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The why and how of a circular blue-green bioeconomy integration

Marija Banovic[a,b,*], Jamileh Javidpour[c,d], Mette Lübeck[e], Jessica Aschemann-Witzel[a,b], Morten Tønsberg Limborg[f], Annette Bruhn[b,g], Simon Bahrndorff[e]

[a] The MAPP Centre, Department of Management, Aarhus BSS, Aarhus University, Fugelsang Allé 4, 8210, Aarhus, Denmark
[b] Center of Circular Bioeconomy (CBIO), Aarhus University, Denmark
[c] SDU Climate Cluster, The University of Southern Denmark, Denmark
[d] Department of Biology, University of Southern Denmark, Denmark, Campusvej 55, 5230, Odense, Denmark
[e] Department of Chemistry and Bioscience, Aalborg University, Fredrik Bajers Vej 7H, 9220, Aalborg, Denmark
[f] Centre for Evolutionary Hologenomics, University of Copenhagen, Øster Farimagsgade 5, Copenhagen, Denmark
[g] Department of Ecoscience, Aarhus University, CF Møllers Allé 3, 8000, Aarhus C, Denmark

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ABSTRACT

The transition to sustainable food systems requires innovative frameworks that move beyond siloed approaches to resource use. While both blue and green bioeconomies hold immense potential, their integration remains underexplored, particularly regarding circular product design for food and feed production. This gap limits the efficient valorization of waste- and by-products across these domains. The aim of this commentary is to outline why and how blue and green bioeceonomies should be converged within a circular framework. Drawing on case studies and recent advances, we adopt a conceptual approach to identify four 'crystallization points' for integration, which dissolve boundaries between 'blue' and 'green' and integrate both into a joint circular framework. This commentary highlights opportunities and challenges setting an agenda for future research and practice, underscoring pathways toward more sustainable, resilient, and resource efficient food systems. By integrating blue and green bioeconomies, it addresses critical environmental challenges while enhancing resource use and generating broader stakeholder benefits.

1. Introduction

Earth has transgressed six of the nine planetary boundaries, and feeding humanity puts enormous environmental pressure on our planet (Richardson et al., 2023). For example, current food systems are responsible for a third of global anthropogenic emissions of greenhouse gasses and for the degradation of both surface and groundwater supplies through overuse of water and emissions of pesticides and nutrients (EC, 2023b; EEA, 2025). The growing realization that our current linear economy has reached its limits (Richardson et al., 2023) underscores the urgent need to transition towards a new societal and economic model (EMAF, 2015). This shift emphasizes sustainable practices (Herrero et al., 2020) and circular utilization of resources, positioning the circular bioeconomy (CBE) as a pivotal strategy for realizing sustainable development, promoting social equity, and ensuring a 'just transition' (EC, 2020a, 2025). Within the discourse on CBE, diverse interpretations emerge (Carus & Dammer, 2018; Muscat et al., 2021), but with a consensus that CBE entails the efficient management and utilization of biological resources, turning them into renewable products, while incorporating circular economy (CE) principles to maximize resource use, extend product lifecycle, and minimize waste. Despite the CBE concept being embedded in both the 'blue' (aquatic) and 'green' (terrestrial) sectors, it often remains isolated in separate silos, leading to a significant integration gap in resource management, innovation collaboration, and policy alignment (D'amato & Korhonen, 2021; EC, 2025; Herrero et al., 2020; Philippidis et al., 2024) (Fig. 1). The blue bioeconomy is defined as the sustainable use of aquatic resources (including fisheries, aquaculture, algae, and marine by-products) for food, feed, and biomaterials (EEA, 2025; Thomas et al., 2022). The green bioeconomy, by contrast, refers to the sustainable use of terrestrial resources (including crops, forests, livestock, and land-based biomass) for food, feed, energy, and materials (D'amato & Korhonen, 2021; EC, 2020b; EEA, 2025). These definitions serve as the foundation for our analysis and highlight how the two domains, despite their shared

* Corresponding author. Center of Circular Bioeconomy (CBIO), Aarhus University, Denmark.
E-mail addresses: maba@mgmt.au.dk (M. Banovic), jamileh@biology.sdu.dk (J. Javidpour), mel@bio.aau.dk (M. Lübeck), jeaw@mgmt.au.dk (J. Aschemann-Witzel), morten.limborg@sund.ku.dk (M.T. Limborg), anbr@ecos.au.dk (A. Bruhn), sba@bio.aau.dk (S. Bahrndorff).

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0924-2244/© 2025 Elsevier Ltd. All rights reserved, including those for text and data mining, AI training, and similar technologies.

circular ambitions, often remain siloed.

This gap may in part stem from a lack of innovations and expertise in how products are designed, processed, and brought to market, that aligns with CBE's circular principles and simultaneously ensure economic viability and social acceptability (Aguiar et al., 2022; EC, 2025; EEA, 2025; Schandl et al., 2025). In this context, to facilitate the integration of blue and green bioeconomies and support sustainable development, circular product design (CPD) is needed to enable maintenance of the biological resources and minimize the generation of their waste and loss. CPD refers to the design of products in ways that maintain biological resources, extend product lifetimes, and enable multiple functions such as reuse, repair, remanufacturing, and recycling, thereby minimizing waste and resource loss (Sassanelli et al., 2020; Vilochani et al., 2024). CPD emphasizes creating products that incorporate durability and longevity (e.g., extending product shelf-life through preservation techniques), material reutilization and reusability (e.g., and/or upcycling by-products), system adaptations for efficiency (e.g., modular systems in food processing), and conservation and regeneration of natural systems to support ecosystem balance (Aguiar et al., 2022; Den Hollander et al., 2017; Desing, 2023; Mestre & Cooper, 2017; Wang et al., 2022). CPD is relevant when looking at the whole supply chain from farm to fork, particularly because new products have not been developed with circular design in mind.

Within the CBE context, CPD shows potential to establish a sustainable flow of food and feed products through systems that not only reduce waste but also provide additional value to by-products by creating new products, thus enhancing the economic value of biological resources. Despite, the recognition of its importance (Den Hollander et al., 2017; Mestre & Cooper, 2017), there has been a lack of practical implementation of CPD in the blue and green bioeconomies. Many products on the market today were not developed with a CPD approach in mind, including those in the food and feed sectors (Urbinati et al., 2020). The success of CPD, and thus CBE, hinges on overcoming various micro and macro barriers, including technological, economic, and regulatory challenges (D'Adamo et al., 2022).

This commentary explores an integrative and circular framework, providing practical examples of blue-green integration to emphasize the efficient use of biological resources across bioeconomies. It identifies key crystallization points that will advance the future integration of blue and green bioeconomies, both at macro and micro levels, by highlighting key aspects of CPD approach.

2. Conceptual approach to blue–green bioeconomy integration

This commentary adopts an integrative conceptual approach (Paul & Criado, 2020; Snyder, 2019) to explore pathways for integrating blue and green bioeconomies within a circular framework. It critically engages with European policy documents (e.g., EC, 2020b; EC, 2025) together with recent academic and policy contributions on sustainability transitions and bio-based innovation (EEA, 2025; Philippidis et al., 2024; Schandl et al., 2025). The aim is to synthesize insights across these domains to identify key drivers, barriers, and opportunities for integration, highlighting underexplored connections and setting an agenda for future research and practice, rather than testing hypotheses or providing empirical generalization (Grant & Booth, 2009). Importantly, this commentary builds on the combined expertise of academics from environmental sciences, marine and evolutionary biology, food technology, entomology, and social sciences, adopting an interdisciplinary approach that reflects the complexity of circular bioeconomy integration. Such an interdisciplinary approach is increasingly recognized as essential for achieving sustainability transitions (Schandl et al., 2025). This interdisciplinary lens also reflects the complexity of circular bioeconomy integration and supports the identification of challenges and opportunities for future research and practice.

3. Circular product design as framework for integration

To realize the circular potential of blue and green bioeconomies, it is essential to co-create intelligent solutions through CPD along the production line from farm to fork (Aguiar et al., 2022; Den Hollander et al.,

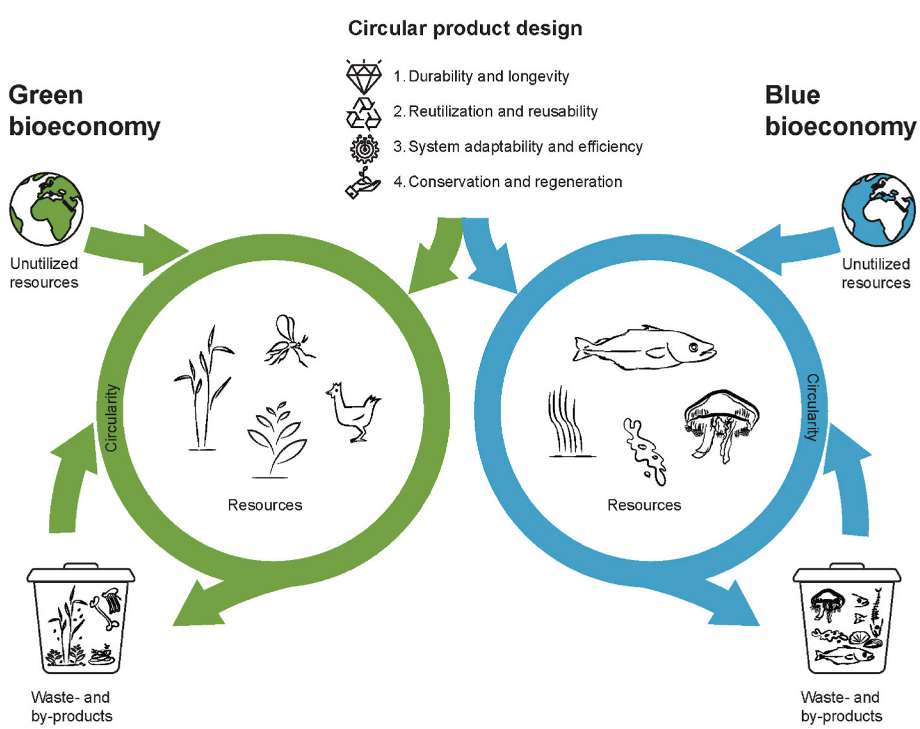

Fig. 1. Current state of blue and green bioeconomies and their potential. Blue and green bioeconomies are typically separated into siloes, where circular product design drives either the blue or green bioeconomy in a separate fashion. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

2017). The goal is to rethink how waste- and by-products in the green bioeconomy can be used to develop products in the blue bioeconomy and vice versa (Desing, 2023; Wang et al., 2022). Therefore, the key elements of CPD are suggested that enable the integration of blue-green biological resources.

One key aspect relevant to both blue and green bioeconomies is the durability and longevity of products, which focuses on extending their shelf life through innovative strategies such as advanced packaging and preservation techniques, thus reducing waste- and by-products and thus more efficient resource utilization. Such practices help curtail over-exploitation of resources and address the negative environmental impacts that may not be fully mitigated by recovery and recycling efforts (D'amato & Korhonen, 2021; Thomas et al., 2022).

The second component focuses on resource reutilization and reusability, emphasizing the use of biodegradable or fully recyclable materials and ingredients that can be reused or upcycled (Aschemann-Witzel et al., 2023). It also involves repurposing of biological resources from one realm (blue or green) as inputs for another, thus maintaining circularity within the system (Desing, 2023).

The third component advocates for system adaptability and efficiency in the processing of blue-green resources, highlighting the need for modular processing systems that can be readapted to accommodate the specificities of CBE products, such as variable biomass inputs, seasonality, and perishability (Sassanelli et al., 2020). These systems utilize technologies that can be easily adjusted or repaired, ensuring a continuous and adaptable flow in areas such as food and feed production. For example, novel biotechnological approaches could be employed to optimize resource use and minimize environmental footprints, which are crucial for promoting sustainable growth within blue-green integration (Herrero et al., 2020; Muurmann et al., 2024).

The fourth component focuses on the conservation and regeneration of ecosystems, emphasizing the sustainable management and use of both blue and green resources essential for food and feed production (EC, 2020a, 2020b; Muscat et al., 2021). It highlights the critical importance of maintaining and enhancing the functionality and biodiversity of blue-green ecosystems, which play a pivotal role in supporting the resilience and adaptive capacities of resources (Thomas et al., 2022).

4. Blue-green circular product design cases

4.1. Overcoming the silo mentality: blue and green bioeconomy integration

The CBE approach has primarily evolved under the guidance of practitioners, policymakers, and business-oriented entities such as associations and foundations (EC, 2020b; EMAF, 2015). It often presents nuanced differences from the academic perspective (Carus & Dammer, 2018; Muscat et al., 2021; Stegmann et al., 2020). Most disagreements revolve around the overall framework for CBE, particularly its relationship with other concepts like the CE. Further, the blue or green sectors are often examined in silos rather than collectively integrated in a circular manner. This deficiency may be partly due to the inherent challenges associated with macro-level, top-down policies, as well as the stakeholder and technological challenges that are crucial for proper integration of the blue and green sectors (Urbinati et al., 2020).

Strategies and roadmaps for green transition within blue and green bioeconomies are well-represented, yet there is a noticeable lack of macro and micro strategies for integrating the blue and green bioeconomies at both local and transnational levels. At a European level, the partnership, *"Circular Bio-Based Europe"*, supports projects that include both the blue and the green bioeconomies, albeit rarely explicitly in the same calls. The Industry Organisation, 'Bio-based Industries (BIC)' support Circular Bio-Based Europe. Another European Partnership 'Sustainable Food Systems for People, Planet & Climate' and the 'Farm to Fork' strategy under Horizon Europe explicitly highlight the need for an integrated systems approach between terrestrial and aquatic feed and food production (EC, 2020a; 2023a). They also emphasize the importance of sustainable resource use and establishing connections between the blue and green bioeconomies, with specific calls for developing low-trophic aquaculture. Additionally, the EU has proposed an action to fully harness the potential of algae (EC, 2023a). However, there is still no framework to achieve this. Further, despite several Sustainable Development Goals (SDGs; e.g., 12, 13, and 14) emphasizing the need for sustainable resource use, at the EU level, only the "green deal" and the "restore our ocean and waters" missions (EC, 2023b) explicitly address these goals. In 2024 however, the EU Commission proposed a revision of the Bioeconomy strategy, under the initiative: *"Building the future with nature: Boosting Biotechnology and Biomanufacturing in the EU"*. The revised strategy is expected to be adopted by the end of 2025, and aims to reinforce circularity, sustainability, and innovation across the European bioeconomy (DGE, 2025). While the Commission has not yet introduced a formal *"Circular Bioeconomy Act"* (EC, 2025), such a legislative proposal remains under discussion as a possible instrument to operationalize these ambitions. Although CPD is not explicitly mentioned in the current strategy documents, this concept could provide a concrete pathway for implementing circularity by linking blue and green bioeconomies within the forthcoming regulatory framework.

Currently blue and green bioeconomies are mainly studied in isolation rather than in conjunction (D'amato & Korhonen, 2021; Thomas et al., 2022) and without employing a CPD approach (Desing, 2023; Wang et al., 2022). However, the utility of blue and green waste- and by-products can be enhanced through the integration of these resources across systems (Fig. 2). Although the butterfly model is often used to illustrate circular economy principles (Geissdoerfer et al., 2017; Kirchherr et al., 2017), the figure presented here focuses more narrowly on integration points between blue and green resources to highlight their specific relevance within a circular bioeconomy context. Currently, many blue and green resources are utilized for energy production and landfill, although a significant opportunity exists to upcycle these resources for food and feed production.

In the following sections, cases are presented showcasing the integration of the green and blue bioeconomies (Fig. 2), and challenges and opportunities, particularly in upcycling with a CPD approach, are discussed. By creatively transforming these untapped resources through CPD, their full potential can be unlocked, fostering a more sustainable and integrated bioeconomy.

4.2. Green bioeconomy: biomass for blue and green food and feed production

Spent grain (SG) is an example where a transformative CPD approach for integrating blue and green bioeconomies can be applied (Fig. 2). Spent grain from alcohol production is one example of a "green" biomass that is produced globally in large amounts throughout the year (Mitri et al., 2022). The primary biomass for producing SG originates from starch-containing crops such as barley, wheat, corn, rice, or other cereals that are used for alcohol production (Lynch et al., 2016). Spent grain is cheap and lacks economically feasible applications. It can be upcycled for use in both blue and green systems as both food and feed, thus potentially allowing for a more CPD (Fig. 2). As an example, 70 % of all brewers' spent grain (BSG) is currently used as animal feed, 10 % is used for biogas production, and the remaining 20 % are disposed in landfills (Mitri et al., 2022). However, BSG is a nutrient-rich industrial by-product, which makes it a very good candidate for valorization through integration of the blue and green bioeconomies with the use of different processing biotechnologies (Lynch et al., 2016; Mitri et al., 2022; Muurmann et al., 2024).

SG, rich in protein and fibre, offers versatile uses in human diets, including their direct application in foods, such as applying the dried SG, or a as a flour substitute in bakery products (Lynch et al., 2016; Zeko-Pivač et al., 2022). Additionally, these grains can be processed into

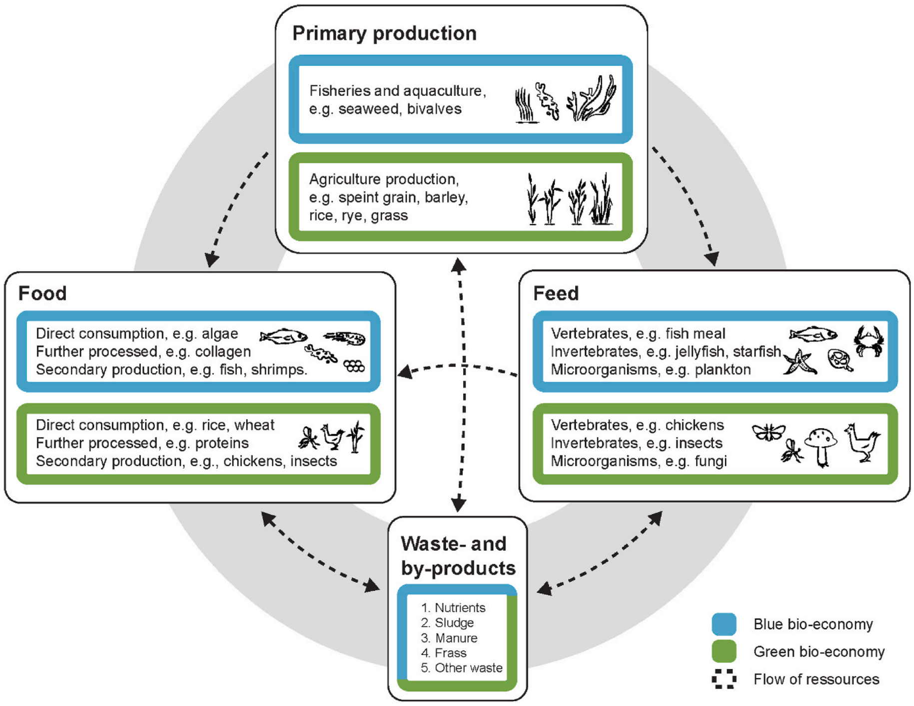

Fig. 2. Example of integration of the blue and green circular bioeconomies using circular product design. Black arrows indicate where blue and green waste- and by-products can be valorized through the integration of these resources across systems. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

various food items to enhance nutritional content, albeit in limited quantities due to a high content of non-digestible lignocellulose. A more refined utilization involves biofractionation, which separates the grains into distinct macromolecules, notably proteins and fibers. Isolated proteins hold significant value for both human consumption and animal feed, such as for fish, by providing a high-quality protein source. SG can serve as an eco-friendly feed for fish, insects, and microorganisms, which can then be transformed into food sources for humans (Fig. 2) (San Martin et al., 2020). These methods significantly reduce environmental impact, making them crucial for the sustainability of future agriculture and aquaculture (Stentiford et al., 2020). Notably, the approaches do not require additional arable land, emphasizing their sustainability benefits if integrated into a CPD for sustainable food and feed production (Zeko-Pivač et al., 2022).

Insects, such as house flies, black soldier flies, crickets, and grasshoppers, due to their ability to thrive on a wide range of substrates, such as SG, manure, sludge, organic household waste, and grass (Laursen et al., 2024; Muurmann et al., 2024) are particularly valuable in converting waste- and by-products into resources within both blue and green food and feed systems. Further, their nutritional value is similar or higher than e.g. soy and fish meal (Orkusz, 2021). By using insects as an intermediary to convert e.g. green low-value by-products into high-quality insect protein for e.g. fish, environmental impacts can be minimized (San Martin et al., 2020). Carnivorous fish can consume insects that feed on side-streams from SG, a strategy that is particularly relevant as the growing blue bioeconomy demands more feed produced in a more sustainable way, which can be supplied by these green by-products.

Although aquaculture is the fastest growing food production sector, the integration of green resources into the blue sector hinges on developing alternative raw materials that can supplement fishmeal and fish oil while simultaneously enhancing feed efficiency (Rocker et al., 2022), allowing for CPD. It is well established that many farmed fish grow well on insect protein (Mastoraki et al., 2022), but the limiting factor for expanding this potential of increased sustainability is that insect meal is more expensive than fish meal and other alternatives. While the aquaculture industry prioritizes sustainable production regimes, it is necessary to negate large cost gaps between less and more sustainable feed ingredients. It is foreseen that the sustainability potential of using insect meal in fish feed can be realized by using insects to bridge energy flow from green waste and into high quality blue protein. By utilizing different green waste- and by-products, the production cost of insect proteins can be lowered, which is exemplified by the use of SG for insect feed. Using other waste- and by-products from agricultural production may even lower production prices further. This example also showcase how aquaculture, for example, can achieve enhanced resilience by leveraging local and shorter value chains, and similarly, how these value chains can benefit in return. To achieve this however, policies and regulations are needed to facilitate use of insects together with new developmental research that paves the way for reduced production costs (Muurmann et al., 2024).

4.3. Blue bioeconomy: biomass for blue and green food and feed system

The blue bioeconomy offers a huge potential for better integrating underutilized marine biomass, such as seaweeds and filter feeding bivalves, and at the same time reducing environmental impact and promoting sustainability. Blue aquaculture production of low trophic species offers a potential for turning climate and environmental challenges into opportunities for water quality restoration (Duarte et al., 2022), and reduced CO_2 emissions while boosting production of sustainable animal protein (Theuerkauf et al., 2022). Many coastal ecosystems in developed regions struggle with alarmingly high concentration of nutrients derived from agriculture in the green bioeconomy, which has led to eutrophication and poor environmental status of coastal ecosystems (Malone & Newton, 2020). Blue aquaculture of low trophic species, such as seaweed and filter feeding bivalves for human and animal feed, offer not only a local sustainable protein source but also added environmental benefits, functioning as an instrument for emission capture and utilization of both nutrient and CO_2 emissions. For example, filter feeding mussels do not require feeding as they transform available nutrients in the water into new biomass (Pessarrodona et al., 2024). Another example is reducing land-based aquaculture nutrient emissions by cultivating seaweeds (Shpigel et al., 2017). This process not only captures excess nutrients but also produces valuable biomass that can be used as food and feed. Seaweed-based feed additives may even reduce methane production in cattle (Kinley et al., 2020). Similarly, almost 100 % of seaweed species can be used for downstream valorization as they contain valuable molecules such as hydrocolloids, proteins, and secondary metabolites (Holdt & Kraan, 2011). Hereby, linear resource streams are turned into circular nutrient streams, while providing blue foods with low environmental food prints (Duarte et al., 2022). It is envisioned that low-trophic aquaculture, as a type of 'regenerative ocean farming' bridging green and blue production regimes holds great potential if given political priority, both supporting the European Blue Growth strategy and the goal of EU Water Framework Directive of achieving good ecological conditions in the EU waters.

Another example is jellyfish, often considered a nuisance due to their excessive biomass, are emerging as a valuable asset in both the blue and green bioeconomy (Maschmeyer et al., 2020). Some species of jellyfish, not only serve as food for humans but are also utilized in livestock feed (The FishSite, 2017). Jellyfish venom extracts exhibit a wide range of biological activities, including antihypertensive, antimicrobial, and anticancer effects, further illustrating how the bioactive compounds in jellyfish hold untapped potential for nutraceutical developments (Nisa et al., 2021). In agriculture, the application of jellyfish biomass as organic fertilizers presents a novel approach to enriching soil quality and promoting sustainable farming practices. This not only aids in soil health but also illustrates the circularity of resource utilization within the blue economy, where by-products from one sector serve as inputs for another (Emadodin et al., 2020). Similarly, in aquaculture, jellyfish can serve as a sustainable feed source, illustrating the circularity of resource utilization within the blue economy (Edelist et al., 2021).

The blue sector also has the potential to manage its waste, such as sludge from aquacultures (uneaten feed, fish excrement, and other particulate organic matter), by repurposing it as valuable fertilizer inputs for the green bioeconomy. This circular design approach is outlined in the context of biofloc technology, which allows for the sustainable utilization of aquaculture waste. Biofloc technology enhances water quality through nutrient recycling and generates biofloc, which can be used as a feed supplement and possibly as fertilizer (Nisar et al., 2021). Additionally, blue resources such as weathered rock flour from Greenlandic glaciers offer unique opportunities for the green bioeconomy. These deposits, naturally produced by glacier erosion of bedrock and deposited in easily accessible lacustrine deposits can be repurposed as green fertilizers, without the need for energy-intensive grinding (Gunnarsen et al., 2023). A proof-of-concept study has already demonstrated how the application of mechanically crushed silicate minerals to agricultural soils significantly improves crop yields while simultaneously capturing and storing atmospheric CO_2 by sequestering inorganic carbon through enhanced mineral weathering (Gunnarsen et al., 2023). Entrepreneurial efforts are now focusing on linking these naturally occurring minerals from the blue biosphere to climate friendly crop production embedded within the green bioeconomy.

5. Challenges for blue-green integration

To harmonize CPD within the CBE framework across blue and green bioeconomies, there are several obstacles including socio-economic, technological, and legislative challenges. Each of the obstacles can significantly affect the pace and effectiveness of integrating and utilizing blue-green resources in a circular manner.

Socio-economic challenges: The integration of blue and green resources and implementation of CPD often encounters economic hurdles, such as the high costs associated with sustainable materials and labour (Wang et al., 2022). These financial challenges can deter companies from adopting circular practices, as the initial investment and operational costs may be substantially higher than conventional methods, affecting the overall viability and adoption of CBE initiatives. Addressing these cost barriers is crucial for sustainable progress to develop a new business within upcycling, and for society to embrace new food types. Further, societal factors, including safety concerns, low consumer acceptance, and lack of awareness about the benefits of circular bioeconomy practices, among others, can also obstruct the successful integration of blue-green bioeconomies and implementation of CPD (Aguiar et al., 2022; Muscat et al., 2021). These barriers can prevent the widespread adoption of circular products and practices, as consumer preferences and societal norms play a critical role in shaping market demand and acceptance of new, sustainable innovations (Aschemann-Witzel et al., 2023). Both in the green and blue realm, market acceptance and demand for products derived from nuisance biomass or bycatch are not guaranteed. This is primarily due to several factors, including consumer preferences, market dynamics, and regulatory challenges (Banovic et al., 2019, 2025). Despite the potential of using underutilized fish species and bycatch to create value-added products, there is often a lack of consumer awareness and acceptance of these products. For instance, studies on the valorization of bycatch fish species into new food products have demonstrated varied consumer acceptance, with some products receiving higher purchase intentions than others depending on their sensory characteristics and perceived quality (Banovic et al., 2019). Products made from jellyfish or macroalgae may face skepticism or cultural reluctance, affecting their marketability (Torri et al., 2020). Similarly, consumers are reluctant to include insects as part of their diet, and while seen as advantageous for the environment and nutrition, most consumers show low level of acceptance (Muurmann et al., 2024). Creating a market for these products requires not just quality and reliability but also strategic marketing, consumer education, and sometimes, a shift in cultural norms.

Technological challenges: A significant impediment to the integration of blue-green bioeconomies and CPD is due to a lack of innovative technologies and expertise (Muscat et al., 2021; Wang et al., 2022). Generally, the development and application of new technologies are crucial for the effective waste reduction and reuse of resources (Carus & Dammer, 2018). However, the gap in necessary technological advancements, and the scarcity of skilled professionals can hinder sustainability progress (Banovic et al., 2025; Muurmann et al., 2024). For example, the challenges associated with usage of SG is e.g. the lignocellulosic components, the high-water content, and that it is predisposed to microbial decomposition (Robertson et al., 2010). Some hours after exposure to air, microbial fermentation may already start causing dry matter loss and modifications in the SG (El-Shafey et al., 2004). Thus, methods to either use the SG directly or find ways of storing are important (El-Shafey et al., 2004). In the blue realm, the process of transforming fisheries bycatch such as jellyfish into valuable products is not straightforward. It involves complex steps of processing, preservation, and transformation, each requiring specific technologies. For instance, extracting high-quality collagen from jellyfish demands sophisticated techniques to ensure purity and functionality. Modern approaches require innovative processing technologies that align with the principles of sustainable utilization. Developing and refining these technologies not only requires significant investment but also a deep understanding of the biological characteristics of the bycatch. Unlike targeted fishing, bycatch can be sporadic and varied, making it difficult to establish a steady supply chain (Shester & Micheli, 2011). The perishable nature of marine organisms adds another layer of complexity, necessitating rapid processing and well-coordinated logistics to prevent spoilage and ensure that the raw materials reach processing facilities in optimal condition. Developing robust systems for collection, transportation, and storage is crucial to make the valorization of bycatch viable.

Legislation challenges: The absence of a systematic legislative framework, that for example ensures the safe use of resources (e.g., manure as feed for insects, insects as feed for fish or fishery bycatch), or novel food regulations (where new sources need to account for anti-nutrients, allergens, toxins, and residues of pesticides and heavy metals.), poses a considerable barrier (Varzakas & Smaoui, 2024). Inadequate policies and regulations can lead to uncertainty and inconsistency in applying CBE principles, impeding the adoption of circular practices and the sustainable management of blue-green resources. Using SG as an example, macro-level top-down policy drivers are essential. This includes both funding to drive the technological advances and their implementation, as well as changes in legislation needed to set the direction for a new sustainable blue and green food system. For example, changes in legislation are needed when technological advances allow for a broader use of different waste and by-products, ensuring the necessary food safety. Different legislation may also exist for what feed can be used across blue and green economies. Regarding the use of insects as feed, for nearly two decades, the European Union prohibited the use of processed animal proteins in farmed animal feeds (Regulation EC 999/2001; Regulation EU 2021/1372). However, in 2017, the European Commission authorized the utilization of insects (processed animal proteins) as feed for aquaculture and in 2021, the authorization was extended to include pigs and poultry (Regulation (EU) 2017/893, Regulation (EU) 2021/1372). This illustrates that legislative regulations can be specific to separate sectors, making it difficult to bridge or apply these legislations across blue and green bioeconomies, but also showcase how it is possible to have political support to change legislations when relevant.

6. Conclusion

This conclusion serves as an integrative synthesis, bringing together the cases and challenges discussed to highlight four crystallization points through which CPD can foster deeper integration of the blue and green bioeconomies (Fig. 3). Considering the challenges, both practical and promising cases have been identified in the field, converging on four 'crystallization points' that can drive further integration of the blue and the green bioeconomy (Fig. 3). These points aim to dissolve the traditional boundaries between 'blue' and 'green' merging them into unified, circular framework where CPD playas a central role. In the following, these four points are proposed and elaborated upon as pathways for advancing integration.

First, it is observed that **practical, micro-level, bottom-up examples**, such as the interactions between aquaculture, plant-based resources, and insects, are the most advanced among the described cases. These examples offer valuable insights for other applications and serve as models into better integrating blue and green bioeconomies. CPD plays a pivotal role in realizing and scaling up this potential. However, CPD often originates within niche innovations, where actors have the freedom to experiment with new practices, fostering the development of unique circular products that can drive bottom-up integration of the CBE framework.

Secondly, it is argued that another key driver for the future integration of blue and green bioeconomies lies in the trend toward **resilience achieved through local and shorter value circles.** Blue and green bioeconomies often need more biomasses or need to 'get rid' of biomasses locally. This dynamic is evident in the described cases, where blue production, such as aquaculture, requires more feed, which can be sourced from green side streams, while blue production also needs to 'get rid' of wastes that become valuable inputs for green processes. These bottom-up cases demonstrate that time is critical for efficiently utilizing resources flowing between blue and green bioeconomies. Integration at the local level shortens transport times and closes resource loops, ensuring timely use of perishable resources. Emphasizing local and shorter value circles over globalized systems is crucial, as they not only ensure resource efficiency but also offer greater resilience to disruptions, allowing systems to quickly adapt to change and reduce vulnerability to external shocks.

Third, it is argued that an important driver of integration is providing

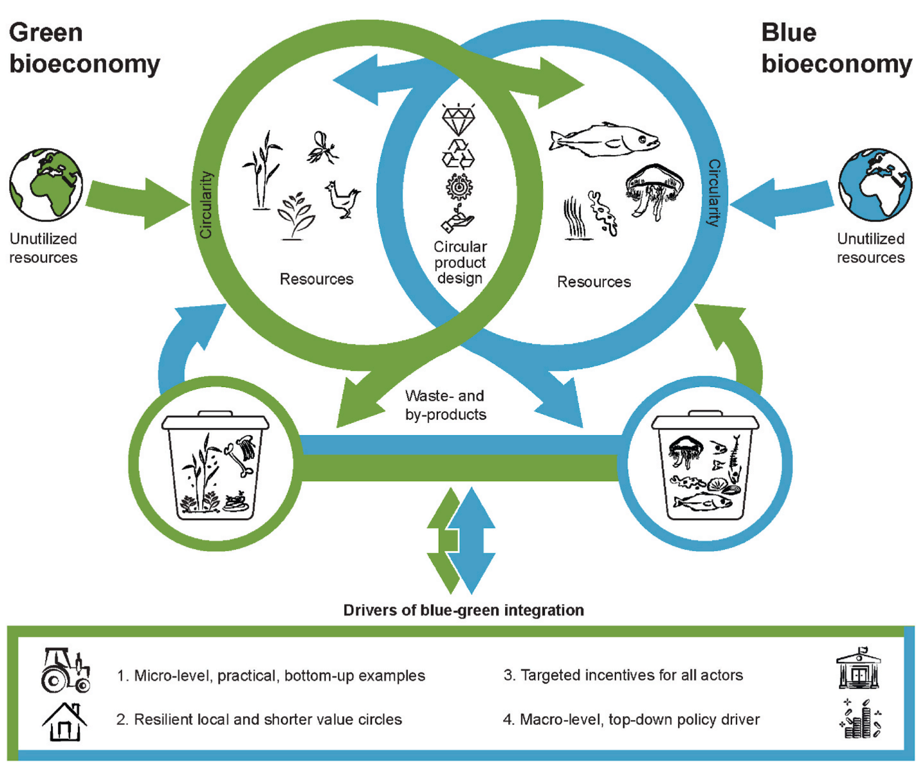

Fig. 3. Blue and green bioeconomy integration through circular product design. Illustrating how to successfully integrate and fully unlock the circular potential of blue and green bioeconomies within the CBE framework, moving beyond basic, isolated resource utilization and waste upcycling. The figure highlights blue and green resources alongside waste- and by-products, identifying key 'crystallization points' that foster deeper integration between the blue and green bioeconomy. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

targeted incentives for all actors across the value circle. Such incentives can take the form of *financial measures* (e.g., subsidies, tax breaks, or green public procurement), *regulatory incentives* (e.g., preferential treatment in permitting or certification), *market-based mechanisms* (e.g., eco-labeling, carbon credits), and *innovation* support (e.g., research funding and knowledge-sharing platforms). It is acknowledged that the circular bioeconomy involves numerous stakeholders, and a significant barrier lies in ensuring that each actor has a compelling reason to engage. This becomes even more complex when both blue and green actors are expected to collaborate. A key driver for such integration is recognizing the need to create a tailored 'what's in it for me' for each actor - consumers included - across the entire value circle. It is proposed that the full integration of blue and green circular bioeconomies can ensure this alignment because, in solely green or solely blue cases, some actors may not perceive a specific benefit. A fully integrated approach can provide advantages for all stakeholders, from health benefits for consumers, cleaner water, and new jobs at the municipal level, to economic profitability for producers and the achievement of environmental goals for governments.

Fourth, it is argued that a **macro-level, top-down policy driver** is also critical for integrating blue and green circular bioeconomies. This may initially seem surprising, given that, to the best of current knowledge, no EU funding calls have explicitly demanded such integration - most focus solely on either green or blue bioeconomies. Additionally, current legislation often treats blue and green bioeconomies as separate sectors. However, a close reading of EU policy reveals that systemic thinking, cross-disciplinary collaboration, ecosystem involvement, and circular design thinking are the underlying vision and goals. With the anticipated revision of the EU Bioeconomy Strategy in 2025, CPD and the integration of blue and green bioeconomies should be explicitly prioritized. It is therefore natural to expect this integration to become more evident in future funding calls and projects. Such initiatives will also increase pressure to harmonize regulations, making the integration of blue and green bioeconomies more feasible in practice.

Credit author statement

Marija Banovic: Conceptualization, Funding acquisition, Investigation, Project administration, Resources, Validation, Visualization, Writing – original draft; Writing - review and editing. Jamileh Javidpour: Conceptualization, Investigation, Resources, Validation, Visualization, Writing – original draft; Writing - review and editing.

Mette Lübeck: Conceptualization, Investigation, Resources, Validation, Visualization, Writing – original draft; Writing - review and editing.

Jessica Aschemann-Witzel: Conceptualization, Investigation, Resources, Validation, Visualization, Writing – original draft; Writing - review and editing.

Morten Tønsberg Limborg: Investigation, Resources, Validation, Writing - review and editing.

Annette Bruhn: Investigation, Resources, Validation, Writing - review and editing.

Simon Bahrndorff: Conceptualization, Investigation, Resources, Validation, Visualization, Writing – original draft; Writing - review and editing.

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Data availability

No data was used for the research described in the article.

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