement to hold legitimacy (H.-C. Li et al., 2017) and secure their social licence to operate (Bräuer-Provasnek & Sentic, 2016). Moreover, innovations focusing on sustainability benefits will produce spillover effects during the diffusion phase potentially generating a greater competitive advantage for organisations (Montalvo, 2006; Rennings, 2000). During the diffusion process, new uses and users may be found and thus the characteristics of the innovation and the way of how it is used might also change (Kemp & Pearson, 2007).

Olfe-Kräutlein (2020) argues that CCU technology can be considered as an example of sustainable innovation with an intention of having scalable positive impacts on the economy, society, and environment. Cultivating diatom algae can be looked at as a CCU initiative, since carbon is used in photosynthesis, thus this chapter accepts novel ways of cultivating and harvesting diatom algae as a sustainable innovation. However, given that the effect of an innovation determines its sustainability position, also the way that the innovation is diffused should be sustainable. This means that the utilisation of the diatom algae is critical.

Sustainability of innovation diffusion

Within the CCU framework, the principles of Rogers' Diffusion of Innovations theory may offer valuable insights (Rogers, 2003). Diffusion, within this framework, encapsulates the journey of CCU technologies from mere conceptualisation to their widespread acceptance and implementation across varied industries and regions (Mac Dowell et al., 2017). This process isn't merely about the technological adoption; it equally emphasises the proliferation of knowledge, fostering awareness, and cultivating a collective recognition of CCU as an essential solution to carbon emissions (Aresta et al., 2013).

Simultaneously, as diffusion strategies ensure CCU technologies gain traction, the focus shifts to utilisation. This is the transformative phase where captured CO_2 transitions from being a waste product to a valuable resource (Sundaram et al., 2023). The actualisation of this phase sees CO_2 being harnessed for the production of chemicals, fuels, and building materials, and even for processes like enhanced oil recovery.

In essence, Rogers' theory paints a landscape where diffusion sets the stage, creating an environment ripe for CCU technologies' acceptance, while utilisation embodies the tangible, beneficial actions stemming from that acceptance (Mac Dowell et al., 2017).

Rogers defines diffusion as the "process by which an innovation is communicated through certain channels, over time among the members of a social system" (Rogers, 1983, p. 5). While Rogers's innovation theory is fundamental when understanding how innovations diffuse, this framework may benefit from a discussion when it comes to investigating the adoption of "sustainable innovations" (Driessen & Hillebrand, 2002; Karakaya et al., 2014).

According to Rogers (1983), five elements determine between 49% and 97% of the variation in diffusion: (1) *relative advantage:* refers to the degree of how much better an innovation is perceived than the idea it replaces. The degree of relative advantage can be measured in several ways, which could include economic terms, convenience, satisfaction, and social prestige factors. With ordinary diffusion of innovation, the perception of advantage is often cantered around economic benefits, convenience, or increased social prestige (Rogers, 2003). However, with sustainable diffusion, it focuses on the knowledge of a product's real and positive environmental impacts (Hargreaves, 2011). This can incentivise adoption among environmentally conscious consumers, although proving and communicating these impacts can be challenging (Hargreaves, 2011). Relative advantage also extends to environmental benefits such as reduced emissions or resource conservation, which may appeal to those valuing sustainability (Klewitz & Hansen, 2014). (2) *Compatibility:* refers to the degree of how an innovation is seen as consistent with existing values, past experiences, and needs of potential adopters. If the innovation or the idea is not compatible with current values or norms within the social system, the adoption process will take longer for the innovation, if compared to one that is compatible. For an incompatible innovation to be adopted, it often requires the adoption of a new value system. Innovations that fit well with potential adopters' existing values and needs are more quickly adopted (Rogers, 2003). With the case of sustainable diffusion of innovations, adoption is potentially slow, as adopters are typically required to embrace new values or behaviours such as environmental responsibility or responsible consumption (Hargreaves, 2011).

(3) *Observability*: refers to the extent to which the benefits and outcomes of an innovation are visible and easily noticeable to potential adopters. In the context of diffusion theory, the more easily an innovation's positive impact can be observed and understood, the more likely it is to be adopted by individuals and organisations (Rogers, 2003). However, when it comes to sustainable innovations, observability can present unique challenges. Many of the benefits of sustainable innovations, such as reductions in carbon emissions or resource conservation, might not be immediately visible or easily quantifiable. The positive environmental impact of a sustainable innovation can be complex, multifaceted, and often occurs over an extended period, making it less observable compared to more immediate traditional benefits (Hargreaves, 2011). This lack of immediate observability can hinder the adoption of sustainable innovations. Potential adopters may struggle to recognise the long-term benefits, especially if these benefits are not directly evident or easily measurable in their everyday experiences. Communicating the long-term environmental and social benefits of sustainable innovations becomes crucial in overcoming the observability challenge (Klewitz & Hansen, 2014). (4) *Complexity*: refers to the degree of how an innovation is seen as difficult to understand and use. Some innovations are widely understood by members of a social system while others are more complex and will be adopted more slowly. New ideas that are easier to understand will in general be adopted more rapidly compared to innovations that require the user to develop new skills or understandings: less complex innovations, or those easily understood by potential adopters, diffuse more quickly (Rogers, 2003). Sustainable innovations may often be perceived as more complex due to unfamiliar technologies or misconceptions sustainability, necessitating educational efforts (Klewitz & Hansen, 2014). (5) *Trialability:* refers to the degree of how an innovation can be tried and experimented with. New ideas will be adopted more rapidly if they can be tried before adoption compared to innovations that cannot. An innovation that is triable reduces the uncertainty for the potential adopter, as it is possible for the individual to learn by doing: innovations that can be experimented with before adoption also spread more quickly (Rogers, 2003). The ability to try sustainable products can reduce uncertainty and encourage adoption, especially since benefits may not be immediately obvious (Klewitz & Hansen, 2014).

The diffusion of innovations, as conceptualised by Rogers, primarily considers how and why certain innovations spread across social systems and why some innovations are adopted while others aren't (Rogers, 2003). However, when integrating this theory with sustainability, additional criteria may become essential to ensure that innovations not only serve functional or efficiency-based needs but also contribute holistically to the well-being of both the environment and society. Sustainable diffusion refers to the dissemination and adoption of practices, technologies, or innovations that strike a balance between utility and the overarching principles of sustainability. To understand this better, other aspects must be taken into consideration. For example, the aspect of (6) *ecological integrity* which considers that sustainable innovations should ideally have a minimal negative impact on the environment and, if possible, provide ecological benefits (Brundtland, 1987). There is also the aspect of (7) *economic viability*: since sustainable innovations should demonstrate long-term economic viability, ensuring that they remain beneficial and feasible in the long run (Elkington, 1997). In addition, (8) *social aspects* are present with an expectation that innovations should be accessible to, and benefit, all sections of society, promoting overall social well-being (Sen, 1999). Additionally, (9) *cultural and ethical values* come into consideration as innovations need to: align with, or at the very least, respect the cultural and ethical values of its potential adopters (Shove, 2010). Given the rapidly changing ecological and social landscapes, innovations that are rigid might become obsolete. Adaptive capacity, thus, ensures that innovations can evolve based on changing circumstances (Adger, 2003). Finally, it is also worth mentioning that sustainable innovations often thrive when they are the result of inclusive participation and collective efforts (Ostrom, 1990).

In the remainder of this chapter, we will discuss several avenues of diffusion for the microalgae cultivated at Finnfjord. We will discuss their properties and the potential products that present a challenge with regard to the sustainable diffusion of this innovation.

Method

This study explores the sustainable diffusion of products derived from diatoms. Rooted in a qualitative research design, our examination is steered by four potential diffusion pathways highlighted by the Finnfjord research group. The foundation of our analysis, however, rests upon a literature review that narrows down on the most interesting areas of application for diatoms.

Data for this study was, as such, sourced from a spectrum of scholarly articles. Key platforms included Google Scholar, Web of Science, and Scopus, complemented by data from authoritative governmental sources. Selection criteria prioritised potential advantages of integrating diatoms into diverse products. Fundamental to our methodology is the understanding of diffusion dynamics. We evaluated each product's relative advantages, compatibility, observability, integration complexity, and trial feasibility. To make sure that diffusion is sustainable, we strived for a complete sustainability lens. The data had to resonate with principles of ecological integrity, economic feasibility, societal welfare, and ethical alignment. An additional layer of scrutiny was applied to assess CO_2 emissions throughout the product's life cycle. Through this multidimensional lens, we strive to unveil the opportunities and obstacles associated with the sustainable propagation of diatom-based products.

Context and background

The study at hand is situated within the collaborative exploration between UiT-The Arctic University of Norway and Finnfjord AS. This partnership has investigated the potential of utilising factory emissions as a resource to cultivate diatoms, with

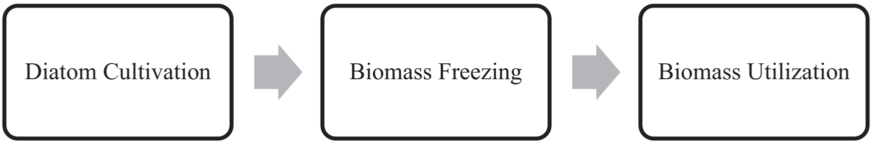

Figure 8.1 General model for production chain of diatom biomass.

the outlined process depicted in Figure 8.1, which delineates the sequential steps in the production chain of diatom biomass.

Diatom cultivation

At its core, the cultivation of diatom algae at Finnfjord operates as a carbon capture initiative. Factory emissions are intentionally channelled through pipes into algae tanks, where photosynthesis takes place (Eilertsen, this publication). The efficacy of CO_2 uptake during this process is contingent on the rate at which emissions are introduced into the tanks; a slower introduction correlates with increased CO_2 uptake. For instance, while test productions have shown a 35% uptake, a more deliberate introduction of emissions can enhance uptake to up to almost 100% (Eilertsen et al., 2022). The goal is absorption of half of the Finnfjord Ferrosilicon Factory CO_2 emission of 300,000 tons. This would significantly contribute to the local CO_2 emission. Furthermore, NO_x emissions, typically regarded as pollutants, have been found to be beneficial for algae, potentially resulting in an annual algae biomass production ranging from 16,500 to 47,000 tonne (Eilertsen et al., 2022).

In their natural form, diatom algae produce 20% of the world's oxygen (McQuatters-Gollop et al., 2011; Omar et al., 2023). Upon their life-cycle completion, diatoms descend to the water body's bottom, effectively sequestering absorbed carbon into the sediment – a process recognised as the "biological pump." Carbon relegated to deep ocean sediments is thus sequestered, distanced from atmospheric interaction for extensive periods ranging from hundreds to thousands of years. This efficient sequestration mechanism, coupled with negligible water footprint, underscores algae cultivation's environmental sustainability (Nagappan et al., 2021). Previous research suggests that water footprints linked to microalgae cultivation could be diminutively reduced by approximately 90% (Pugazhendhi et al., 2020), accentuating its environmentally conscientious water use.

Microalgae cultivation is characterised by its minimal nutrient requirements, permitting growth in various mediums including seawater and wastewater (K. Li et al., 2019). Further, innovative techniques have been used to cultivate algae such as efficiency and reducing the costs associated with the mass cultivation of photoautotrophic microalgae. One significant innovation is in the realm of illumination, which is crucial for the synthesis of biomass. Strategies have been devised to enhance illumination efficiency, leading to a reduction in the energy costs pivotal to algae cultivation (Eilertsen et al., 2023). This research has shown that blue flashing lights not only stimulate the growth of diatoms but also facilitate a biovolume production comparable to that achieved with blue linear light at equivalent maximum intensities (Eilertsen et al., 2023). The use of larger diatom cells was also a novel approach, since the minimise self-shading, which in turn, enables more effective utilisation of light (Eilertsen et al., 2023). The innovation extends to the application of technology designed to optimise microalgae cultivation. By focusing on variables such as algae photosynthetic efficiency, the spectrum and intensity of light, and the absorption and scattering of light in the cultivation medium, novel technological applications and processes are applied. These are anticipated to significantly advance the field of microalgae cultivation. Therefore, innovations in microalgae cultivation techniques not only contribute to economic competitiveness but also hold promise in advancing climate mitigation efforts and promoting a circular economy. By harnessing the potential of microalgae to capture carbon dioxide and generate valuable bio-based products, sustainable innovation in this domain becomes a vital pillar of addressing pressing environmental challenges while simultaneously fostering economic growth.

Biomass freezing

Post-cultivation, the harvested algae are subsequently extracted from the tanks and are subjected to freezing for preservation over extended durations. It is imperative to note that the only CO_2 emissions generated during the freezing process are those associated with electricity consumption. The final consideration, and the primary focus of this paper, pertains to the CO_2 emissions resulting from the eventual utilisation of the biomass.

Biomass utilisation

Biomass utilisation includes processes for converting biomass into products such as foods, fuel, chemicals, and electricity (Ouchida et al., 2016). This chapter focuses on four products; biofuel, battery production, fish feed, and photovoltaics as will be explained next.

Biofuel

The transformation from diatoms to fuel can be achieved through either thermochemical or biochemical processes (Mobin et al., 2019; Zheng et al., 2023). On the one hand, thermochemical conversion leverages heat, producing syngas and subsequently generating fuels, alongside heat and electricity. Common methods within this conversion include gasification, liquefaction, and pyrolysis (K. Mishra et al., 2023). On the other hand, biochemical conversion encompasses a combination of biological and chemical processes, such as anaerobic digestion, fermentation, and esterification (Osman et al., 2021).

Although diatom-based biofuels might witness substantial CO_2 emissions during oil extraction and biodiesel conversion (Saranya & Ramachandra, 2020), on the consumption side, these biofuels are often perceived as carbon-neutral. This

Table 8.1 Biofuel.

Criteria	*Fossil fuels*	*Conventional biofuel production*	*Diatom-based biofuel production*
Resource sustainability	Finite resource; extraction becomes more difficult and environmentally damaging over time	Uses food crops (corn and sugarcane), leading to food versus fuel debate – requires large tracts of arable land, potentially causing deforestation	Diatoms are microalgae that don't compete with food crops for arable land. Can be cultivated in non-arable areas, including wastewater
Water usage	Water is used extensively in the extraction and processing of fossil fuels	Traditional biofuel crops require substantial amounts of water for irrigation	Diatom cultivation can occur in saline or wastewater, reducing freshwater usage
Environmental impact of resource acquisition	Extraction processes (like fracking and drilling) cause significant environmental degradation. Risk of oil spills and other environmental disasters	Use of pesticides and fertilisers in crop cultivation can cause environmental harm. Land-use changes for biofuel crops may result in loss of biodiversity	Minimal use of chemicals in diatom cultivation. No need for significant land-use changes, protecting biodiversity
Carbon footprint	Highest carbon footprint due to high emissions during combustion and release of methane during extraction	The cultivation, harvest, and processing of traditional biofuel crops can be energy intensive. Not all biofuels offer significant carbon emission reductions	Diatoms sequester carbon during growth, potentially offering a lower carbon footprint. Energy-efficient harvesting and processing methods are being developed
Energy return on energy invested (EROEI)	Generally high EROEI, but diminishing as easier-to-access deposits are depleted	EROEI varies but can be low for some biofuel crops	Preliminary studies suggest that diatoms might offer a favourable EROEI, but further research is needed
Waste generation	Produces high amounts of waste, including CO_2, ash, and other pollutants	Crop residues and processing by-products need careful management to minimise environmental impact. Produces similar CO_2 through combustion as fossil fuels	Diatom cultivation may produce less waste, and by-products can potentially be used for other applications. However, combustion delivers CO_2 similar to fossil fuels

(*Continued*)

Table 8.1 (Continued)

Criteria	*Fossil fuels*	*Conventional biofuel production*	*Diatom-based biofuel production*
Land use	Extraction sites can cause large-scale environmental disruption, including habitat destruction	Requires significant amounts of arable land, often leading to land-use conflict and deforestation	Can be produced in ponds, tanks, or bioreactors, being more land effective
Biodiversity impact	Habitats are often destroyed or degraded at extraction sites, negatively impacting biodiversity	Monoculture plantations of biofuel crops can negatively impact biodiversity	Cultivation in controlled environments can mitigate impacts on natural biodiversity
Social impact	Industry jobs are often dangerous and can cause community displacement due to extraction activities	Land acquisition for large plantations might lead to displacement of local communities	Smaller-scale, decentralised diatom cultivation facilities may offer local employment without mass displacement

is because the CO_2 they emit upon combustion is approximately equal to the CO_2 consumed during growth (Chisti, 2007; Searchinger et al., 2008). The CO_2 emissions from diatom-derived biofuels are comparably aligned with fossil fuels (Priya et al., 2022; Sethi et al., 2020). While the utilisation of such biofuels may aid in carbon emission reduction, the production phase remains multifaceted and warrants scrutiny (Sethi et al., 2020). As critics of CCU argue that it merely postpones emissions without offering true mitigation (Markewitz et al., 2012), the perceived carbon-neutral stance of microalgae-derived biofuels thus necessitates an in-depth evaluation (Bradley et al., 2023). It is, therefore, essential to balance the CO_2 intake during microalgal growth against the emissions produced during biofuel processing to achieve a comprehensive understanding of the carbon dynamics associated with these biofuels (Gupta & Hall, 2011; Hall et al., 2014; Khan et al., 2023; Murphy & Hall, 2010; Sundaram et al., 2023).

Battery production

In the evolving landscape of battery production, the incorporation of diatoms presents both potential benefits and challenges. There is a burgeoning global demand for innovative solutions like Li-ion batteries for diverse applications, from electronics to vehicles (Etacheri et al., 2011; Tarascon & Armand, 2001). Traditional carbon coatings in batteries, known for their capacity limitations and stability challenges (Winter et al., 1998), are seeing potential replacements with microalgae, a pioneering approach offering improved performance parameters (Xia et al.,

Table 8.2 Comparison between conventional and diatom-based battery production.

Aspect	*Conventional batteries*	*Diatom-based batteries*
Resource cost	Costs fluctuate due to reliance on graphite and scarce and expensive metals (e.g., lithium, cobalt)	Cultivated, renewable diatoms potentially lead to lower and stable resource costs
Production cost	Well established but can be costly, given the use of expensive materials and energy-intensive processes	Substantial initial costs for further R&D and setting up new production facilities but when cultivated through factory fumes, it is cost-efficient
Operational efficiency	Efficiency and lifespan are often material limited, leading to more frequent replacements	Enhanced efficiency and capacity might result in longer life cycles and less frequent replacements
Waste and recycling	Complex and costly recycling and disposal processes due to toxic materials	Biodegradable and non-toxic diatoms facilitate cost-effective waste management and recycling
Market development	Benefits from established markets, supply chains, and consumer trust	Facts challenge in market acceptance and need investment in consumer education and market development
Complexity in production	Complex and energy-intensive mining and refining processes with established technologies	Less complex cultivation and engineering process but requires new technologies and expertise
Regulatory compliance	Subject to regulations with well-established approval pathways	May face stringent regulatory scrutiny and need extensive testing and certification
Long-term viability	Rising costs of materials and environmental compliance may impact long-term viability	Promising long-term economic benefits due to environmental and operational advantages
Risk and uncertainty	Known risks with established mitigation strategies	Significant risk and uncertainty due to being a new technology

2016). Notably, diatom frustules, subjected to minimal processing, have demonstrated their prowess as efficient anodes in Li-ion batteries, indicating not only enhanced capacity but also reduced electrolyte decomposition issues (Lin et al., 2022). When assessing the environmental footprint during the operational phase, batteries harnessing diatom frustules as anodes don't contribute to direct CO_2 emissions, unlike some traditional counterparts. A holistic life-cycle assessment suggests that the potential environmental merits of diatom-based batteries, especially when considering longevity and performance enhancements, might counterbalance the initial production emissions. Additionally, the opportunity to recycle diatom biomass post-lipid extraction further underscores the sustainability prospects of this approach (X. Li et al., 2009; Zhou et al., 2007).

Fish feed

Microalgae-based products, particularly fish feed, have showcased a significantly reduced carbon footprint relative to their conventional counterparts. Taelman et al. (2013) affirmed that microalgae-sourced fish feed exhibited a substantially diminished carbon footprint when compared to pilot-scale fish feed. These findings are bolstered by the intrinsic capacity of microalgae to sequester carbon dioxide, with evidence indicating a capture rate of up to 1.8 kg of carbon dioxide per kilogram of microalgae (Preedy, 2021). Additionally, the cultivation requirements for microalgae are minimalistic. Given their adaptability to thrive in seawater or wastewater, their water footprint is virtually negligible (K. Li et al., 2019). This assertion aligns with Nagappan et al. (2021), suggesting a near-zero water footprint, and with Pugazhendhi et al. (2020) emphasising the potential to curtail the water footprint of microalgae by 90%. Further, Sánchez et al. (2003) underscored the environmental advantage of microalgae cultivation, elucidating its potential to reduce atmospheric carbon emissions, especially when scaled up.

Using diatom algae in fish feed further could replace the need for soy, which is currently grown in the Amazon rainforest (Eilertsen et al., 2022; Rotabakk et al., 2020). The Amazon rainforest is crucial for the environment for reasons, such as biodiversity, carbon sequestration, and climate regulation, and faces the dual threats of deforestation (Malhi et al., 2008). Diatoms also play a significant role in global oxygen production, with marine phytoplankton, including diatoms, being vital contributors to the world's oxygen through photosynthesis (Field et al., 1998).

The Finnfjord CCU project is noteworthy for its use of algae that can naturally capture CO_2. As a vital CO_2 absorber, this effort helps reduce the pressure on the Amazon. Today, sardine-based maritime oil is a component in fish feed (Lall & Dumas, 2022). However, transporting sardines to Norway releases CO_2 (Johansen et al., 2022). Therefore, using algae for marine products might be a more efficient way of using marine resources (Eilertsen et al., 2022).

Diatom algae serve as a natural nutritional source for marine species such as salmon. Their nutrient profile, enriched with omega 3 and 6 fatty acids, plays a pivotal role in fish development and growth (Eilertsen et al., 2022). A notable observation by Eilertsen et al. (2021) reveals a lower prevalence of salmon lice in specimens fed with diatom algae as opposed to those sustained on traditional feed.

Elaborating on the previously mentioned study by Eilertsen et al. (2021), a detailed analysis of salmon diets incorporated variations like diatom supplements, fish oil, *Calanus* sp. oil, and rapeseed oil. Following an experimental period, salmon from divergent diet groups were exposed to salmon lice copepodites. Remarkably, those on the diatom-enriched regimen exhibited fewer lice infestations. Yet, the underlying cause remained elusive, as the unique fatty and amino acid profiles did not provide a discernible reason. The evidence pivoted toward a potential anti-lice component in diatoms or a diatom-induced deterrent production within the salmon, although the precise mechanism necessitates further exploration (Eilertsen et al., 2021).

Therefore, if algae-based fish feed can significantly replace traditional feed, it might significantly reduce emissions from feed production (Onyeaka et al., 2021; Tham et al., 2023).

Table 8.3 Fish feed.

Criteria	*Conventional fish feed*	*Diatom-based fish feed*
Nutritional content	– Requires addition of various nutrients, which can be synthetic or sourced from fish meal and fish oil – Nutritional content can be inconsistent	– Naturally rich in essential fatty acids, proteins, and other nutrients – Provides a balanced and consistent nutritional profile
Sustainability	– Over-reliance on fish meal and fish oil is unsustainable. Production of synthetic nutrients can be energy intensive	– Diatoms can be sustainably cultivated with a lower environmental impact
Feed conversion ratio (FCR)	– FCR can vary and is often not optimised, leading to waste and inefficiency	– High nutritional content and digestibility of diatoms can improve FCR
Environmental impact	– Production and sourcing contribute to overfishing, habitat destruction, and carbon emission	– Diatom cultivation has a lower environmental footprint and can contribute to carbon sequestration
Cost	– Volatile prices of fish meal and fish oil impact cost. Synthetic additives can also be expensive	– Diatom cultivation systems, once established, can offer a potentially cheaper and steady source of high-quality feed
Health impact on fish	– Might not optimally support fish health and growth, necessitating supplements or medications	– Diatoms support fish health due to their rich nutritional profile, reducing the need for supplements or medications
Disease and parasite management	– Does not inherently contribute to disease or parasite management	– Diatoms might help manage aquaculture challenges like lice infestations in salmon farms
Complexity of production	– Production process can be complex due to the need for various ingredients and nutritional additives – Managing sustainability is also challenging	– Initial setup of diatom cultivation systems can be complex, but the process can be streamlined once established. Complexity also lies in maintaining optimal conditions for diatom growth

Photovoltaics

Diatom frustules, with their unique structures, can scatter light and potentially enhance solar cell performance by improving light absorption and conversion efficiency (Morales et al., 2019). Integrating diatoms into solar cells is still in its nascent stages, with challenges like ensuring diatom durability in solar environments (Uwizeye et al., 2021; Yan et al., 2018). As of 2021, the commercial use of diatoms in photovoltaics remains

Table 8.4. Photovoltaic.

Criteria	*Conventional PV production*	*Diatom-based PV production*
Material efficiency	Uses crystalline silicon, CIGS, or CdTe, requiring resource-intensive processes. Availability and cost of materials can be limiting	Inherent nanostructures of diatoms enhance light absorption without complex fabrication. Abundant and easily harvested, providing a sustainable material source
Energy input	High-energy input needed for silicon PV cells production and installation. Energy payback time (EPBT) is often cited as a drawback	Lower energy needed for material extraction and processing, potentially leading to a shorter EPBT
Toxicity and environmental impact	Some thin-film technologies use toxic materials posing disposal and recycling challenges – Silicon tetrachloride, a by-product, is hazardous	Diatoms are non-toxic, reducing environmental and health risks associated with production and disposal
Light absorption and efficiency	Limitations in light absorption efficiency. Improvements often result in increased costs	Nanostructures of diatoms can trap and utilise light efficiently, potentially increasing energy conversion efficiency without significant additional costs
Manufacturing complexity	Silicon cell manufacturing involves complex processes; thin-film technologies, while simpler, have their own challenges	Diatom-based PV cells might utilise simpler, bio-inspired processes, reducing complexity and costs
Waste and recycling	Contains materials that are challenging to recycle, contributing to e-waste	Potentially more recyclable due to biological origin, reducing e-waste and facilitating circular economy approaches
Material scarcity	Relies on rare or scarce materials, causing sustainability and price volatility concerns	Diatoms are abundant, offering a solution to material scarcity issues
Complexity of production	Production processes are intricate and sophisticated, requiring advanced technology and expertise. Thin-film technologies simplify production but introduce new challenges	Production might be less complex due to the biological nature of diatoms, but optimising their use in PV cells will require specialised knowledge and technical competence

largely experimental (Chen et al., 2022). Diatoms showcase intricate nanostructures surpassing the capabilities of many advanced synthetic procedures (M. Mishra et al., 2017). Growing diatoms requires equipment, water, nutrients, and often artificial light, but they absorb CO_2 during photosynthesis, offsetting some emissions (Najiha Badar et al., 2021). Once grown, extracted silica frustules from diatoms undergo processes like drying and chemical treatment, which consume energy (The Norwegian University of Science and Technology (NTNU), 2012). The incorporation of diatom material into solar cells varies based on the solar technology and integration method (Huang et al., 2015; Jeffryes et al., 2011). Solar cells with diatoms might have CO_2 emissions comparable to conventional solar cells during usage, which is nearly zero, while end-of-life handling could add to emissions (Muteri et al., 2020; Wang et al., 2022). The CO_2 emissions from each stage should be weighed against potential benefits, like increased efficiency (Huang et al., 2015). Leveraging renewable energy and biotech advances can minimise these emissions. Detailed life-cycle analyses are necessary for precise CO_2 emission assessments (Yang et al., 2022).

Discussion

The sustainable diffusion of diatoms across various applications holds significant promise, primarily when evaluated through Rogers' diffusion of innovations theory (Relative Advantage, Compatibility, Observability, Complexity, Trialability) and extended to encompass ecological integrity, economic viability, societal welfare, and cultural and ethical norms.

Relative advantage: One of the key driving forces behind the adoption of an innovation is its relative advantage over existing alternatives. In the four product categories we have examined, the use of diatoms seems to have some advantage over the traditional product. However, a significant critique lies in the domain of carbon neutrality. Biofuels from diatoms, while deemed carbon-neutral, release as much CO_2 upon combustion as fossil fuels. The reasoning behind the "carbon-neutral" label is that the CO_2 released during combustion was originally absorbed from the atmosphere during photosynthesis, creating a closed loop. Yet, it's crucial to understand that diatoms, through photosynthesis, effectively sequester carbon, removing CO_2 permanently and releasing oxygen. This nuanced difference is pivotal for a well-informed discussion. The observable benefits, although real, need a broader context. Further, diatoms may offer solutions to the challenges faced by traditional carbon-coated batteries. Their enhanced performance in terms of capacity and efficiency serves as a clear relative advantage. The advancements in this field are evident, especially when one considers the growing demand for electric vehicles and renewable energy storage solutions.

The unique nanostructures of diatoms can also enhance the performance of solar cells, tapping into the escalating demand for renewable energy. The observable efficiency improvements in diatom-integrated solar cells provide a measurable advantage over conventional systems.

Compatibility: Diatoms, microalgae with intricate silica structures, represent a congruent fit in the global trajectory towards sustainable solutions. Their multifunctional capabilities span from potential contributions to carbon-neutral vehicle propulsion, to the augmentation of battery efficiency, and even as a contender in aquacultural practices. In every product category, they offer an improvement to an already existing product, with established markets and as such, the compatibility is high.

When it comes to complexity, observability, and trialability: The diatom-based products will inevitably be compared with the traditional products considering these factors. Thus, it is important to which degree the diatom-based product can substitute the established products. As such, the diatoms exhibit considerable potential across various applications, yet the intricate processes involved can impede their broader integration. For successful mainstream adoption, it’s imperative that such applications are scalable and undergo thorough validation. Emphasising these trials will mitigate scepticism and diminish potential barriers to adoption. Here the concept of substitution might be useful: Can the sustainable product successfully substitute the established product in terms of complexity, observability, and trialability.

Ecological integrity: In terms of carbon cycling, diatoms excel by actively photolyzing CO_2, bolstering their role as environmental custodians. However, when transitioning diatoms into biofuel applications, it’s imperative to assess their long-term impact on carbon sequestration. While diatom-derived biofuels offer a commendable alternative to fossil fuels, potential pitfalls in their carbon balance should be critically examined. The exploration into diatom integration in photovoltaics and battery technology demands a comprehensive ecological assessment to fully appreciate any potential environmental trade-offs. Moreover, in the domain of aquaculture, the introduction of diatom algae as fish feed holds promise, especially as an alternative to the established soy-based feed. Cultivating diatoms for this purpose can promote sustainability in the sector, potentially offering an ecologically balanced feed source that aligns with the aspirations of sustainable aquaculture.

Economic viability: The financial feasibility of diatom-based technologies is critical for their mainstream adoption. In the realm of energy, the increasing demand for renewable sources and efficient storage make diatom applications in both biofuel production and battery enhancement promising. However, the energy-intensive process of biofuel generation calls for a thorough cost–benefit analysis. Similarly, leveraging diatoms for photovoltaics aligns with growing renewable energy trends, but its economic viability needs assessment. In aquaculture, diatom algae’s potential as sustainable fish feed could provide economic benefits, given the challenges faced in traditional feed sources. Each pathway demands a detailed financial analysis to ensure its economic soundness amidst evolving market demands.

Societal equity and welfare: The broader societal benefits of diatoms are implicit in their potential applications. Healthier fish stocks due to diatom-based feed, for instance, directly contribute to food security and industry stability. Cleaner energy storage solutions and carbon-neutral combustion also align with societal welfare by promoting a cleaner environment.

Cultural and ethical norms: Diatoms resonate with the global narrative of sustainability, climate change mitigation, and eco-consciousness. Their diffusion aligns well with the ethical mandate to combat climate change and adopt environmentally friendly practices

Table 8.5 outlines a summary of findings for various applications of diatoms when evaluated through Rogers’ diffusion of innovations theory.

Table 8.5 Summary of findings.

Diatoms used for	*Relative advantage*	*Compatibility*	*Observability*	*Complexity*	*Trialability*	*Ecological integrity*	*Economic viability*	*Societal equity and welfare*	*Cultural and ethical norms*
Biofuel	Perceived carbon neutrality compared to fossil fuels	Directly compatible with current technology	Effectivity of use can be observed and measured	Comparable complexity to fossil fuels	The effectiveness of biofuels can be easily tested and validated	Lower carbon footprint than fossil fuels. However, CO_2 is out in the atmosphere	High economic viability with market demand for alternative fuels	Societal equity remains unaffected	Ethical concerns centre around the fuel-based tech versus electric; societal discussions regarding energy source sustainability are pertinent
Battery	Addresses challenges posed by traditional carbon-coated batteries	Functionally equivalent to ordinary batteries	Efficiency and capacity enhancements are observable and measurable	Specialised knowledge and techniques may be required for optimal usage and maintenance	Diatom-based batteries can be easily tested and validated for efficiency and capacity	Potentially reduced waste due to longer-lasting batteries	Substantial R&D investment needed; long-term economic viability contingent upon optimisation of performance and reliability	Neutral impact on societal equity	Aligns with international sustainability objectives and ethical standards promoting green technology
Photovoltaic	Enhanced solar cell performance	Compatible with the growing demand for alternative energy sources	Observability of efficiency improvements in energy conversion	Specialised knowledge and techniques necessary for installation and maintenance	The efficiency of diatom-based photovoltaic cells can be easily tested and validated	Reduced carbon footprint and environmental impact with sustainable energy conversion	Requires significant R&D investment; economic viability is subject to performance optimisation and market demand	Provision of cheaper, sustainable energy promotes societal welfare	Ethical considerations align with global sustainability goals and the promotion of renewable energy sources
Fish feed	Diatom-based feed aligns more closely with the natural diet of fish	Direct alignment with natural fish diets	Observable reduction in lice infestation and general improvement in fish health	Comparable complexity to traditional feed options	The effectiveness of diatom-based fish feed can be easily tested and validated	Sustainable alternative contributing to the overall health of marine life	Economic viability dependent on market demand for sustainable fish-feed options	Positive impact on societal welfare through the provision of healthier fish	Aligns with ethical standards promoting sustainability and animal welfare

Conclusion

Finnfjord's algae project exemplifies sustainable innovation through advancing the cultivation of diatom algae which captures and photolyze CO_2. The diatom biomass may then be utilised into valuable products.

Upon scrutinising the sustainability aspects of utilising cultivated diatoms, it is imperative to discern its wide array of application. The discussion in this paper has focused on four product categories and shown that the organic biomass from diatom algae can be beneficial to each of them. Among these, some applications stand out for their dual advantage of sustainability and market potential. For instance, the production of fish feed from diatoms not only presents a sustainable feeding source but also one that is similar in the fish natural diets which again offers better fish health (Eilertsen, Ingebrithsen and Striberny, this publication; Elvevoll and xx, this publication). On the other side, production of biofuel from algae may bring up the classic criticism of CCU that it only delays the emission of CO_2, not removing it completely (Langhelle and Sareen, this publication). The production of photovoltaic and batteries, however, are promising, but need more research and development.

It is crucial to recognise that the sustainability of diatom-based products is inherently tied to the modes of their production and utilisation. Each step, from cultivation to product development and market diffusion, needs to be executed with an unwavering commitment to environmental stewardship, economic viability, and societal benefit. While diatoms indeed offer a promising route for CCU, the degree to which they contribute to climate mitigation as compared to conventional CCS depends substantially on the life-cycle analysis of the resulting products and their respective markets.

Nevertheless, this discussion has shown that innovating on microalgae cultivation may augment climate mitigation efforts and advancing the principles of a circular economy (IPCC, 2018; Olfe-Kräutlein, 2020). In addition, it can bolster the provision of new avenues for various techniques, products, and industries (Bhattacharya & Goswami, 2020; Mahmood et al., 2023). Viewing CO_2 as a continuously renewing, low-cost, and non-toxic resource – thanks to its persistent industrial emissions – presents a potential for a paradigm shift in its management (Eilertsen et al., 2021; Gately et al., 2013). As highlighted by Eilertsen et al. (2021) and Sánchez et al. (2003), large-scale diatom cultivation can significantly cut carbon emissions, highlighting its contribution to climate change mitigation efforts.

Limitations and future research

While the prospects of diatoms appear promising, it is essential to address the limitations of our current understanding: (1) *complex processes*: some diatom applications, particularly in biofuel production, are energy intensive, which might offset their environmental advantages to some extent. (2) *economic feasibility*: the cost implications of large-scale diatom integration, especially in sectors that demand high-energy inputs, remain relatively unexplored. (3) *mechanistic ambiguity*:

Finnfjord's algae project epitomises a compelling iteration of CCU, bringing a spotlight to the viability and sustainability of turning captured CO_2 into valuable products, while contrasting itself from traditional CCS approaches. As elucidated in the introduction, while CCS solely focuses on the containment of CO_2, CCU endeavours further, envisioning CO_2 as a pivotal resource. The Finnfjord initiative embraces this ethos, wherein harvested CO_2 is not merely stored but ingeniously converted into microalgae, particularly diatoms.

Upon scrutinising the sustainability aspects of utilising cultivated diatoms, it is imperative to discern that their applications span extensively, from energy to aquaculture, each bearing distinctive sustainability credentials. Among these, some applications stand out for their dual advantage of sustainability and market potential. For instance, the production of biofuels from diatoms not only presents a renewable energy source but also offers a mechanism for long-term carbon sequestration, thereby aligning with global climate mitigation targets. Furthermore, diatoms' utilisation in creating high-value products like nutraceuticals can foster economic sustainability while contributing to health and wellness.

However, it is crucial to recognise that the sustainability of diatom-based products is inherently tied to the modes of their production and utilisation. Each step, from cultivation to product development and market diffusion, needs to be executed with an unwavering commitment to environmental stewardship, economic viability, and societal benefit. While diatoms indeed offer a promising route for CCU, the degree to which they contribute to climate mitigation as compared to conventional CCS depends substantially on the life-cycle analysis of the resulting products and their respective markets.

To delineate, while CCS provides a straightforward approach to reducing atmospheric CO_2 levels, its impact is predominantly environmental. In contrast, CCU, as embodied by the Finnfjord project, promises not only environmental benefits but also economic value, which is integral to the project's long-term viability and success. Nonetheless, for CCU to be genuinely mitigating and sustainable, the end-use of captured carbon, in this case, the diatoms, should be meticulously chosen to maximise the mitigation potential while ensuring economic feasibility.

Thus, as we evaluate the potential widespread application of Finnfjord's innovative approach, a careful and holistic examination of its environmental, economic, and social implications is paramount. By doing so, we can discern the true sustainability of this endeavour, understanding whether and how it contributes to a more sustainable and resilient future. In steering the diffusion of this innovative effort, prioritising applications that are not only economically viable but also environmentally benign and socially beneficial is imperative. Through this lens, diatoms indeed offer a promising horizon, yet the path to realising their full potential requires navigating through complexities with informed and deliberate choices.

Given the limitations and the vast potential of diatoms, the roadmap for future research should be multifaceted: comprehensive research focusing on the complete life-cycle emissions of diatom-based applications will provide clarity on their net environmental impact. Deeper dives into the cost structures and economic implications of diatom applications will be pivotal in understanding their commercial viability. A focus on the biochemical interactions that grant diatoms their unique properties might not only explain observed phenomena but also unveil new applications. As the world moves more assertively towards sustainability, research should also pivot towards understanding the societal and cultural implications of widespread diatom adoption.

In essence, diatoms, with their inherent advantages, present a promising horizon for a sustainable future. While current research has illustrated their potential, the path ahead signals a nuanced, thorough exploration to harness their capabilities for global betterment. In addition, certain observed benefits, such as the deterrence of lice in salmon fed with diatom algae, are yet to be explained at a molecular or chemical level, leaving room for uncertainties.

Note

1 Authors are listed alphabetically and contributed equally.

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