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Review

A Digital Living Laboratory Approach to Determine Appropriate Key Performance Indicators for Advancing Needs of Bioeconomy Sector Using a Peatland-Based Integrated Multitrophic Aquaculture Demonstration Site—A Perspective

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Abstract: Developing the bioeconomy is important for resource management, food security and to protect our fragile environment. Critical to meeting emerging circular ambitions is the effective demonstration of viable biobased products at scale for appropriate business models and to mitigate risk. This case study addresses the use of digital twins (DTs) to support development of a novel integrated-multitrophic aquaculture (IMTA) demonstration site in the Irish peatlands for various needs using a living laboratory concept. It highlights the role of harnessing cross-cutting multi-actors for advancing DTs across this IMTA site such as using an integrated Penta Helix hub framework that intimates key measurement and performance indicators for the bioeconomy sector. Combinational use of such digital tools will advance eco-innovation along with linked educational and societal needs from a bottom-up user perspective that will commensurately tailor top-down local and regional policies with a global orientation. Clustering and connecting bioeconomy demonstration activities using DTs will potentially meet expectations for real time diversification and added value that will inform regional resilience, competitiveness and job creations.

Keywords: digital twin; living laboratory; bioeconomy policy; key performance indicators; IMTA; innovation helix hubs

1. Introduction

The bioeconomy is emerging as an important sector for society to address the appropriate sustainable management of finite natural resources. There is a commensurate pressing need to understand and communicate its purpose across other linked strategic policies, in order to effectively develop, scale and regulate new eco-innovation [1,2]. Notwithstanding this, it is appreciated that there are multiple interpretations of the 'circular economy' that can potentially cloud stakeholder understanding of its importance, value and ambitions [1]. For example, Tan and Lamers [3] noted that "there are over 100 definitions of circular economy that principally means different things to different people".

The Ellen MacAthur Foundation (EMAF) has defined the circular economy as a framework for the economy that is restorative and regenerative by design [4]. This model aims to create economic, natural and social capital based on three core principles: design out of waste and pollution, keep products and materials in use, and regenerate natural systems (industrial system). This is in marked contrast to linear economic models as "circular economic models emphasize economic growth and activities that are dissociated from the consumption of finite resources and minimize system wastes, ultimately achieving positive society-wide benefits" [3]. Thus, how companies interpret, develop and implement appropriate circular economy frameworks will be reliant upon how its decision makers or stakeholders including end-users also interpret the concept and its definitions [2]. Additionally, this will depend on what will enable new eco-innovation meet regulation and boost revenue. Stakeholders have highlighted the importance of developing relevant pilot and commercial bioeconomy demonstration facilities that simplify, co-create and produce at scale tangible eco-products from waste biomass and cascades with stakeholders for viable business opportunities [1,2]. Finally, given its infancy, there is gap in the literature on selection of appropriate key performance indicators to guide, monitor and assess impact and added value of bioeconomy activities policies for the environment, economy and society [1].

There has been an increased focus on the use of integrated multi-actor hubs to advance innovations that meet complex societal challenges ranging from improvements in healthcare to efficiencies in reducing waste using circularity approaches [1,2,5]. The European Commision, and several Member states, advocated promotion of a robust circular bioeconomy to underpin implementation of Europe's Geen Deal and to meet climate neutral ambitions by 2050. For example, Skondras et al. [2] examined 20 cases studies arising from 61 circular bioeconomy governance models for enabling regional government good practices. The topology of regional bioeconomy governance models within the EU-27 distinguished between four bio-based transformation paths (TPs), each representing distinct trajectories towards a circular bioeconomy: fossil fuel substitution (TP1), boosting primary sector productivity (TP2), new and more efficient biomass uses (TP3), and low-bulk and high value-applications (TP4). While this provided valuable insights for policymakers to support co-development and replication of effective circular bioeconomy strategies across diverse European regions, the authors noted that managing conflicting goals remains a challenge. Findings highlighted that regions can attract investments in local demonstration or flagship projects for identifying the local availability of feedstocks from various sources (such as agriculture, agri-food industries, forestry, and residual material streams); thereby, "fostering local job creation, regional economic growth, and opportunities in the regional primary production sectors". Data analysis from the 20 governance models suggested that most of them primarily aligned with TP3 (65%) and TP2 (60%), with other transformation pathways being less prevalent. Interestingly, the incorporation of financial organizations was identified as central actors in just two of 20 case studies. While it was appreciated that incorporating of capital markets into regional circular bioeconomy governance models is in its infancy, the authors advocated that blending this function utilizing a penta-helix approach is essential to guarantee effective implementation and governance of regional circular models. However, this insightful review did not address the role of identifying and achieving consensus on relevant key performance indicators (KPIs) to assess data from bioeconomy hub activities that would inform tangible viable innovation, job creation along with regional resilience and regeneration [2]. Consensus on the appropriate KPIs for emerging projects and eco-solutions for the EU Just Transition territories would be particularly beneficial given strong need to define and manage viable alternative eco-innovation such as for circular economy [1].

We have previously discussed the benefits of using digital tools in an Integrated Multi-Trophic Aquaculture (IMTA) system that frames bioeconomy demonstration activities at Mount Lucas peatland site in Ireland [6,7]. Fisheries and aquaculture constitute an important sector to support food security and to meet demand from growing populations globally where innovation and training in aquatech will help unlock opportunities and challenges [1,8,9]. An IMTA is an ecosystem that integrates different species for various trophic levels in a single aquaculture model [9–11]. Essentially, the IMTA model establishes a defined naturally-balanced synergistic ecosystem enabling nutrient flows and inter-species relationships that negate environmental impact, improve water quality and enhance biomass yield. In the context of this novel IMTA peatland site, circularity involves nutrient recycling from excreted faeces produced in finfish cultured ponds that is rich in nitrogen and phosphorus serving as a key resource for lower trophic primary producing species and plants in connecting channels; thus ameliorating nutrient loads and the occurrence of eutrophication [1]. Other IMTA ecosystems have been successfully deployed globally including intertwined relationship between fish production with reed bed filtration in the UK [12]; blending shrimp farming with restoration of mangroves in Indonesia that enhances carbon sequestration and reduces erosion [13]; and integrating salmon farming with seaweed and shellfish cultivation in Canada that enhances nutrient recycling and environmental impact [14].

A digital twin (DT) is a virtual model of a physical entity of which it mirrors its behaviour and states [15]. The DT concept has been applied in many sectors to enable smart systems, including agriculture [15] and manufacturing [16]. A core component, Asset Administration Shell (AAS) is recognized as the implementation of

DT in Industry 4.0 standard, which defines passive and active AAS types to facilitate autonomous and intelligent interactions among system components [17]. Passive AAS types represent the static or real-time information of physical assets (entities), accessible through file exchange or Application Programming Interfaces (APIs). In contrast, the Active AAS type build upon these passive components, incorporating the capability to actively interact with other Digital Twins or physical entities to exchange data or trigger actions. Recent studies have shown the adaptability of AAS types in agriculture domain [18,19], which inspires this paper to propose a peatland-based IMTA living lab leveraging passive and active DTs alongside other digital technologies. Notably, DTs are widely used to demonstrate concepts and prove feasibility across many industries, acting as a nexus between theoretical ideas and real-world implementation. Furthermore, by creating a virtual replicate of a dynamic system before it is initiated or completed, stakeholdes can use them as proof of concepts to evaluate risks, costs and performance without the danger of committing extensive finances to prototypes or systems.

The aim of this perspective paper is to provide novel insights as to how digital twins can be leveraged to develop the first IMTA bioeconomy demonstration site at scale in the Irish peatlands at virtual living lab for Mount Lucas. Informed by onsite stakeholder engagements and by review of best-published literature, we propose an initial set of KPIs to help advance these IMTA activities in this bioeconomy sector. By introducing DTs into commercial bioeconomy demonstration, such as at Mount Lucas and at other scalable sites, this will potentially reduce labour costs, ensure authorized data access, preserve data sovereignty, and enhance system interoperability.

2. Integrated Multi-Trophic Aquaculture (IMTA) Infrastructure

The peatland-based IMTA system located in the Irish midlands at Mount Lucas in County Offaly [17]. This IMTA site currently comprises a 16-channel duckweed lagoon, macroalgae tanks, and four D-end fish culture ponds and operates to zero waste and zero pollution principles. The site does not use pesticides nor chemicals [1]. The microalgae and duckweed biomass utilize nitrogen and phosphorus from fish waste streams to return clean water to the D-end ponds. It does not discharge to receiving waters unless affected by extreme weather events such as periods of high rain fall [9]. Wind turbines supply electricity to the site to provide power to innovation suite and for oxygenation and mixing in ponds and channels [9]. Established and pending infrastructure at this IMTA site comprises a welfare unit, business and innovation suite, extended reality unit; living laboratory, conversion system and biorefinery including valorisation for waste stream, and tank-based macroalgae cultivation [1]. The entire site is being upgraded for 5G connectivity (wireless). Onsite use of drones for aerial imagery of land coverage including foliage and biomass optical reflectance and for measurement of GHG emissions. GHG emissions are measured by sensors in fish pond with a focus on N_2O emissions. Noting CO_2 is currently not measured as not required under Intergovernemtnal Panel on Climate Change (IPCC_ guidelines for wastewater systems and similar systems are considered biogenic. Sensors are deployed for physiochemical measurement within ponds and channels including pH, dissolved oxygen, oxidation-reducation potential (ORP), nitrate, ammonium, turbidity, total suspended solids and phycocyanin. Real time data is used to support onsite extended reality experience for training and innovation [1].

3. Use of Digital Twins to Support and Enhance Bioeconomy Activities at IMTA Site

Appropriate sensors can be deployed across Mount Lucas facilities to provide input data for the passive DTs—either historical data accessible through file formats or real-time data accessible via application programme interfaces (APIs). Figure 1 presents the overall architecture of the IMTA living lab at the Mount Lucas site, integrating an aerial drone image of the site at the bottom. The sensors and facilities that are currently deployed—or could be implemented—at Mount Lucas site are mapped onto the infrastructure layer. The Mount Lucas Living Lab Digital Twin comprises three types of DTs along with services for DT management, access, and analysis. A blockchain-based Decentralized Data Space enables the sharing and exchange of DTs among aquaculture living labs while simultaneously preserving data sovereignty.

The Mount Lucas living lab can also employ active DTs that contain processing logic to operate on these passive DTs, enabling responsive actions to changes within site facilities. Active behaviours are initiated and executed through actuators. For example, the speed of airlifts in each split pond can be intelligently adjusted to control water circulation based on analyses of water quality and fish health DTs. Drones may also be regularly deployed to monitor duckweed coverage and productivity across the site's ponds, contributing to improved operational efficiency in wastewater treatment and recirculation [9]. Although no robotics are currently deployed at Mount Lucas, similar systems have been used for pond cleaning [20] and the removal of diseased fish [9]. Fish feeding can also be made more efficient and precise when automated systems are integrated with real-time monitoring parameters. These labour-intensive tasks can ultimately be scheduled and optimized automatically by active DTs.

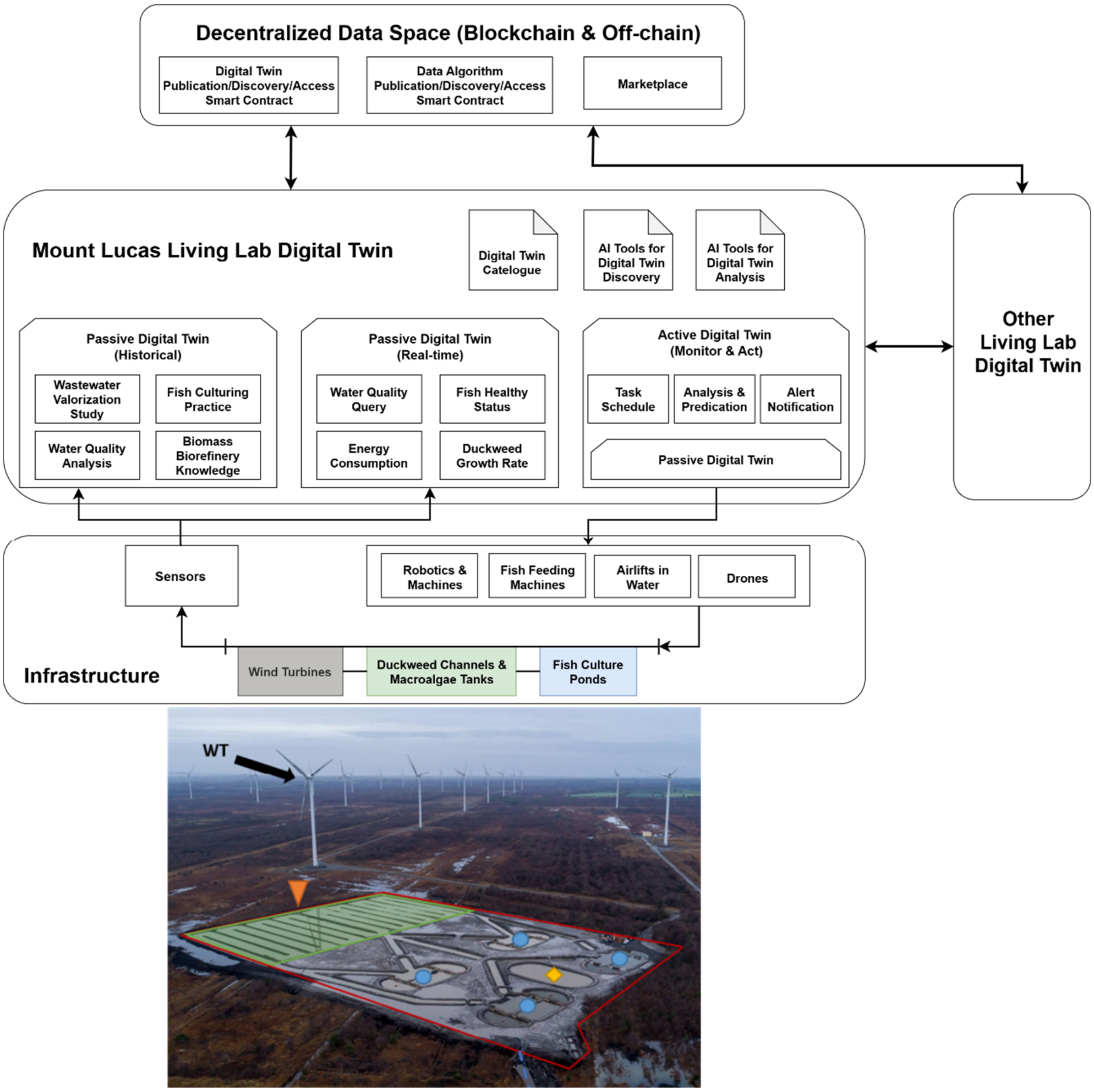

Figure 1. Mount Lucas Living Lab Architecture. Perimeter of IMTA site (red line), fish ponds (blue circles), reservoir (yellow rhombus), lagoon (orange triangle), wind turbine (WT).

3.1. Mount Lucas Living Lab

The Mount Lucas living lab serves as the virtual representation of its peatland-based IMTA site. It is designed to create, share, manage and save DTs. Historical passive DTs may include site-specific data such as weather reports, water temperature readings, oxygen levels and pH values in pond water, as well as knowledge of fishing practices used to improve yields. All such data can be stored with timestamps to generate comprehensive reports for knowledge sharing and for big data analysis supporting AI modelling and training. Moreover, another type of passive DTs can be accessed via APIs to provide real-time data of the site. These APIs defines the standardised formats for querying the properties and functionalities of the physical facilities. For example, Mount Lucas administrators can efficiently and directly query current water quality, fish status, or electricity consumption rates using the living lab platform.

Active DTs integrate both active and passive components. The passive component interacts with passive DTs based on predefined conditions—for example, activating paddlewheels in the fish culture area when the oxygen level drops below a specified threshold. The active component represents the knowledge base that enables intelligent and autonomous behaviour, consistent with the definition of an active asset administration shell (AAS) described in [17].

As shown in Figure 1, the Analysis & Prediction module is responsible for monitoring passive DTs and executing analytical logic to detect anomalies or schedule events. Active DTs can make predictions and provide recommendations by applying AI algorithms to historical datasets, thereby assisting site management such as handling extreme weather conditions and preventing fish diseases. Alert Notification module is automatically and promptly triggered when system abnormalities arise, in accordance with predefined rules. The Task Scheduling model serves as a key element of active DTs, enabling service negotiation (e.g., duckweed channels requesting harvesting robots), workflow optimization (e.g., determining task execution sequences), and decision-making for task coordination (e.g., scheduling drone operations). The integration of both active and passive DTs will enable more intelligent and efficient maintenance and management of the Mount Lucas site.

To make Mount Lucas DTs accessible to other living labs, organizations and individuals, a local Digital Twin Catalogue is proposed to register all DTs associated with the site, therefore providing a searchable and reviewable list of available DTs. AI tools can be developed to facilitate DT discovery and querying, making the process more human-centric and user-friendly including for precision aquaculture [21]. For instance, the AgTech system [22] has implemented an assistant layer that uses Natural Language Processing (NPL) technology to interpret user input, perform deep searches for relevant information and generate coherent responses. Furthermore, AI algorithms and analytical tools can be developed and deployed within the living lab to support specific task execution and enhance DT-based decision-making.

3.2. Decentralized Data Space

The development of peatland-based IMTA systems is emphasised as a means to contribute to the United Nation's sustainable development goals [1]. However, to the best of our knowledge, these is a lack of IMTA demonstration sites worldwide; thus, it will be important to standardized aninteroperable framework to support open knowledge exchange among this and future scalable sites. The blockchain-based Decentralized Data Space layer in Figure 1 is proposed as a solution. A state-of-the-art platform Pontus-X [23] could be implemented and extended as this decentralized data space, enabling each living lab to store its DTs locally while providing DT publication, discovery, and access services through smart contracts. In addition to DT sharing, the Decentralized Data Space also supports the publication and access of processing algorithms, allowing users to deploy or reuse analytical models across different living labs. To ensure scalability and efficiency, algorithm execution can leverage offchain computing, where data processing occurs outside the blockchain network. This approach enables the handling of intensive or sensitive tasks without overloading the blockchain, while verified results are securely referenced onchain to preserve integrity and transparency. This hybrid architecture combines the trust guarantees of blockchain with the performance and flexibility of external computing infrastructures such as edge or cloud resources. The Marketplace component promotes collaboration and innovation between stakeholders with protecting data ownership and privacy. Mechanisms such as identity management and access control are essential to ensure data sovereignty, allowing DT holders to retain full control over who can access their data. Furthermore, effective data transmission between living labs, i.e., accessing and exchanging DTs, requires the definition and implementation of standardized data communication protocols. An ICT partnering company manages open data for visualization and real-time analysis onsite for promoting activities to broad stakeholders that is not affected by intellectual property protection.

4. Use of Integrated Penta-Helix Hub Framework to Advance Use of DTs and to Inform KPIs at This IMTA Site

A concerted effort to strategically develop the bioeconomy sector internationally from top-down policy perspective that will hopefully inform a swarm of bottom up activities that will deliver on effective viable new products, markets and job creation centred on circularity [1,2]. There has been a commensurate interest in converging skill sets and resources from different actors to meet such complex societal challenges regionally, such as using combinations of these actors in the form of triple, quadruple and penta-helix arrangements or models [2]. Table 1 highlights the potential benefits of using a Penta-helix hub framework for meeting established and emerging needs of the bioeconomy across the linked themes of (a) multiactor integration, (b) technical support training and co-creating innovation, (c) regulatory, (d) business and dissemination, (e) sustainability, (f) social sciences and (g) educational technologies. This describes how DTs can potentially enable co-creation of new innovation on site virtually that will derisk prototyping and support justification for investment.

Table 1. Addressing Bioeconomy needs using IMTA demonstration by adopting a Penta Helix hub.

Activity	Description	Benefits	Refs.
Multi-actor, integrated Hub approach 	▪ Multi-actor (specialist) inputs	▪ Holistic problem solving ▪ Access to specialist equipment/staffing/mentors ▪ Clustering of resources ▪ Suits small to large operations ▪ Tangible impact (KPIs) + use of AI ▪ Ecosystem building for end-users (enterprise accelerator)	Rowan [1,6] Rowan et al. [7] Rowan and Casey [24] Richter et al. [25] Naughton et al. [26] O'Neill et al., [27] DAFM/JT [28]
Technical Support, testing, Co-creating, verification 	▪ On site living lab, innovation suite, biorefinery ▪ Test the tech ▪ Fully digitized (monitoring)	▪ Testing and demonstration of technologies/products (TRL7+) at scale ▪ Ecosystem building (end-users) ▪ Risk mitigation/attract investment ▪ Ideation, eco-design thinking ▪ Knowledge/IP management ▪ Environ sustainability of bio- based product & value chains ▪ Operates to zero waste and zero pollution principles	Rowan et al., [7] Richter et al. [25] Naughton et al. [26] Ruiz-Salmon et al. [29] O'Neill et al. [30] Brazil et a. [31] Wang et al. [32] Rowan [33]
Regulatory 	▪ Demonstrates products under verification and validation	▪ Ensure environmental sustainability of feedstock (ecotox/environ balanced) ▪ Appropriate methodology deployed for demonstration for verification ▪ Aquaculture licence compliant ▪ Risk Management	Rowan [1,34,35] McBride et al. [36] Sachs [37] O'Neill et al. [38] Tahar et al. [39] Rowan and Galanakis [40]
Business & Dissemination 	▪ Business model canvas, SWOT and accelerator ▪ New products and markets	▪ Financially viable product/value proposition/access to finance ▪ Providing key resources and expertise across TRLs ▪ Physical and virtual demo ▪ Networking key partnerships ▪ Optimized value stream ▪ Integrated ecosystem building	Rowan [1] Shondkas et al. [2] Rowan and Casey [24] Almeida et al. [41] Rowan and Pogue [42]
Sustainability 	▪ Operates to zero waste and zero pollution principles ▪ Alternative to fossil fuel products	▪ Meets strategic policies (bioeconomy+) ▪ Green technology, product demo ▪ Holistic approach (penta-helix) using multi-actors ▪ Develop skills for EU bio-based sector ▪ Carbon sink (wet paludiculture) ▪ Energy/emission footprint (LCA) ▪ Technical, political, societal LCAs	Rowan [1] Almeida et al. [41] Cooney et al. [43] Ruiz-Salmon et al. [29] DAFM/JT [28] Pogue et al. [44]
Social Sciences 	▪ Social enterprises ▪ Outreach activities ▪ Citizen Science	▪ Informs and enables many UN SDGs for social inclusiveness ▪ Helps people and communities pivoting under EU JTF region ▪ Promote peatland innovation for a shared approach to 'greening' ▪ Promotes behaviour change	Rowan and Galanakis [40] O'Neill et al. [45] Domegan [46]
Educational technologies 	▪ Bespoke educational training across all IMTA activities and disciplines	▪ Training next-generation of eco-'game-changers' including for disinfection ▪ Universal design by learning, Lean Six Sigma ▪ Enhanced Productivity/Efficiency ▪ Unlocking societal solutions ▪ Measurable impact and disruption ▪ Promotes Industry 5.0	Rowan and Casey [24] Domegan [46] Rowan [47] Kremer et al. [48] Schuelke-Leech [49] Wan-Mohtar et al. [50]

KPI (Key performance indicators); LCA (Life Cycle Assessment); JTF (Just Transition Fund); AI (Artificial Intelligence); TRL (Technology Readiness Level).

A review of published literature in PubMed search engine over the past decade has revealed 46 different innovation helix frameworks with just 2 addressing the bioeconomy [1,2] that is explained in part by its infancy. Rowan [1] described this IMTA demonstration model with emphasis on creating a circular economy with stakeholders underscored by aquaculture. Skondras [2] reviewed differrence bioeconomy governance models that adopted Triple or Penta helix approaches. A review of Pubmed and Scopus databases using the words "bioeconomy" and "aquaculture" over the past decade revealed 19 publications which were predominantly conceptual or review articles that included aquaculture as a theme. For example, Zhang et al. [51] evaluated fermentation technology as a sustainable solution to the "food-fee-fuel", three competing lands uses. Coronado-Contreras and co-workers [52] reviewed pathways for biomass valorization and sustainable biorefineries where use of aquaculture was mentioned once in relation to using biological resources from it to produce value-added products. Keohavong [53] mentioned aquaculture in relation to nutrition and limitations to sustainable protein and nutrition in circular bioeconomy models. Nneonma et al. [54] discussed use of aquaculture for its wastewater content when considering hybrid biofactories, specifically integrating microalgae and engineered microbiomes for enhanced bioful production in circular carbon systems. Fabris et al. [55] discusses how emerging technologies such as synthetic biology, high-throughput phenomics, and the application of the internet of things (IoT) automation of algal manufacturing technology can advance our understanding of algal biology, and ultimately, drive the establishment of an algal-based bioeconomy. Rowan [33] described operational activities to develop IMTA site for bioeconomy demonstration. While Peladarionos et al. [56] reviewed how smart agriculture could be potentially enhanced by using DTs, but did not specifically address the bioeconomy.

In general, there is a marked gap in describing key performance indicators (KPIs) to monitor and evaluate hub performance such as developing and seeking consensus for the use of KPIs. Table 2 provides an indicator name and unit for advancing the bioeconomy sector provided by the Irish Department of Agriculture, Fisheries and the Marine in agreement with the EU Just Transition where indicative DTs are suggested for each based on use of the Mount Lucas IMTA Bioeconomy Demonstration model. These KPIs evolved from discussions with DAFM from prior change of land use scoping study using the peatlands through exensive engagement with stakeholders via bespoke onsite workshops [1]; but, also from review of best-published work on this bioeconomy demonstration at scale topic internationally [example 1 to 10]. Initial KPIs focused on level of company engagement to grow scale and capacity, thereafter the types of biomass produced and added value for new markets. Additionally, Figure 2 provides indicator name for KPIs for developing the bioeconomy sector a *micro* (such as company or actor), *meso* (such as innovation Hub) and *macro* (such as overarching strategic policy) levels based on both publications and specifications described in bioeconomy funded instruments, particularly for Ireland. It is apparent that strategic development of pilot and commercial demonstration sites for supporting bioeconomy activity (*meso* level) can be served by use of Penta-helix hub actors (such as industry, academia, regulators, finance, society) at a critical interface to tailor and to inform policy. However, there remains a pressing need to delineate and modify range of KPIs (such as developing aquaculture for the bioeconomy [57]), which will be potentially fine-grained over a longitudinal period encompassing independent reviews and audits for demonstrating and verifying their appropriateness.

In conclusion, the bioeconomy is emerging as an important sector for co-creating new eco-innovation, sustainable resource management and change of land use, and protecting our fragile environment encompassing soil, water and air. Use of appropriate demonstration facilities at scale will aid definition and testing of viable 'tangible' products and business plans including de-risking for investment and for protecting our environment. These pilot and commercial bioeconomy demonstration sites will operate at the interface between bottom-up end-user activities and top-down strategic policies to co-develop new innovation. Digital living labs have the potential to support and accelerate activities and drive innovation in real time for the bioeconomy by demonstating concepts and proving feasibility for a diversity of companies and endusers including policymakers; thus, acting as a nexu between theoretical idas and real world implementation. By creating a virtual replica of a dynamic system before it is initiated or completed, these stakeholders can use DTs as proof of concept to evaluate risks and to enable improvements in efficiency and efficacy that cross-cuts to education, innovation and social enterprises. However, it is important to delineate appropriate KPIs from bottom up end-user perspective that will help guide and tailor regional strategic policies along with cohesion of different polices. Rewetted peatlands offer possibilities of co-creating, testing and developing new eco-innovation operating to zero pollution and zero waste principles where the guiding operational framework can be potentially replicated globally, which includes safe and sustainable by design ethos. The integrated convergence of stakeholders, such as using Penta helix innovation hubs, offers end-to-end opportunities for advancing ambitions of the bioeconomy sector that addresses socio-economic and environmental needs. This integrated blueprint can also facilitate interaction and consensus on clustering different bioeconomy demonstration sites for added value to ensure all stakeholder interests are met that will strategically support our circular economies. There is a significant wave of activity globally to strategically advance the bioeconomy sector where identifying and seeking consensus on use of appropriate KPIs will help to monitor and guide progress for all stakeholders that will inform rural regeneration, regional resilience, competitiveness, employment and will protect our fragile planet.

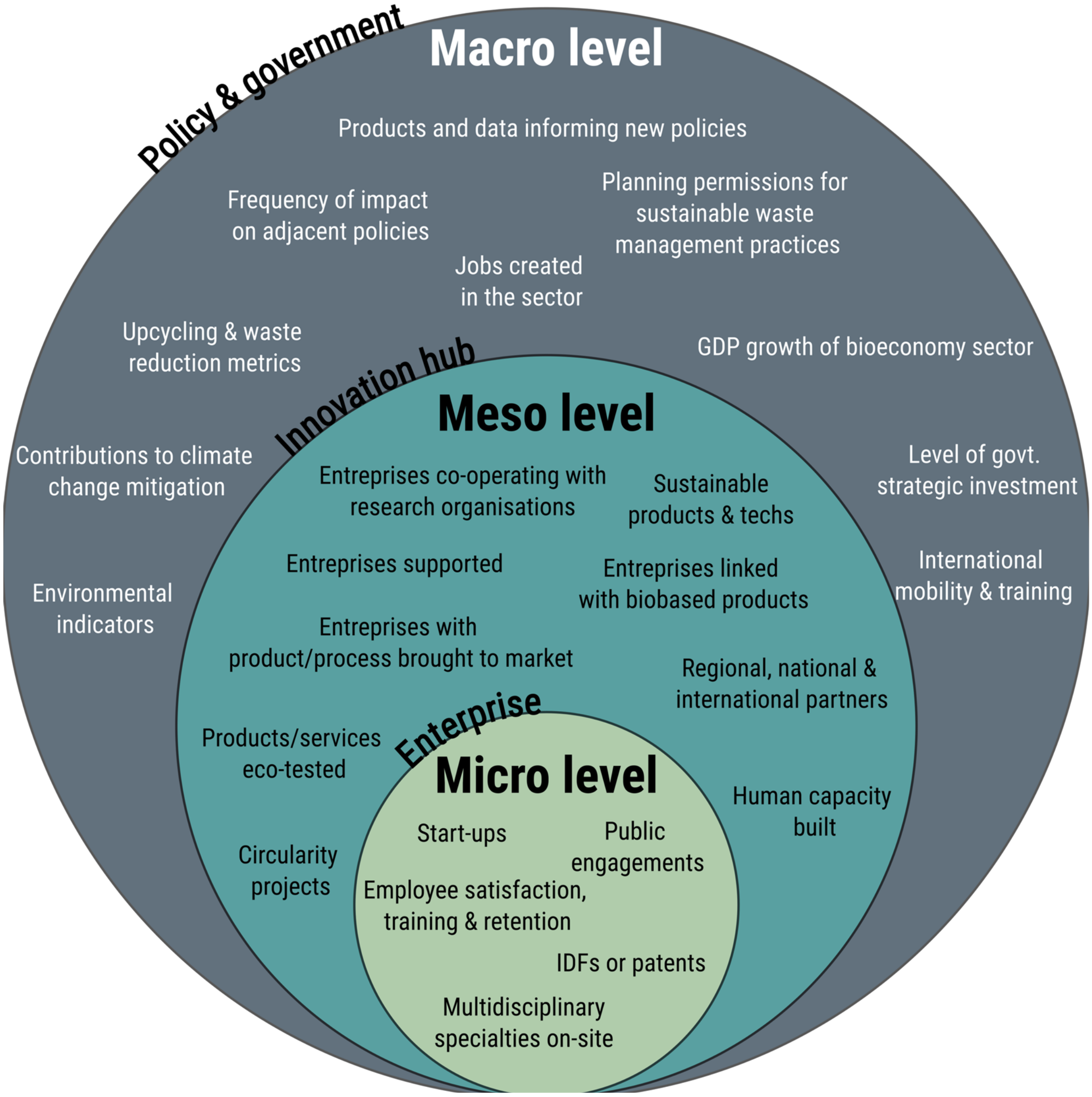

Figure 2. Candidate key performance indicators for monitoring efficacy of bioeconomy activities at demonstration site using Penta-helix framework at micro, meso and macro levels of engagement.

Table 2. Combined use of Digital Twin(s) to support monitoring and efficacy of bioeconomy demonstration (BD) for specific KPIs.

KPI Indicator Name *	BD Measurement Unit	Example of KPI Activity at Mount Lucas BD site	Digital Twin
Strategic participation and integration of feedstock producers and suppliers towards large-scale valorisation and sustainable biomass	➢ No. of primary producers, involved as project beneficiaries and/or engaged in value chains ➢ No. of (bio)waste management actors, involved as project beneficiaries and/or engaged in value chains also at project level	➢ Finfish, Algae (Micro and Macro), Duckweed ➢ IMTA site is recirculating & operating to zero-waste principles using open access	➢ Algae and Duckweed Growth Rate ➢ Fish Feeding Frequency ➢ Biomass Yield ➢ Biomass Refinery Practice
Unlock sustainable and circular bio-based feedstock for the industry	No of innovative bio-based value chains created and enabled based on sustainably sourced biomass	Onsite conversions systems for aquaculture, aquatech, algae duckweed for cosmetics, biopharm/pharma value chains	➢ Biomass Harvest Schedule ➢ Resource Recirculation Knowledge for Value Chains
Ensure environmental sustainability of feedstock	➢ No. of projects using feedstock generated with practices that contribute to enhanced biodiversity ➢ No. of projects using feedstock generated with practices aiming at zero-pollution (soil, water, air) ➢ No. of projects using feedstock generated with practices contributing to climate change mitigation and/or adaptation	➢ Algae, duckweed and other plants, fish waste stream informing aquatic ecosystem ➢ Water (aquatic) zero-pollution process ➢ GHG emissions and energy efficiency via IMTA using non-fossil fuel resources	➢ Fish Waste Outputs ➢ Fish Healthy Status ➢ Water Quality Reading
Improve environmental sustainability of bio-based production processes and value chains	➢ No of projects with innovative & sustainable processes that contribute to GHG emissions reduction 60 ➢ No. of projects developing innovative & sustainable processes to zero pollution ➢ No. of projects with innovative & sustainable process with improved energy efficiency ➢ No of projects with improved life cycle environmental performance	➢ IMTA process is designed and operated to contribute to GHG emissions reduction ➢ Direct understanding of process emissions with broader implications for nature based engineeering and bioeconomy approaches ➢ Bioremediation process using algae/duckweed for fish waste ➢ Use of wind turbine—future production of biofuel onsite ➢ LCA to be conducted as BD site is in its infancy	➢ GHG Emission Value ➢ Wind Turbine Energy Generation ➢ Energy Consumption ➢ Bioremediation practices/knowledge
Expand circularity in bio-based value chains	➢ No. of innovative products that are biodegradable, compostable, recyclable, reused or upcycled (circular by design) ➢ No. of projects developing circular production practices (incl. industrial & industrial-urban symbiosis)	➢ Bio-based products from Algae, Duckweed other peatland-growing plants using fish waste stream ➢ IMTA BD process is fully recirculating (end-to-end)	➢ Number and types of generated bio-based products ➢ Practices to reuse and upcycle using fish waste
Increase innovative bio-based outputs and products	No. of innovative bio-based dedicated outputs, with novel or significantly improved properties v's relevant alternatives.	Future use of bio-based products for cosmetics, biopharma and pharma sectors	➢ Training slides/materials for innovative bio-based products
Improve the market uptake of bio-based products	No. of brand owners involved as project partners and/or engaged with other mechanisms	Brand owner engaged per add value stream in IMTA process	➢ Product value chain (tracking origin-to-market of bio-based aquaculture products)
Attract investment on the bio-based sector	No. of actions implemented as project level to attract investment and/or to create awareness in the investment/funding community	Onsite business accelerator, training, bespoke workshops, grant writer supported by BIM, Teagasc etc to attract investors	➢ Techno-economic and lifecycle cost twin (integrating CAPEX/OPEX and carbon impact)
Increase resilience and capacity in the bio-based sector	No. of projects contributing to develop the skills and capacity needed by the EU bio-based sector	Aquaculture/aquatech for EU Just Transition in Irish midlands	➢ Increased number of living lab platforms in EU

* DAFM/EU Just Transition Call specification for Bioeconomy Demonstration Initiative 2 [28]; BD (Bioeconomy Demonstration), LCA (Life cycle assessment), KPI (Key Performance Indicator); IMTA (integrated multi-trophic aquaculture) system; GHG emissions reduction 60—European Union aims for at least a 60% reduction in greenhouse gas emissions as target and goals for initiatives by 2030 [1].

Author Contributions

Q.W.: conceptualization, investigation, data curation, methodology, writing—original draft preparation, reviewing and editing; Y.Q.: funding acquisition, supervision data curation, writing—original draft preparation, reviewing and editing; A.F.: visualization, investigation, methodology, original draft preparation, reviewing and editing ; E.A.O.: investigation, methodology, original draft preparation, reviewing and editing; D.T.: conceptualization, investigation, methodology, writing—reviewing and editing; E.C.: investigation, methodology, data curation, original draft preparation, reviewing and editing; B.R.: investigation, methodology, data curation, original draft preparation, reviewing and editing; N.J.R.: conceptualization, investigation, funding acquisition, supervision, methodology, investigation, original draft preparation, reviewing and editing. All authors have read and agreed to the published version of the manuscript.

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Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

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