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Review

Unlocking challenges and opportunities presented by COVID-19 pandemic for cross-cutting disruption in agri-food and green deal innovations: Quo Vadis?

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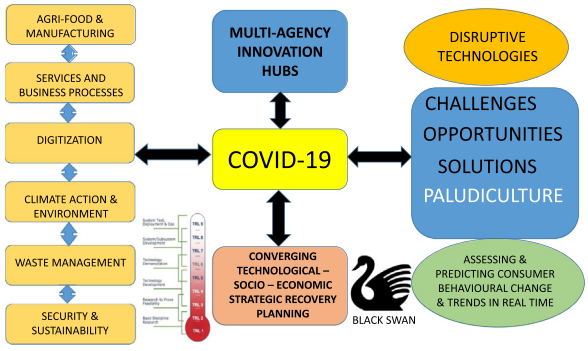
HIGHLIGHTS

- COVID-19 pandemic presents opportunities for sustainable agri-food production and to accelerate green innovation.
- Sensible yet ambitious technical-economical recovery plans are urgently needed when countries reopen.
- COVID-19 may create disruptive technologies that cross-cuts agri-food, ICT, health, and environment.
- Multi-agency converging innovation hubs have the potential to accelerate socio-economic recovery.

GRAPHICAL ABSTRACT



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ABSTRACT

COVID-19 pandemic is on a trajectory to cause catastrophic global upheaval with the potential to alter geopolitical and socio-economic norms. Many countries are frantically responding with staggering financial stimulus recovery initiatives. This opinion-paper reviews challenges, opportunities, and potential solutions for the post-COVID-19 era that focuses on intensive sustaining of agri-food supply chain in tandem with meeting the high demand for new green deal innovation. For example, the development of wet peatland innovation, known as Paludiculture, can intensively sustain and blend agri-food and green innovations that will help support COVID-19 pandemic transitioning. The future looks bright for the creation of new sustainability multi-actor innovation hubs that will support, connect, and enable businesses to recover and pivot beyond the COVID-19 pandemic. The nexus between first 'Green Deal' initiative supporting 64 selected European Startups and SMEs (European Innovation Council) and 43 Irish Disruptive Technology projects are addressed in the context of cross-cutting developments and relevance to COVID-19. Candidate areas for future consideration will focus on climate action, digitization, manufacturing, and sustainable food production, security, and waste mitigation. Recommendations are also provided to facilitate community transitioning, training, enterprise, and employment to low carbon economy.

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Contents

1. Introduction

Coronavirus (COVID-19) has caused dramatic and unprecedented upheaval to socio-economic norms since first reported in Wuhan, China, earlier this year (Rowan and Laffey, 2020; Guan et al., 2020). COVID-19 pandemic is impossible to predict, with many countries experiencing second or successive waves of infection. Akin to a 'Black Swan' event, there is a significant gap in published research to inform companies where most have neither prepared for it nor have they planned to transition beyond it (Taleb, 2010; Reid et al., 2020). COVID-19 impacts upon health systems, governments, and businesses alike with unprecedented implications for companies worldwide. Companies are feeling the market and financial shock of the COVID-19 outbreak by factories' shutdown, labor shortages to cash flow stress, and disruptions in the supply chain (Reid et al., 2020). The global mitigation response has focused on public health strategies to curtail and reduce the spread of viral transmission through hand hygiene, social distancing, lockdown (staying-at-home, cocooning), and, community wearing of protective face masks that now occurs in 50 countries (Rowan and Laffey, 2020; Silva et al., 2020). This fact has resulted in an unprecedented technical-socioeconomic earthquake that has left many sectors seeking emergency COVID-19-related unemployment benefits (Rowan and Laffey, 2020; Guan et al., 2020). The food supply chain sector does not comprise an exception (Galanakis, 2020). Sarkis et al. (2020) noted that there is a window now for transitioning to sustainable supply chains in the aftermath of COVID-19 that includes rethinking vulnerabilities created by over-reliance on 'just-in-time' or 'business-as-usual' practices. Barcèló (2020) highlighted challenges affecting the environment and health caused by COVID-19 pandemic along with recommendations for monitoring and mitigation.

Similarly to other countries, the Republic of Ireland has been in lockdown for 3 months to flatten the curve in COVID-19 cases. On the other hand, it is in a relatively privileged position where it is adopting a phased reopening of the country that commenced 18th May 2020, with phase five intimated for 10th August 2020 (Fig. 1). While Ireland is emerging from the first phase of reopening, likely, the vast majority of foodservice and businesses will not return to regular operation for several weeks. Covid-19 adjusted employment in the Republic of Ireland has reached 28.2%, compared with traditional 5.4% for the same month last year, which is estimated to cost the Irish exchequer €6.4bn until the country reopens. COVID-19 pandemic has introduced dramatic uncertainty and unpredictability where this volatility has the potential to cause socio-economic chaos across many sectors when Ireland and other countries reopen for business (Guan et al., 2020).

While there are financial stimulus support packages (Government of Ireland, 2020), there is an unprecedented dearth in critical information (such as marketing of new consumer trends and behavioural change to offset sheltering-in-place and social distancing) in order to enabling businesses to make priority decisions on core needs for recovery post-COVID-19 (Sarkis et al., 2020). As there was almost simultaneous closure of countries due to COVID-19 mediated lockdowns (Guan et al., 2020), the Republic of Ireland will re-emerge from the COVID-19 bubble ahead of many other trading countries that will provide a useful lens to gaze through to inform recovery. This scenario will help inform real-time situational-analysis and will reveal the main challenges where different geopolitical and socio-economic landscape now potentially exists internationally. The lack of food security means that countries are dependent upon imports but may not earning sufficient foreign currency to purchase vital imported goods. The post-COVID-19 era also presents equal opportunities to address climate change and to advance green innovation matched with driving sustainable food production and security.

2. International financial recovery stimulus support initiatives for business during and post COVID-19

Europe needs to be reopened as quickly as sensible, but this will involve significant risk. In response, there has been major national, EU, and international stimulus financial aid to offset this potential socio-economic crisis potentially. On 27th May 2020, the European Commission presented an economic stimulus plan of €750 billion to help mitigate the shock from this COVID-19 pandemic and pave the way for a sustainable future. While there is a commitment to support recovery financially, there is currently a lack in specific detail underpinning a techno-socio-economic ecosystem unroadmap to guide F&D companies through and beyond COVID-19 when countries reopen. There is a recognition that the EU will still need to prioritize climate actions and a digital strategy, but also to update the new EU health program. This action is important to ensure continuity of supply chain for food and medical products, services across the EU to offset critical shortages arising for existing and future pandemics. In the Republic of Ireland, the Department of Health and the Department of Agriculture, Food and the Marine (DAFM) are collaborating as part of a holistic response to COVID-19, e.g., although remaining open for business sector (DAFM, 2020). At the time of writing, two very stark documents published in Ireland - the Irish Fiscal Advisory Council (2020) and the ESRI UK and Ireland (2020) both warned of ballooning unemployment, huge deficits, massive accumulations of public debt and painful budgetary adjustments

Phase 1 May 18th, 2020	Phase 2 8th June, 2020	Phase 3 29th June, 2020	Phase 4 20th July, 2020	Phase 5 10th August, 2020
Phased return of outdoor workers Remote working continues for all that can do so.	Limited return to onsite working subject to compliance capability Remote working continues for all that can do so.	Return to low-interaction work. Remote working continues for all that can do so.	Return to work where employees cannot remote work. Staggered hours. Remote working continues for all that can do so.	Phased return to work across **all** sectors. Remote working continues for all that can do so.
Retail that is mainly outdoor and homeware, opticians, motor, bicycle & repair, office products, electrical, IT, phone sales & repair open. All subject to social distancing.	Small retail outlets with control of numbers open. Marts open. All subject to social distancing	Open non-essential retail outlets with street level access.	Gradual easing of restrictions on higher-risk services. e.g. Barbers and hairdressers	Further easing of restrictions higher-risk services. e.g. shopping centres, tattoo, piercing.
Farmers markets, gardners and other outdoor workers return to work – social distancing requirements continue to apply . Remote working continues for all others that can do so . Return to Work Safety Protocol is the operative guide for employers and employess	Small retail outlets can reopen with a small number of staff on the basis that the retailer can control the number of individuals that staff and customers interact with at any one time.	The opening of all other non-essential retail outlets will be phased in on basis of a restriction on number of staff and customers per square metre so that social distancing can be maintained. This is to be limited to retail outlets with a street-level entrance and exit and does not include those in enclosed shopping centres due to higher risk.	Restrictions will gradually be decreased on the numbers travelling in major urban centres on public transport and in private cars. Specific measures will be introduced at ports and airports.	Enclosed shopping centres can reopen, with social distancing. A further loosening of restrictions for services involving direct physical contact for periods of time between people for which there is not a population-wide demand for later phases due to risks . Non-resident tourist travel to offshore islands can resume. Social distancing and hygiene measures are to continue for public and private transport.
Data source - https://www.gov.ie/en/news/58bc8b-taoiseach-announces-roadmap-for-reopening-society-and-business-and-u/ (accessed June 4th, 2020)				

Fig. 1. Reopening of economic, retail and commercial activities in the Republic of Ireland using a phased approach during 2020.

to the tune of up to €14bn by 2025. IBEC (2020), the group that represents Irish business, published proposed solutions to COVID-19 imposed liquidity crisis, e.g., supporting vulnerable businesses using emergency cashflow and liquidity measures from the Irish government. IBEC also denoted the importance of maintaining the operation of food and other processing facilities. This action includes specific liquidity and financing needs of farmers, fishers, and agri-food businesses and for the banks to offer flexibility to their customers at an early stage to discuss emerging cashflow issues.

3. Agri-food industry – an example of challenges ahead post COVID-19

The agri-food sector comprises a dynamic societal-technical innovation ecosystem and is one of the largest manufacturing industries (Saguy et al., 2018; Rowan, 2019). In the EU, this increasingly important sector accounts for €1098 billion turnovers and employs 4.24 million (Saguy et al., 2018). The food and drink (F&D) industry has doubled in size in the United States over the past decade, where it was estimated to be worth £6 trillion in 2015 with packaging comprising almost £1.9 trillion (Statista, 2020a). Revenue in the food market amounts to US $924,389m in 2020; the market is expected to grow annually by 1.8% (Statista, 2020a). The rate of global population growth is staggering, and there is a commensurate need to match this demand that will put increasing pressure on food production and security (Richie et al., 2018; Michelini et al., 2018). There is a pressing need to diversify the food supply chain and identify sustainable technologies across food systems that will meet changing diets, increasingly aging, ethnic and cultural population, diet-related diseases, more personalized products (Galanakis, 2020). DBEI (2018) projects that there will be a ca. 70% rise in demand for more food products and services over the next 40 years. In the years ahead, it is envisaged that organic, unprocessed, and healthy food will drive growth in domestic markets (Statista, 2020b). For example, the estimated value of shipments of the industry was US$795.4 billion in 2019, where. 15.1% of the cost of shipments generated from dairy product manufacturing.

The agri-food and beverage sector is Ireland's most important indigenous industry where the sector produced €13bn of exports to overseas markets in 2019 on foot of decades of accelerated growth where the value of exports in this sector increased by 67% (Duffy, 2020). However, at this time of writing, the impact of COVID-19 pandemic with associated international lockdown has pretty much instantaneously shut down world economies. Duffy (2020) reported that COVID-19 would also bring about a dramatic collapse in merger and acquisition activity with deals stalled, put on hold, or canceled outright. With such uncertainty and unpredictability – post-crisis, the likely immediate focus of business owners will be on managing core business and recovery. It is very challenging to forecast at this stage, for the F&D sector, the outcome and when new dawn may emerge. Duffy (2020) postulated that deals likely to be created from COVID-19 circumstances include "(a) forced mergers and acquisitions transactions as those companies unable to recover from this crisis will seek buyers, (b) corporate entitles with competitive cost structures, strong balance sheets, and case resources may seek cheaper deals including lower valuations for businesses post COVID-19, (c) consolidation of some companies of similar size to withstand market uncertainties and strengthen their financial standing by securing new customers/markets; (d) companies may seek to remedy supply chain problems, such as cash-rich retailers transitioning to procure certainty of supply for certain food products; (e) companies to see out value by adding traceability solutions to improve food security – where they will find themselves facing enhanced requirements to satisfy consumer needs for accurate and transparent information on the food they are producing". COVID-19 will be trying to understand if changes to consumer purchasing practices are permanent and how/where to adjust post-COVID-19.

4. Transitioning COVID-19 crisis by exploiting green peatland innovations (Paludiculture) - a useful nexus between agri-food, climate action, and circular economy

Europe has set out its ambitious vision to become the world's first climate-neutral continent by 2050 (A European Green Deal, 2020), while in 2019, the Irish Government published of the All of Government Climate Action Plan - to tackle Climate Breakdown. The food and environmental sectors are tightly bound. The environmental industry is nowadays facing societal changes that force companies to pay more

Table 1
European wet-peatland technologies (Paludiculture) funded projects and relevance to green deal innovation and COVID-19 pandemic recovery.

Project	Aims and approaches	Partners	Activities	Impacts
Interreg NW Europe Carbon Connects 2018–2021 €4.5 M funding https://www.nweurope.eu /projects/project-search/ cconnects-carbon-connects/	To reduce the high carbon footprint of peatland soils in Northwest Europe by introducing new bio-based business models developed for sustainable land management practices. Estimated stats offered are 50% reduction in CO_2 emissions caused by traditional practices Promote alternative approaches to wet agriculture to protect environment Low lying peatlands – can be done by raising water levels and introducing alternative crops Facilitating transformation in land use to wet agriculture – develop new business models Enhancing wetland ecosystems	Research partners Netherlands Belgium, France UK Ireland Local authorities Farmers Consumers Research Institutes	'Paludiculture or wet peatland innovation' Wet crops New business models Cattail [food/construction material/biomass] Sphagnum moss Alder carr Wild rice Blue services [water retention, cooling] Carbon credits. Online toolbox for processes leading to Carbon sink modelling Carbon and blue credit scheme for peatlands Pilot sites for testing of new business models	To reduce emissions by ca. 3200 t per year on pilot sites across ca. 80 ha Protection against environmental issues Partnerships create innovation ecosystem (living labs) with local authorities, Research Institutes, farmers, landowners Educational Programme Share best processes and knowledge
Interreg North Sea Region CANAPE €5.5 M https://northsearegion.eu /canape/measuring-greenhouse-gases-in-wetlands/	To measure greenhouse gases in wetlands. To support the restoration of 95 ha of peatland, and support the restoration of 3 peatland lakes. The project Creating a New Approach to Peatland Ecosystems responds to these issues by restoring wetland areas to reduce their CO_2 emissions and improve their capacity to store water, and by aiming to develop the markets for products produced from wetland ecosystems - a type of farming known as Paludiculture. Physical restoration of the landscape, raising water levels in drained bogs and fens, and restoring lake edges to improve their water quality. This will halt the release of CO_2 that occurs on drained peatlands, and restore the capacity of the land to act as a buffer to floods and droughts. Improving water quality will improve the recreational value of the	UK Denmark Germany Belgium The Netheralnds Pan Euroean (Nordic Baltic Wetland Group)	Paludiculture – typha, mosses and grasses Retrain Carbon sink and water store Sphagnum mosses Reed (compost, biocher] Waste wood (cooking charcoal and biocher) Greenhouse Gas Emission Site Types (GEST) Methodology. This uses the water classification and the plant types growing on the site to estimate emissions. These are based on a review of scientific literature, and uses previous studies to establish an average for each site which meets certain criteria. Deliverables Create over 60 ha of new bog habitat Create over 20 ha of new reedland habitat Trial 10 ha of new agricultural production,	Clear understanding of production methods for each product Costs and potential sale price Identify market for products Produce Carbon Pocket Guide Inform policy makers of benefit of paludiculture as alternative form of land use

	waterways and support tourism by reducing incidents of toxic algal blooms. Demonstrating sustainable use of the land, through piloting agricultural products that can be grown on wet land (known as Paludiculture), and showing that there is a viable economic alternative to draining land for agriculture.		including reed, sphagnum moss, and purple moorgrass.	
Interreg NW Europe Care-Peat €6.24 M 2019–2022 https://www.nweurope.eu/projects/project-search/care-peat-carbon-loss-reduction-from-peatlands-an-integrated-approach/	Reduce CO_2 emission and restore Carbon storage capacity in peatlands to set up and demonstrate innovative technologies for new restoration and carbon measurement techniques and involve local and regional stakeholders. Therefore the nature organisations, together with local landowners, restore peatlands of five different pilot sites ranging from 10 to 250 ha and demonstrate the (potential) carbon savings of the restoration. For each pilot site different restoration techniques are used - from manual labour to growing additional peat moss.	Scientific Research National Centre French Geological Survey Lancashire Wildlife Trust Manchester Metropolitan University National University of Ireland Galway Eurosite Natuurmonumenten University of Orleans		By 2022 – expected ca 7800 t of Carbon emissions to be retained in 5 pilot sites – equivalent greenhouse gas emission of 6072 passenger cars driven per year
Eurpean Commission – LIFE PEAT RESTOTE Project – https://life-peat-restore.eu/en/	To reduce greenhouse gas emissions by 40% until 2030 compared to 1990. Therefore conservation of peatlands must be integrated in the climate and energy policy. Especially the Baltic States as well as Poland and Germany have huge areas of peatlands, which are partly heavily degraded and which need conservation and restoration. In the project the emissions and storage of greenhouse gases, the water level as well as the wildlife (flora and fauna) will be documented, analysed and compared. This helps to prove rewetting measures and gives the chance to regulate aberrations quickly. Also the potential climate effects of the rewetting can be calculated.	Poland, Latvia, Estonia, Lithuania, Germany	The LIFE Project Peat Restore aims to rewet degraded peatlands in the partner countries Poland, Latvia, Estonia, Lithuania and Germany, covering an area of 5300 ha to restore the function as carbon sinks. National events, information materials, a photo exhibition and a documentary film will contribute to raise public awareness and to inform about the project's progress.	During the drainage of peatlands, oxygen gets into the peat, which leads to aeration and decomposition of organic matter into smallest parts. In this aerobic zone microorganisms are extremely active, so the rate of decomposition is especially high. As a result the greenhouse gases (CO_2, N_2O) are emitted into the atmosphere, what reverses the function of peatlands as a store into a source of greenhouse gases.

considerable attention to develop services, processes, and products that meet the strict legislative requirements as well as a result in a greener production, cleaner environment, and a more sustainable world. Simultaneously, companies deal with increasingly competitive markets in which innovation is regarded as a survival requirement (Galanakis, 2019). Subsequently, there is a pressing need to consider smart new solutions for ensuring the intensive sustainability of agriculture and food production processes that respond to the challenges of pandemics and climate change.

Globally, peatlands account at present for ca. 3% of the earth's surface and play a significant role in offsetting CO2 emissions through sequestration. Peatlands store 1.4 trillion tonnes of carbon-equivalent to 75% of all carbon in the atmosphere, which is twice that stored in forests. Bord Na Mona, the Irish state body that owns 80,000 ha of peatlands, are transitioning from burning peat to transitioning to a green footprint. For example, there is a strong trajectory for Bord Na Mona to develop wet peatland innovation (known as paludiculture) for new business models with academic partners and other industries under a new Empower Eco Sustainability HUB platform that is also supported by the government (Just Transition Programme, 2020). Bord Na Mona is exploiting the 'Empower Eco' platform to accelerate its transition from 'Brown to Green' during COVID-19 that will also stimulate regional development, community transitioning to low carbon economy, training, enterprise, and employment. These transitioning activities will be informed by necessary knowledge transfer from several related European-funded Interreg projects that seek to restore peatlands, including measuring greenhouse gases (GHGs), to improve biodiversity and carbon sequestration, along with developing green paludiculture innovations and blue services such as water retention (Table 1). Wet peatland crops such as cattail, sphagnum mosses, moor-grasses, Alder carr, wild rice, typha, reed, and waste wood for the food and construction industry (Carbon Connects, 2020: Restore, 2020; Care-Peat, 2020; Canape, 2020). Those mentioned above will enable carbon and blue credit scheme for the peatlands. Paludiculture will also facilitate the ambitious of advancing EU collective agriculture policy beyond 2020 (Peatlands in the EU, 2020).

This approach will also facilitate the urgent need for sustainable alternatives and innovative business models for farmers and land managers on rewetted peatlands, which will also enable significant carbon sinking. O'Neill et al. (2020) have recently reported on the development of freshwater aquaculture for high-value perch and trout in the Irish peatlands using cut-away flooded peatlands using organic principles, which is powered by a wind turbine (Fig. 2). Water quality and waste remediation are maintained in this paludiculture-based aquaculture process by using natural microalgae and duckweed. Naughton et al. (2020) also reported on the use of this freshwater aquaculture process for testing new innovations, such as the real-time relationship between the use of hand-held AlgalTorch™ on the farm and relationship with flow-cytometry to measure vital physicochemical parameters. O'Neill et al. (2019) also used this freshwater aquaculture process to demonstrate the efficacy of using microalgae as a smart green innovative tool to evaluate the ecotoxicological quality of effluent that included robustness for used during climate change, such as drought. Advances in bioinformatics and next-generation sequencing will also help with improvements in different microalgae used for this purpose as well as the determination of microbial populations in the system, including the emergence of pathogens or problematic microorganisms (Naughton et al., 2020). This is particularly relevant as less than 5% of aquatic microorganisms are culturable on conventional agar media (Rowan, 2011; Rowan et al., 2015; Fitzhenry et al., 2019). It is envisaged that there will be continued advances and potential for technology disruption in forestry and horticulture for future environmental-proofing such as the delivery of cocktail of helper microorganisms and bioactives through hydrogels from adjacent manufacturing and materials industry to respond variances in climate change and resilience. Peatlands also present an opportunity for improving pollination and ecosystem service management (Naughton et al., 2017; All Ireland Pollinator Plan, 2020). These actions include supporting new medical plant and herbs (such as Calendula, Meadowsweet, Plantain, Valerian, Marsh Mellow, Peppermint), extraction of medicinal sap from birch trees, and production of honey as a social enterprise for rural communities. These timely activities align strongly with the finding of Robroek et al. (2017), who reported that plants that makeup peat bogs adapt exceptionally well to climate change compared to diverse plant communities (such as dunes and grasslands). Peatlands lose fewer plant species as a result of climate and environmental change as they are more resilient. Robroek et al. (2017) also noted that peatlands protect ca. 10% of global CO_2 emissions and act as a sponge in our landscape for holding vast amounts of drinking water, which can be used to offset uncertainty for climate change, such as drought.

The development of peatlands presents opportunities to accelerate leading-edge knowledge and competency through innovation hubs, which would tap into abundant, diverse natural resources for enterprise development and to facilitate transition beyond COVID-19. This will inform the next generation of entrepreneurs to stimulate regional creation and environmental knowledge base with a low carbon orientation. Exploiting wet peatland innovation, known as "paludiculture"), will contribute to the new EU Farm to Fork Strategy, which is at the heart of the European Green Deal, aiming to make food systems fair, healthy, and environmentally-friendly. It will also support Europe's ambitious vision to become the world's first climate-neutral continent by 2050 (A European Green Deal, 2020). In so doing, accelerating paludiculture innovation will advance the economic diversification of territories most affected by the climate transition and the reskilling and active inclusion of their workers and jobseekers. Companies are coming under pressure to engage in sustainability and eco-friendly innovation, but lack a clear progression pathway. This new paludiculture multi-actor ecosystem platform will accelerate entrepreneurship and commercialization that will contribute to supporting the recovery from COVID-19, and possibly other future pandemics. Such a paludiculture innovation platform is being actively pursued in the Irish midlands, known as Empower Eco, which will provide sustainable transitioning-solutions for those unemployed and underemployed as a result of reliance upon burning peat as fossil fuel. It is envisaged that exploiting digitization will also advance the rate of paludiculture innovation along with creating opportunities for promoting the recovery of tourism with the support of Citizen Science. Multi-actor sustainable Hubs will also build enterprise programs by bundling added value through R & D collaboration, facilitating design and technological maturation activities, and commercial planning that should encompass financial, legal, supply chain, and market entry activities. This platform should support startup and SME funding instruments to be leveraged through elevant regional, national and European funding models, such as under Green deal and sustainable agriculture that will potentially inform technology disruption. The core tenets of multi-actor transnational innovation hubs, that connects complimentary technological core facilitities, have been successfully delineated through Interreg Atlantic Area Sharebiotech Project (2012). Such activities will also be supported and accelerated thourugh transnational modelling (Interreg Atlantic Area Neptunus Project, 2018).

5. First "Green Deal" funding from European Innovation Council to support the recovery plan for Europe – strong alignment with Paludiculture platform ambitions

On 23rd July 2020, the European Innovation Council (EIC) announced the awarding of over €307 million in funding to 64 game-changing 'green deal' startups and SMEs that will contribute to the objectives of the European Green Deal Strategy (2020), and the Recovery Plan for Europe (2020). Successful proposals ranged from innovative solutions for the automotive, aerospace, and maritime sectors to advanced materials or Internet of Things technologies (full listing of selected

projets are highlighted at European Innovation Council, 2020). Many of these EIC-funded 'Green Deal' projects align with the core tenets of Science Foundation Ireland Disruptive Technology Innovation Funded projects of 2018 and 2019 (Figs. 3 and 4). Examples of EIC 'Green Deal' selected projects that focus on pollination, bioplastics, renewable energy and GHG emission reduction, waste remediation along with specific COVID-19 interventions are noted in Table 2. Over one-third of EIC-funded companies are led by women CEOs, which is a significant increase (tripling) of the number in previous EIC funding rounds.

This paludiculture research platform aligns with The European Innovation Council (EIC), which supports visionary entrepreneurs who create transformative solutions to pressing societal and environmental challenges, supporting the Green Deal and the recovery plan for Europe (European Commision, 2020; European Innovation Council, 2020; Green Deal for Start-Ups and SMEs, 2020). These startups and SMEs are set to scale up, creating jobs and growth, and giving Europe the global leader in green technologies and solutions. Akin to the EIC's Green Deal, the paludiculture-based hub also supports companies to benefit from exclusive business acceleration services to enable rapid growth and scale (Table 3). It is noteworthy that the EIC is currently in a €3.3 billion pilot phase and is due to be fully-fledged in 2021 as part of the new Horizon Europe program (European Innovation Council, 2020). In March 2020, the Commission amended the pilot EIC 2020 Work Programme to include a €300 m budget through the EIC pilot Accelerator for funding game-changing, market-creating innovations that contribute to the goals of The European Green Deal and the United Nation's 2030 Agenda for Sustainable Development. The scheme offers startups and SMEs the option to apply for either grants or blended finance (grant or equity support). Since the start of the EIC Accelerator Pilot in autumn 2019, a total of 140 startups and SMEs active in all technology-intensive sectors (health, digital, energy, etc.) have been pre-selected for equity financing for a total of over €500 m. The amended pilot EIC Work Programme also introduced special provisions to support applications by SMEs and startups with female CEOs.

Climate change and environmental degradation are an existential threat to Europe and the world. To overcome these challenges, Europe needs a new growth strategy that transforms the Union into a modern, resource-efficient, and competitive economy where there are no net emissions of greenhouse gases by 2050 (European Innovation Council, 2020). The European Green Deal is an ambitious roadmap for making the EU's economy sustainable, which will happen by turning climate and environmental challenges into opportunities across all policy areas and making the transition just and inclusive for all. The European Green Deal provides a timely roadmap with actions that will (1) boost the efficient use of resources by moving to a clean, circular economy, (2) to restore biodiversity and cut pollution. It outlines the investments needed and financing tools available and explains how to ensure a just and inclusive transition. Those mentioned above paluciculture-focused transitioning initiative strongly aligns with A European Green Deal Action Plan (2020) including (1) climate ambition, (2) clean, affordable and secure energy, (3) industrial strategy for a clean and circular economy, (4) sustainable and smart mobility; (5) greening the ordinary agricultural policy / 'Farm to Fork Strategy, (6) preserving and protecting biodiversity, (7) towards a zero-pollution ambition for a toxic-free environment, (8) mainstreaming sustainability in EU policies, and (10) supporting the EU as a global leader in the green innovation.

6. Solutions to accelerate agri-food recovery for post-COVID-19 potential technology disruption

Several economies across the globe are braced for a short-term economic slowdown (Guan et al., 2020), where they have implemented economic stimulus measures. Reid et al. (2020) suggested that corporate leaders should consider five key steps they can take to reshape their business and plan for recovery: (i) prioritize people safety, (ii) reshape strategy for business continuity through stress-testing to evaluate short-term liquidy and risks, (iii) communicate with relevant stakeholders in a clear, transparent and timely manner, (iv) maximize the use of government support policies and packages, and finally (v) build resilience in preparation of the new reality with bold strategies based on stress tests. Companies will then have to define internal guidelines based on experience learned from the first COVID-19 wave, as well as to develop contingency to respond better to a second wave, and faster to future pandemic crises.

Virtual accelerator hubs for connecting Micro with SMEs that exploit advances in ICT through immersive technologies will become more popular for informing disruptive innovation in situ and for remote end-user applications. This tendency will enable hurdling restrictions that may come with networking and training innovators or employees in meeting rooms that may persist as a barrier to innovate for post-COVID-19 disruptors. It can be actualized through ICT and Quality of Experience (QoE) such as virtual reality (VR) and augmented reality (AR) (Braga Rodrigues et al., 2020). Rowan (2019) reported on the potential benefits of combining immersive with educational technologies for remote workforce training that has significant implications for the future provision of remote workforce training for new skills linked to education. EIC 'Green Deal' startups and SME selected projects also focus on virtual reality and training that includes provision for COVID-19 (Table 2). There is a pressing need to exploit existing or to create new multi-agency enterprise-hubs related to academia that will support and accelerate innovators and businesses (such as in agri-food) as well as full-span commercialization of products and services using the 9-stage technology readiness assessment (Mankins, 2009). This fact should include off-site pilot-data generation where there is an increasing trajectory towards sustainable innovation, the green agenda, and digitization (Table 3). This multi-agency innovation HUB concept is under strategic development in the Irish midlands region to facilitate transitioning to green innovation and for recovery post-COVID-19 era, which will facilitate resource utilization, help recovery of businesses, and accelerate technology disruption post-COVID-19 (Just Transition, 2020).

7. Definitions of disruptive technologies

Disruptive technologies (DTs) or disruptive innovations were initially defined to address market disruption in established markets, where a new product or service (a technology) is introduced (Bower and Christensen, 1995; Christensen et al., 2004). DTs arise from a global drive to discover innovations that will lead to greater competitiveness, impact and value to businesses and society (Christensen and Bower, 1996; Lauer and D'Agostin, 2013; Yongfu et al., 2017; Geels, 2018; Li et al., 2018; Sousa and Rocha, 2018). Innovations may be viewed as disruptive when they take the place of established or broadly accepted ideas arising from scientific inquiry, or in methodologies or in paradigms that disrupts knowledge (Kuhn, 1962).

In recent times, definitions of DT focus on broad factors affecting the industry and address the nexus between learning experience arising from substitutable innovations that relate explicitly to competitive pricing and performance (Rowan, 2019). The recent review by Schuelke-Leech (2018) provides an excellent insight into a diversity of DTs - where products are reduced in size (such as exploiting leading developments in nanotechnology); more lightweight and efficient (such as utilizing additive manufacturing and material science); more competitively and affordably priced (such as exploiting resource management and production including advances in innovative service and business processes); more excellent dexterity and convenience in design and functionality (using researcher creativity blended with artificial intelligence, augmented and virtual reality and so forth that includes future-proofing for needs across various platforms); and more significant performing products and services (such as exploiting physico-chemical developments combined with the use of robotics

and AI for design linked to advances in education and workforce training). For example, this concept may be applied to the food industry for the introduction and training of new technologies across the supply chain from production, distribution, and storage. Developing DTs in the agri-food domain is core to supporting and driving national strategic development plans as these generate jobs, add-value, troubleshoot, and enhance quality in changing marketplaces. These important deliverables are also strongly evident in Green Deal selected projects awarded by European Innovation Council (2020).

In the interesting work of Schuelke-Leech (2018), Beth Ann described a conceptual model to understand the orders of magnitude of DTs that may disrupt markets, businesses, institutions, and the societal norm, which constitute 'the innovation ecosystem.' Specifically, such disruptions occur at two different levels. First order-level disruption is the focus of much the business literature where it considers and addresses disrupters in innovation. Second-order includes technological disruptions that permeate through society, influencing substantial change. Second-order disruptions are more extensive than first-order disruptions. There is great desire to understand the process whereby one identify candidate technology disruptors as that is connected to innovation ecosystem (Nagji and Tuff, 2012) Schuelke-Leech (2018) noted that factors leading to the creation of DTs arise for the localized opportunity (Christensen, 2003), creativity and problem solving (Rowan, 2019), financial investments (such as from self-financing to Venture Capital and Angel investors, Rowan, 2019), networks (Rowan, 2019), broad applicability for an innovative technology (Schuelke-Leech, 2018), and supporting infrastructure and institutions (such as clustering of human capital, networking and so forth to enable a creative process to occur, Drucker, 1985).

8. How might DTs accelerate recovery post-COVID-19 and transition towards sustainable food systems?

Herrero et al. (2020) recently reviewed and identified technologies and approaches that have the potential to accelerate the transition towards a sustainable food system. While this was a pre-COVID-19 study, it is evident that many of the innovations identified as future technologies may also be led to disruption and inform recovery post-COVID-19 pandemic in terms of sustainable food production and socio-economic recovery plans. For instance, preference for functional foods or nutraceuticals that boost immune-system and wellbeing for COVID-19 are likely to become popular (Masterson et al., 2019; Murphy et al., 2020; Galanakis, 2020). Given the gap in knowledge, there has been an increasing number of preprint publications that specifically focused on the potential benefits of nutraceuticals for used to improve the health and mental wellbeing of citizens, including a focus on those recovering post-COVID-19 pandemic. Target compounds under evaluation include vitamins, polysaccharides, natural polyphenols, bioactive lipids, and peptides (Gonzalez, 2020). Companies claim more recognition of immune-boosting ingredients (Daniells, 2020). They have seen an opportunity to develop relevant products (e.g., chocolate balls rich in β-glucan) targeting immunity during the post-lockdown era (Koe, 2020). These trends will most likely continue to drive the market within the next years (Galanakis, 2020). Subsequently, businesses will be seeking to fill the demand for nutraceuticals and functional foods to address the challenges and opportunities created by COVID-19 disease (Galanakis, 2020). These products may emerge from food processing by-products (Galanakis, 2012, 2013), seaweeds, yeast, algae, plants, and fungi or mushrooms that reduce inflammatory responses that are typically associated with cytokine storm in severe COVID-19 patients (Murphy et al., 2020). Masterson et al. (2020) also

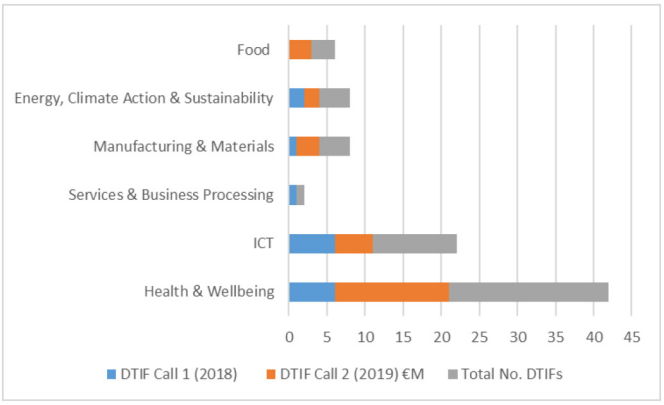

Fig. 3. Number of funded projects awarded per topic in 2018 and 2019 by the Irish Government under Disruptive Technology Innovation Fund (DTIF).

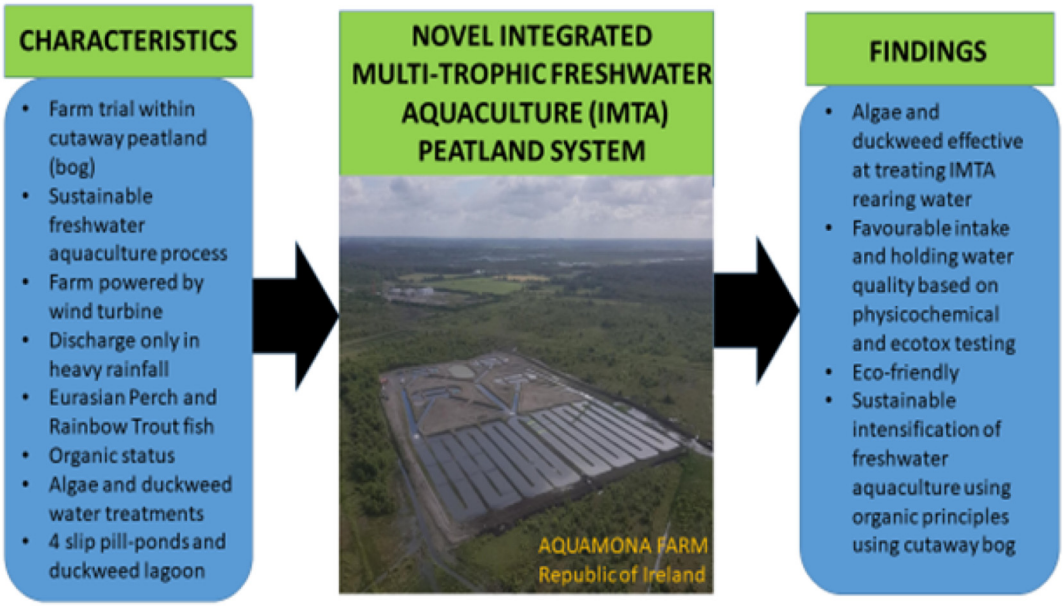

Fig. 2. Peatlands-based Freshwater Aquaculture process (adapted from O'Neill et al., 2020).

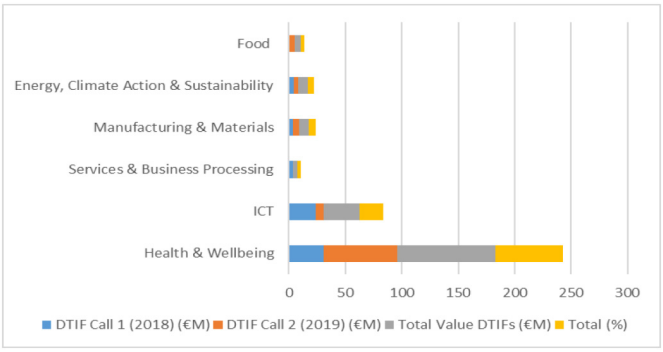

Fig. 4. Amount in Euro of funded projects awarded per topic in 2018 and 2019 by the Irish Government under Disruptive Technology Innovation Fund (DTIF). Proportional representation for each topic in overall DTIF funding is shown as percentage.

reported on the novel use of bioactives from medicinal fungi ameliorates antibiotic-resistant *Klebsiella pneumoniae*-induced pulmonary sepsis.

Future intensive sustainability of the food sector will also be influenced by pressures applied to supply chain, including uncertainties associated with the impact of global warming on crops that will include more flooding and droughts (O'Neill et al., 2019). Fisheries and seafood are viewed as desirable high protein, low carbon-intensive products with the emergence of smart aquaculture processes to meet growing consumer demands (Tahar et al., 2018a, 2018b, O'Neill et al., 2020). However, Ruiz-Salmón et al. (2020) also reported that the seafood and aquaculture sectors across European countries are embracing opportunities to mitigate key environmental pressure points (depletion of resources and climate change), social needs (changing customer attitudes and preferences) or growth in markets (services and business processes along with enhanced competition and worldwide competitiveness). Maintaining satisfactory water quality through developing sustainable innovations to meet growing populations globally will also present significant challenges and opportunities (Tahar et al., 2018c; Tiedeken et al., 2017). De-risking and policy decision making will be increasing influenced by predicitve modelling (Tahar et al., 2017). These pressing challenges are influencing the innovation ecosystem from citizens to policy-makers to adopt and foster more sustainable practices. Sharing of new knowledge across European seafood and aquaculture sector, including innovation in ecolabelling and ecodesign, will have far-reaching and cross-cutting influences to the circular economy (Ruiz-Salmón et al., 2020). Smart changes in these areas may lead to disruptive products and businesses.

Blockchain offers a security-proof approach to recording every digital transaction that can inform a broad spectrum of smart innovations from business processes to 5G networks. In the food disruption context, it has the potential to radically transform and disrupt safety and quality, waste remediation and recycling, security, and authenticity and traceability (Medical Expo, 2020). The robotics industry is estimated to be worth ca. €2.2billion by 2022 and has to potential to transform the food industry through automation, such as personalized food processing (StartUS-Insight, 2020). There has been a global push to re-address dependency on single-use plastics with a greater focus on smart packaging, including the emergence of potential for bioplastics led by large companies such as

Table 2
Examples of EIC Accelerator 'Green Dea'l Selected Projects 2020 including COVID-19.

Startup/SME	Country	Selected Project
B4plastics	Belgium	Complete biodegradable and resistent polymers that allow for circularity and a reduction in plastic consumption and microplastics pollution.
UniSieve	Switzerland	Advanced molecular separation solutions for a wide range of applications of different scales, ranging from propylene or hydrogen purification to biogas upgrading.
Vatorex AG	Switzerland	An eco-friendly solution to kill the Varroa mites and preserve the beekeeping industry.
Nanogence SA	Switerland	Innovative techniques for increasing the efficiency of cement manufacturing and the robustness of materials while achieving energy savings and reducing CO2 emissions in the process
Electrohaea GmbH	Germany	Using biological methanation technology for cost-effective large-scale energy storage and the production of multi-purpose e-fuel for use in transportation, power generation or industrial heating.
Celllugy	Denmark	Using bacteria and yeast starting from sugar or agro-industrial waste for obtaining a biomaterial able to replace plastics in several packaging applications
Brite Hellas SA	Greece	A unique transparent (80%) solar glass panel that generates clean energy. The solar glass combines a nanostructured coating material with silicon solar cell technology to de liver a product ideally suited for greenhouse applications.
Cascade	France	Game-changing disruptive solution for photosynthesis and plant development that makes growing food more sustainable by significantly reducing water, fertilizer, and pesticide use.
Outsight Sas	France	Key enabling laser technology for autonomous vehicles and drones, opening the future of emissions reduction and ecosystem monitoring
Altar	France	A disruptive platform harnessing the power of natural selection for the development of novel microorganisms fulfilling specific industrial needs.
NVP Energy	Ireland	Technology to treat municipal sewage wastewater at ambient temperatures and convert sewage pollutants into renewable biogas
N2 Applied AS	Norway	SmartNitroFarm is a ground-breaking alternative to chemical fertilisers, which reduces greenhouse gas emissions, reduces odour, stops ammonia loss and air pollution.
GlasPort Bio Ltd	Ireland	An innovative platform technology to eliminate greenhouse gas emissions from organic residues and manures that specifically inhibits methane-producing microbes and traps nitrogen.
LightSpace Technologies	Latvia	Next Generation Enhanced Augmented Reality 3D Glasses for medical education, pre-procedural planning, intra-procedural visualization, and patient rehabilitation
Hpnow APS	Denmark	Secure, safe, sustainable and affordable on-site generation of Hydrogen Peroxide
Aquila Bioscience Ltd	Ireland	COVID-19 pandemic: An innovative, safe and effective bio-decontamination technology for non-toxic removal of biological agents, including coronavirus
Reisistell AG	Switerland	Rapid diagnostic for bacterial SEPSIS and AMR urgently needed for ICU patients in COVID-19-like epidemic
Nanoscent Ltd	Isreal	Novel COVID-19 POC Screening Tool Based on Proprietary Nano-Sensors and ML Techniques

Table 3
Multi-agency ecosystem HUB activities to support and accelerate innovators, businesses post COVID-19.

Concentrated Single-Access Supports for Industry, Entrepreneurs, Disruptors	Linked Acceleration Activities
Step-Change Physical Infrastructure & Systems Supports	R&D Collaborative Facilitation
Pre-start Ups	Design Maturation Activities
Ideation & Design Thinking to inform Technology Readiness Level (TRL)	Technical Maturation Activities
Market Research and Enterprise Support	Financial Planning
– Early Needs Analysis	Legal Assistance
– Product Market Fit Analysis	Social and Digital Marketing (including informing customer behavioural change)
Early Technical Validation	Networking
– Test the Technologies	Dedicated Grant Writing/Reporting
– Experimentation/Validation in Pre-Pilot	Connection to Academic Staff/Expertise and Equipment to support commercialisation
– Scaled to Real-Life Setting	
Digitization (including AI, in situ and remote training via AR/VR)	Workforce training - placements
Conduit to State Financial Supports/Agencies	Enable Social Enterprise - Outreach Functions

Diago and Nestlé (Medical Expo, 2020). Food waste management is also the subject of many transnational research and innovation projects such as the European Commission Interreg Neptunus project that combines academic expertise with industry across the Atlantic area to address waste recycling in the fisheries and seafood area, including life cycle assessment, valorization, and ecolabeling (https://neptunus-project.eu/). There is also increasing interest in the development of 3D printers, also known as additive manufacturing, as a sustaining and potentially disruptive technology for a wide range of possibilities for the food industry. For example, 3D food bioprinters permit personalized and repeatable nutrition where it is considered to provide the correct amount of nutrients to match different lifestyles, gender, and health requirements (Brunner et al., 2018). Besides, experimental 3D Bioprinters are designed to prints living cells that have the potential to advance food supply chain needs (StartUS-Insight, 2020). However, the role of social marketing and communication to inform behavior changes and to seek feedback on attitudes, perceptions, and barriers for the uptake of this technology will be necessary (Brunner et al., 2018).

Artificial intelligence (AI) is increasingly used to develop new foods and flavors, such as Coca Cola's research into the Cherry Stripe in 2017 (Medical Expo, 2020). AI will play a prominent role in the personalization of foods and nutrition, exploiting the vast potential of digitalization. Besides, food delivery companies are beginning to concentrate on using the position of artificial intelligence (AI) for problem-solving matched with automation, such as automated guided vehicles. As an example, slow-moving pavement droids to deliver food have been tested by Just Eat, who has partnered with Starship Technologies for this exciting opportunity (StartUS-Insight, 2020). The Internet of Things (IoT) is increasingly becoming relevant for the next-generation food industry, which includes forging innovation in services and business processes. For example, Innet introduced a change suitable for all kitchen devices such as analysis of items for food refrigeration, including taking note of expiration dates with provision for suggesting recipes along with meal preparation. Food security is also an essential factor to have to the fore post-COVID-19, where the monitoring of food from the field to fork using IoT technologies presents a logical solution to this challenge. Given the necessity for food globally, disruption in products and services is likely to emerge from innovations in the delivery and online retail sector as most people remain at home to prevent infection. This infers a focus on food security (such as blockchain and the internet of things in the food supply chain), safety including smart packaging, and alternative, disruptive approaches to food sources such as protein sources. Traceability of infected workers is also very important across the entire farm to fork continuum where there have been clusters of COVID-19 cases reported in meat packaging plants, such as in Ireland (Power, 2020) and Germany (Scally, 2020). The Republic of Ireland has introduced a new COVID-19 Tracker mobile phone app for it's citizens that has ca. 200,000 daily visits.

In terms of potential global economic recovery plans post-COVID-19, and the emergence of Food DTIFs, the significant value may be placed on such things as a review of antibody testing data. For this application, it is hoped that epidemiology will show that many people were infected where this may inform a v-shaped recession with a short sharp recovery. A desirable v-shape economic recovery trend may be more likely due to a wave of online shopping and people working from home. Approximately $6.2 trillion (12.5% of retail total) is spent on food and beverage in the USA: 2015 was the year that more food was brought in than prepared in the home. COVID-19 has shocked that trend, in the US in Q2, $100bn dollars shifted from restaurants to retail space. Monopolies in food grocery services may arise, where smaller independent stores may struggle. In the UK, 7% of the population shop for groceries online, with 4% in the US. Yet, one-third of the US population bought online during the 2nd week of March, and half of them was their first time. Confidence must be provided to ensure continuity in the food supply chain to avoid friction in the food system. It is uncertain as to the state with any degree of confidence what would be the specific impact caused by the global downturn (or potential recession) in the economy as it relates to particular needs and opportunities met by emergent technologies in agri-food (including ingress from adjacent industries). Reuters (2020) described that an alternative U-shaped economic recovery might occur, that takes more than a couple of quarters as economies have suffered a faster and deeper, which Reuters feel may be the likeliest outcome. This reflects thinking that lockdown impact may last for a while after their lifting with a gradual easing of the lockdown where social distancing will continue that will continue to influence the tourist industry and so forth negatively. The occurrences of these combined risks may affect the appearance of a COVID-19-induced recession. The flexibility and adaptability of companies to meet change and adjust business models, including provision for ICT, including online delivery for supply chain, will be better placed for sustain and for potentially cause food disruption practices.

In response to COVID-19, countries may consider nationalizing their supply chains for greater control as to avoid reliance on another country that will significantly affect exports. Yet global trade feeds one-third of the world, and producing locally means buying less and the need for more land. COVID-19 may cause a contraction in the extension of the supply chain, and countries will trade with who they can trust. Question of relative advantage, will countries afford to produce things they aren't familiar with or can do, or will this be a necessity arising from potential supply chain shortage issues – for example, reprocessing Personal and Protection Equipment (Rowan and Laffey, 2020)? There is likely to be an increased demand for ICT, including areas such as robotics, blockchain, algorithms to improve processes, efficiency, and sustain or create more jobs. Industries will need to adapt in real-time – which is challenging, given very little market data available to underpin critical decisions.

9. Strategic funding initiatives to identify and accelerate DTs and relevance to COVID-19 – a case study from the Republic of Ireland.

COVID-19 has been hailed as the "big equalizer," but the reality is that we are not equally resilient as a society. It will fuel the next wave of innovators, both for economic and social impact. Given the importance of transitioning beyond COVID-19, there is likely to be increased interest internationally on providing strategic funding initiatives that merge academia and industry to identify the next disruptive technology. There is a shortage of strategic initiatives that specifically focus on DTs. Still, Enterprise-Ireland has been quick to embrace this need with its Disruptive Technology Innovation Fund (DTIF) that launched in 2018. This DTIF initiative has committed €500 m to identify and supporting DFs Project Ireland 2040 (https://dbei.gov.ie/DTIF) that will run over the period 2018 to 2027 aligned with enterprise co-funding. Relevant questions and responses are available to view on this host website. The nature of the 43 DTIF awards will also have relevance to tackling COVID-19 pressure points (Table 4). DTIF Fund is aligned with the Irish Government's Future Jobs Ireland framework with a focus on 'Embracing Innovation and Technological Change,' where there is an emphasis on creating and advancing technology disruption on a commercial footing. It is envisaged that pursuit of these strategic domains, and harnessing the potential of DTIFS emerging from these cross-cutting areas will also support national economic recovery plan for COVID-19 pandemic.

The DTIF funding initiative in Ireland is resourced to €65 m up to 2022 for projects across many thematic domains encompassing emergent preferences for advancing medical devices, ICT, artificial intelligence, blockchain, robotics, nutraceuticals, therapeutics, manufacturing and environmental and so forth. A more in-depth analysis of all funded project awards over the 2018 and 2019 period highlights the potential benefit of addressing COVID-19 often through cross-cutting contributions from these previously considered separate domains of innovation (Table 3). Analysis of the data provided shows that increased funding for this vital initiative in the priority areas Innovations in Services and Business Processing (1 project, €3.9 m (2.7%)); Food (3 projects from DTIF 2, €5.2 m (3.6%)); Energy, Climate Action and Sustainability (6 projects, €8.3 m (5.6%); Manufacturing and Materials – Advanced and Additive Manufacturing (3 projects, €8.7 m (6.0%); ICT (11 projects,€31.1 m (21.6%)), and Health and Wellbeing including Medical Devices, Diagnostics, and Therapeutics (21 projects at €86.8 m (60.3%) (Figs. 3 and 4). These domains reflect the Republic of Ireland's priority strategic areas of research and innovation to 2023. Fig. 3 describes the number of DTIF project awards in the various fields, including food for this Republic of Ireland government initiative since its' launch in 2018. However, it is appreciated that distribution of funding award to date reflects in part the presence of global Medtech and ICT industries in Ireland, in addition to the crucial partnership with leading academic institutions, Science Foundation Ireland-funded Research Centres and Enterprise-Ireland Technology Gateways that all support MNC, SMEs, startups, and entrepreneurs in a closely-knit innovation ecosystem.

The strong performance of medical technologies and ICT (Table 3) reflects in part the significant presence of global multinationals in this space connected to benchmarking universities and Institutes of Technologies across Ireland. Primary production in Ireland is represented by agriculture, fisheries, and forestry (includes food, drink, and horticulture), which pre-COVID-19 accounted for 10% of total exports worth €13bn reaching 180 markets worldwide. Approximately 80% of Ireland's agricultural land is devoted to grasslands, which makes it highly suitable for food production (Bord Bia, 2020). The innovation ecosystem is such that many of the leading food companies such as Diageo, Kerry Group, Glanbia, and so forth also are key collaborating partners in national research and innovation centers, enterprise-technology gateways, and benchmarking academic institutions that are focused sustaining and food disruption. For example, the Enterprise-Ireland funded Technology Gateways in Athlone

Table 4
COVID-19 (Coronavirus) – list of successful projects and case studies funded in the Republic of Ireland.

Topic of Research	Funding (€)
Irish Coronavirus Sequencing Consortium	378,716
NSPIRE: Facilitating Non-Invasive Ventilation (NIV) during the COVID-19 Crisis	205,667
Critical Reagent Production Addressing Supply Chain Risk for COVID-19 Diagnostics	540,263
Data Platform for Emergency Response Management (DPERM)	402,323
Prognostic indicators of critically ill patients with COVID-19: Impact on early immunology and survival	192,566
SABS-TILDA: SARS-CoV-2 specific AntiBodieS in The Irish LongituDinal Study on Aging (TILDA): an opportunity to assess COVID-19 rates and phenotypes in older adults in Ireland	199,875
Improving long-term patient recovery and reducing disability after COVID-19 critical illness using microRNA-based approaches	199,621
Defining the disease course and immune profile of COVID-19 in the immunosuppressed patient (DeCOmPRESS study)	199,908
Irish COVID-19 Vasculopathy Study (iCVS)	199,036
Screening for antiviral compounds active against SARS-CoV-2	190,036
COVID19: The North Dublin Cohort Study	190,237
Using a back-calculation model to estimate the scale of asymptomatic Covid-19 prevalence by age and determine the critical threshold of available susceptible persons within the community	199,098
Using telehealth to enhance management of vulnerable groups during the Covid-19 pandemic	96,340
Impact of Covid 19 on Individuals with Intellectual and Developmental Disabilities and Caregivers	199,965
Cupid Covid-19: paediatric emergency department attendance during covid-19	62,857
A Rapid Resource Repository for Health Professionals (RRR-HP): An online and social media individualised support intervention for return to practice, reassigned and new to practice, nursing and allied	107,015
Rapid response and learning for later: establishing high quality information networks and evaluation frameworks for the National Ambulance Service response to COVID-19	109,188
Expediting the diagnosis of COVID-19 in a clinical setting using AI enabled analysis of CT scans	62,858
Creating an evidence-based toolbox for targeted public health interventions during COVID-19: a cross-border analysis to disentangle psychological, behavioural, media and governmental responses	107,015
An investigation of psychological responses to COVID-19 in health care workers during the delay and mitigation phase of disease management: longitudinal and nested qualitative study	83,690
Altered lives in a time of crisis: Preparing for recovery from the impact of the COVID-19 pandemic on the lives of older adults	175,013
Autism specific Transition RESources: a response to the COVID-19 related restrictions (TRes)	123,370
Optimising Covid-19 social distancing communications: Identifying and addressing psychosocial determinants of social distancing during the Covid-19 pandemic	148,745
Covid-19: Estimating the burden of symptomatic disease in the community and the impact of public health measures on physical, mental and social wellbeing	199,945
Identifying mental health needs and best practice for psychological support in frontline healthcare workers during and after the COVID-19 outbreak and in future pandemics	187,254
Modelling Real Time Population Wide Impacts of COVID-19	38,310

** For further details see https://www.gov.ie/en/publication/1b4099-covid-19-list-of-successful-projects-and-case-studies/

Table 5
DTIF Projects funded by Irish Government between 2018 and 2019 – putative relationship with 2nd Order disruption for Food and COVID-19.

Title of DTIF Project and Value of Award	Priority Area of Award	Potential cross-link to Food (potential 2nd Order Disruptive Technology)	Potential COVID-19 Use
Disruptive Gene Therapy Platform, Replacing Viruses in the Treatment of Genetic Conditions [€8.4 m]	Health & Wellbeing	Not obvious, as yet	Not obvious, as yet
HOLISTICS - Holistic Human Sensing for Health, Aging and Wellness [€7.4 m]	Health & Wellbeing	Training, as Smart Wearables Industry Value - human-centric intelligent sensors and their wireless communications for products.	Yes, remote training and monitor cocooning
AuriGen Solution for Persistent Atrial Fibrillation [€5.9 m]	Health & Wellbeing	Not obvious, as yet	Not obvious, as yet
'Future of Colorectal Cancer Diagnosis and Treatment: Combining Tissue Responsive Probes, AI and Machine Learning for Medical Care [€5.7 m]	Health & Wellbeing	Not obvious, as yet	Yes, use of AI and Machine Learning
Therapeutic enzymes as a treatment for sepsis and other immune disorder diseases [€5 m]	Health & Wellbeing	Cytoflow5, had potential for informing new innovation in Food – such as nutraceuticals	Yes, potentially
Towards safe and effective off the shelf cellular therapy for cancer [€4.3 m]	Health and wellbeing	Not obvious.	Not obvious as yet
Photonics Manufacturing Pilot Line€4.1 m	ICT- Manufacturing	Pilot Line Hub will develop packaging designs tailored to fast cost-effective packaging processes and equipment and develop and next gen packaging equipment (including test) with reduced cycle-times.	Yes, smart packaging relevant for COVID-19
Microfluidic Gene Transfection Cell Analysis and Sorting Platform (€3.4 m]	Health & Wellbeing	Not obvious	Not obvious, as yet
Cooperative Energy Trading System (CENTS)	ICT	Consumers and communities will be empowered with the necessary infrastructure to generate their own electricity for artisan food production with lower carbon footprint	Yes, by stimulus to COVID-19 recovery for Micro and Small Enterprises
Nex	ICT – Internet of Things	Not obvious	Potentially
ARDENT II [€2.8 m]	Health & Wellbeing	Not obvious.	Potentially
Medical Imaging Ireland €2 m]	Health & Wellbeing	Assess impact on new nutraceuticals for lung health (Masterson et al., 2019).	Yes, lung health
ArtEngine 2.0 bridging automated, AI-Driven 3D World Creation to Market [€2 m]	ICT – AI/AR/VR	Food 3D printing using AI as tool creation of 3D models – cost of 3D content creation is prohibitive for small studios and enables co-development and adoption of AR/VR.	Yes, in Vit D supplementing products and virtual modalities
BioHealx [€1.9]	Health and Wellbeing	Not obvious	Not obvious
Sustainable Bio-Renewable Energy from Wastewater (S-BREW) for the Food & Drink wastewater sector that will reduce land-spread waste and produce high-quality renewable energy [€1.8 m]	Energy, Climate Action and Sustainability	Food waste reprocessing	Yes – economic recovery
E-BAMBI - Enhanced Biocompatibility of Additively Manufactured Biomedical Implants for Improved Clinical Outcomes [€1.9 m]	Health & Wellbeing – Medical Devices	Not obvious – but 3D printing focused	Yes, potentially
High throughput microfluidic drug screening platform [€1.9 m]	Health & Wellbeing – Diagnostics/Therapeutics	Response models for drug testing – may have cross-link to nutraceuticals (GRAS)	Yes, potentially
Future Software Systems Architectures [€1.6 m]	ICT – IoT, AI,	Future use to rapidly operationalise new software systems that are slow – with AI	Possibly, via socio-economic recovery
Irish Lasers for the Internet of the Future (iLife) [€1.6 m]	ICT – Future Networks	Not obvious, as yet	Possibly, in socio – economic recovery
Connected Medical Device Cybersecurity Transparency €1.5 m]	ICT – AI, Data Analytics - Blockchain	Possible use of AI, data analytics, blockchain for real-time platform for 2-way communication of safety-critical security information (vulnerability) across food chain	Yes, in supply chain such as PPE distribution and security
Creating Bionic Man – neural training suit for semimotor impairments[€1.5 m]	Health & Wellbeing	Not obvious	Not obvious
Advanced Environmental Decision Support System for Coastal Areas [€1.1 m]	Energy, Climate Action & Sustainability	Not obvious	Not obvious
Smart-Cardio – a paradigm shift in Cardiac Arrhythmia treatment [€1.1 m]	Health & Wellbeing – Medical Devices	Not obvious	Possibly
DEFINE- AM – Disruptive finishing using electrochemical machining for additive manufacturing €1 m]	Manufacturing & Materials	Future link to food for challenges of post- processing 3D-printed metallic parts	Not obvious
Blockchain in Technology Product Supply Chain [€1 m]	ICT - Blockchain	Food technology product supply chain	Yes, in supply chain
Developing inhaled bioengineered exosome therapeutics [€9.4 m]	Health and Wellbeing	Delivery of smart nutraceuticals via tailored aerosol delivery technology	Yes, in lung delivery of therapeutics
Qunatum computing – a software platform for multiple Qubit technologies [€7.3 m]	ICT	Possible role in financial services and logistics supporting food industry	Yes, in stimulus support to industry
Point-of-care iron stores/Ferritin testing for at risk blood donors [€7 m]	Health and Wellbeing	Not obvious	Not obvious
Data-center audio/visual intelligence on-device [€6.9 m]	ICT	Possible role between in lab and field work for audio and vision-data on devices	Yes
Pharam Latch – [€4.4]	Health & Wellbeing	Not obvious	Yes, possibly
Stroke-CIS [€4 m]	Health & Wellbeing	Not obvious	Yes, possibly
Blockchain and AI-Enabled Stratified Trial System [€3.9 m]	Innovations in Service, Business Processes	Food security – ensuring complete (GDPR) trustworthy, control and ownership of data	Yes, in supply chain and security
FreeSpace Project [€3.6 m]	ICT	Wireless connectivity with ultra-high capacity wireless laser communication technology for broad food industry – delivers combination of bandwidth, availability and distance	Yes, in communications, distribution networks and economic recovery

Table 5 (*continued*)

Title of DTIF Project and Value of Award	Priority Area of Award	Potential cross-link to Food (potential 2nd Order Disruptive Technology)	Potential COVID-19 Use
Transfer print technology for heterogeneous integration of components [€3.6 m]	Manufacturing and Materials	Possibly in food packaging	Yes
EyeVU	Health & Wellbeing	Not obvious	Not obvious
Next generation heat pump for affordable decarbonisation of heating [€2.4 m]	Energy, Climate Action, Sustainability	Possible role in food distribution and storage as zero carbon-emission, refrigerant-free, heat pump	Yes, in efficiency of food supply and security
Haemodialysis Outcomes & Patient empowerment [€2.1 m]	ICT	Possible role of AI enable software and wearable device for chronic diseases	Yes, via AI informed disease mitigation
Connected Enteral feeding healthcare system [€2 m]	Health & Wellbeing	New innovative feed delivery device design, connective and apps	Yes
TRANSPIRE – a trained AI platform for regulation [€2 m]	ICT	Combines human and AI to demystify laws and regulations making it easier to do business while protecting consumers	Yes, in innovations in business services as post disrupter
Video Intelligent Search Platform (VISP) [€1.5 m]	ICT	Not obvious	Yes, in socio-economic recovery
Optimised commercial-scale cultivation of protein-rich biomass from *Palmaria palmata* for the generation of health enhancing plant based proteinaceous ingredients.	Food	Plant-based proteinaceous ingredients as source of high quality protein and contribute to meeting the growing global demand for plant-based proteinaceous ingredients for animal and human food	Yes, economic recovery and health promoting
Beyond Food Labelling	Food	Using massively multiplexed Next Generation Sequencing to provide a crypto-anchor for food authentication and as a substitute for costly, error prone labelling and certification systems	Yes, economic recovery
HYDRO-fish: Combining targeted nutraceuticals and traceability technology for a smarter and sustainable Irish fish aquaculture industry	Food	The project entails reinforcing the supply chain of Irish salmon production	Yes, economic recovery

Institute of Technology supports ca. 300 projects per year with different startups, SMEs, MNCs nationally with cross-cutting links to the agri-food sector, including smart packaging, 3D printing, and nutraceuticals in terms of intelligent delivery systems. Drivers for informing future technology disruption in the agri-food domain will be influenced by needs arising from COVID-19 pandemic along with balancing environmental concerns for more eco-sustainable, climate-friendly products and services.

If one conducts a more in-depth review of the Irelands 43 DTIF projects, it becomes apparent that potentially 20 (46%) at a combined award value of €86.8 m (60.2%) have cross-cutting abilities to cause 2nd order disruption in the food domain (Fig. 3). This would include disruptive training using wearables via wireless communication, use of cytoflow5 for exploiting benefits of nutraceuticals, 3D printing of food, disruptive feed delivery, and future use of nutraceuticals for lung health using aerosol delivery under Health and Wellbeing domain. Disruption in the area of food security could be potentially achieved through the sole Innovative Services and Business Processes project (Table 3). Besides, disruption may be likely made in food distribution and storage through the Energy, Climate Action, and Sustainability project for reveals the use of a new zero-carbon emission, refrigerator-free, heat pump. Science Foundation Ireland has supported a Rapid COVID-19 Response Initiative that funded 26 of 350 applications to address health service readiness, medical countermeasures along with social and policy countermeasures with potential for disruption (Table 5). There is also good thematic agreement with recent Green Deal selected startup and SMEs for COVID-19 interventions (European Innovation Council, 2020).

10. Potential technology, product and business service disruptors in food beyond COVID-19 crisis

In recent times, there has been increasing interest in the augmented use of microorganisms, such as yeast, microalgae, and bacteria, in the form of protein sources. Microorganisms are commonly used in fermented products that we are very familiar with, such as yogurts and sauerkraut. This practice offers a more efficient, innovative approaches to producing the same proteins that we are already familiar with (Medical Expo, 2020). The demand for such alternative food ingredients is pushed by Millennials and Generation X, with changes in eating habits along with corresponding changes in personalized nutrition. From the disruption of introducing Greek yogurt to the emergence of new functional foods such as seaweeds (Mohamed et al., 2012), there has been increasing interest in food ingredients. Such things have informed a trend towards personalized nutrition. Considerable development in this space has been the recent partnership of Nestlé with Corbion. This combines exciting expertise of Corbion's microalgae innovation with Nestlé fermentation abilities that is renowned for its smart plant-based products. Other examples include Impossible Foods, who are making soy heme (typically found in soy plants) for plant-based burgers through microbial fermentation. Impossible food burger is made with soy leghemoglobin that mimics the taste of meat. Such innovations in food ingredients may also complement growing consumer demand for eco-sustainable food sources, which also reflects changing eating habits, diets, and the new role of personalized nutrition. Startup-Insight (2020) noted laboratory-cultured meat might provide an alternative or complementary source to actual meat where the latter requires approximately seven tons of water to produce 450 g of beef. Interestingly, the price for producing around 140 g of artificial meat dropped to €9,59 Euro in 2017 from a non-affordable initial costing base of €274.366. A useful trend to follow for disruption in food production and services is to monitor activities in the United States as more than a third of the world's top food and drink processing companies are headquartered there including Unilever, Danone, Diageo, Kirin, SABMiller, Cadbury Schweppes, Heineken and Asahi Breweries.

High protein feed for animal and human usage will prove relevant, which has been exemplified by an intensive focus on this product for intensive aquaculture production globally. Aquaculture is rapidly developing worldwide and highlights one of the fastest growth areas for the food industry (Fečkaninová et al., 2017; Liu et al., 2017; Tahar et al., 2018a; Tahar et al., 2018b; O'Neill et al., 2019). Aquacultures' pace and scale of expansion reflect a substantial increase in our worldwide population, and the commensurate demand for more safe, nutritious food (Seoane et al., 2014). Fish stocks are depleting on the oceans, and there is a countermeasure push to develop sustainable aquaculture processes to enhance disruption. Hatch-Blue is an example of accelerator SME focused on investing and progressing entrepreneurs to fast-track potential disruptive technologies for the fisheries, seafood, and aquaculture sector

(https://www.hatch.blue/) globally. Precisely, hatch-blue constitutes the first accelerator program for sustainable aquaculture that seeks out, develops, and nurtures Start-ups for disruptive innovation.

11. Conclusion

If one takes a long lens and examines how societies responded to previous catastrophic Black Swan events, (such as the Black Death the devastated the Byzantine Empire, the Cholera outbreak of the 1830s, the Spanish Flu of 1918–1920), World War II (1939–1945), such traumas unleased tremendous changes in thinking, literature, and culture, inspiration, creativity, and ambition will prevail over austerity and fuel the discovery of next-generation disruptive innovations beyond this COVID-19 pandemic. Enhanced innovation leading to the creation of new disruptive technologies in the agri-food domain will inform new exciting new products and services that will address challenges and opportunities for the intensive sustainability of the industry. Modern-day and future disruptive technologies for the agri-food sector will be influenced by the growing demand to produce more safe, nutritious foods to meet growing populations that reflects dynamic changes in eating habits such as personalized nutrition, alternative protein sources, and attitudes towards climate change and digitization. The Black Swan and anti-fragile influences, such as shock to the economy by the occurrence of COVID-19 pandemic, will create both challenges and new opportunities that include emergent or disruptive innovations in service and business processes such as home delivery. A review of the recent 43 projects funded by the Irish government under Science Foundation Ireland's Disruptive Technology Initiatives was used to highlight trends in the innovation ecosystem and the potential for both cross-cutting and future ground-breaking disruption in the agri-food, health, ICT, manufacturing and circular economy sectors with a global orientation. This trend is also reflected in the first 64 'Green Deal' selected start-ups and SME projects recently funded by the European Innovation Projects, which will help support transitioning beyond this COVID-19 pandemic and for future pandemics. Understanding where potential food technology disruptions are likely to occur will be aided by having a holistic perspective and appreciation of the complex socio-technological innovation ecosystem.

Authors' contributions

NJR and CMG conceptualized the manuscript. NJR drafted the manuscript. Both authors read, edited, and approved the final manuscript.

Consent for publication

Not applicable.

Declaration of competing interest

The authors declare that they have no competing or conflict of interests.

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References

A European Green Deal (2020). https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en (accessed 26th July, 2020).
A European Green Deal Action Plan (2020) https://ec.europa.eu/info/sites/info/files/european-green-deal-communication-annex-roadmap_en.pdf (accessed 26th July, 2020).
All Ireland Pollinator Plan (2020). https://pollinators.ie/ (accessed 26th July, 2020).
Barcèló, D. (2020). An environmental and health perspective for COVID-19 outbreak: meteorology and air quality influence, sewage epidemiology indicator, hospital disinfection, drug therapies and recommendations. Journal of Environmental Chemical Engineering. 8 (4) https:doi.org/https://doi.org/10.1016/j.ece.2020.104006.
Bower, J.L., Christensen, C.M., 1995. Disruptive technologies – catching the wave. Harv. Bus. Rev. 73 (1), 506–520.
Braga Rodrigues, T., Ó Catháin, C., O'Connor, N.E., Murray, N., 2020. A Quality of Experience assessment of haptic and augmented reality feedback modalities in a gait analysis system. PLoS ONE 15 (3), e0230570. https://doi.org/10.1371/journal.pone.0230570.
Brunner, T.A., Delley, M., Denkel, C., 2018. Consumers' attitudes and change of attitude toward 3D-printed food. Food Qual. Prefer. 68, 389–396.
CANAPE (2020) https://northsearegion.eu/canape/ (accessed 26th July 2020).
Carbon Connects (2020). https://www.nweurope.eu/projects/project-search/cconnects-carbon-connects/ (accessed 26th July, 2020).
Care-Peat (2020) Restoring the carbon capacity of the peatlands https://www.nweurope.eu/projects/project-search/care-peat-carbon-loss-reduction-from-peatlands-an-integrated-approach/ (accessed 26th July, 2020).
Christensen, C.M., 2003. The Innovator's Solutions:- Creating and Sustaining Successful Growth. Harvard Business School Press, Boston, MA.
Christensen, C.M., Bower, J.L., 1996. Customer power, strategic investment, and the failure of leading firms. Strateg. Manag. J. 17 (3), 197–218.
Christensen, C.M., Anthony, S.D., Roth, E.A., 2004. Seeing What's Next: Using the Theories of Innovation to Predict Industry Change. Harvard Business Press, Cambridge, MA.
DAFM, 2020 https://www.agriculture.gov.ie/customerservice/coronaviruscovid-19/ (accessed 5th June, 2020).
Daniells, S. NPA's fabricant: 'It's a global pandemic. We need to speak a global language when it comes to the science around vitamin D and zinc.' (2020). https://www.nutraingredients. com/Article/2020/05/06/NPA-s-Fabricant-It-s-a-global-pandemic.-We-need-to-speak-a-global-language-when-it-comes-to-the-science-around-vitamin-D-and-zinc. Accessed 11 May 2020.
DBEI, 2018. Ireland's research priority areas 2018-2023. https://dbei.gov.ie/en/Publications/Publication-files/Research-Priority-Areas-2018-to-2023.pdf.
Drucker, P.F., 1985. Innovation and Entrepreneneurship: Practice and Principles. Harper & Row, New York, NY.
Duffy, R., 2020. Ireland's agri-food and drinks sector – M & A outlook during and post-COVID-10. Horizongs – BDOS global viw of mid-market deal activity. https://www.europarl.europa.eu/news/en/headlines/economy/20200513STO79012/covid-19-the-eu-plan-for-the-economic-recovery.
ESRI UK & Ireland. 2020. Business recovery – a strategic approach to recovery –https://www.esriuk.com/en-gb/covid-19/business/recovery (accessed 5th June, 2020).
European Commision, (2020). First "Green Deal" funding from European Innovation Council awards over €307 million to 64 startups set to support the recovery plan for Europe. https://ec.europa.eu/info/news/first-green-deal-funding-european-innovation-council-awards-over-eu307-million-64-startups-set-support-recovery-plan-europe-2020-jul-23_en (Accessed 26th July, 2020).
European Green Deal Strategy, 2020. https://ec.europa.eu/info/strategy/priorities-2019-2024/europeangreen-deal_en (Accessed 31 July, 2020).
European Innovation Council (2020). List of successful funded startups and SMEs under first European Green Deal Strategy. https://ec.europa.eu/info/funding-tenders/opportunities/docs/cap/h2020/eic-smeinst-2018-2020/1900113-eic_list_for_public_accelerator_19_may_2020_en.pdf (Accessed 26th July, 2020).
Fečkaninová, A., Koščová, J., Mudroňová, D., Popelka, P., Toropilová, J., 2017. The use of probiotic bacteria against *Aeromonas* infections in salmonid aquaculture. Aquaculture 469, 1–8.
Fitzhenry, K., Rowan, N., del Rio, A.V., Cremillieux, A., Clifford, E., 2019. Inactivation efficiency of Bacillus endospores via modified flow-through PUV treatment with comparison to conventional LPUV treatment. Journal of water process engineering 27, 67–76.
Galanakis, C.M., 2012. Recovery of high added-value components from food wastes: conventional, emerging technologies and commercialized applications. Trends Food Sci. Technol. 26 (2), 68–87.
Galanakis, C.M., 2013. Emerging technologies for the production of nutraceuticals from agricultural by-products: a viewpoint of opportunities and challenges. Food Bioprod. Process. 91, 575–579.
Galanakis, C.M., 2019. Preface. In: Galanakis, C.M. (Ed.), Innovations Strategies in Environmental Science. Elsevier Inc, Waltham.
Galanakis, C.M., 2020. The food systems in the era of the coronavirus (COVID-19) pandemic crisis. Foods 9, 523.
Geels, F.W., 2018. Disruption and low-carbon system transformation; progress and new challenges in socio-technical transitions research and the multi-level perspective. Energy Res. Soc. Sci. 86, 2317–2324.
Gonzalez, S., 2020. Dietary bioactive compounds and human health and disease. Nutrients 12, 348–351.
Government of Ireland, 2020. https://www.gov.ie/en/news/58bc8b-taoiseach-announces-roadmap-for-reopening-society-and-business-and-u/ (accessed 5th June, 2020).
Green Deal for Start-Ups and SMEs (2020). https://ec.europa.eu/info/funding-tenders/opportunities/docs/cap/h2020/eic-smeinst-2018-2020/1900113-eic_list_for_public_accelerator_19_may_2020_en.pdf (accessed 26th July, 2020).
Guan, D., Wang, D., Hallegatte, S., Davis, S.J., Huo, S., Li, L., Bai, Y., Lei, T., Xue, Q., Coffman, D., Cheng, D., Chen, P., Liang, X., Xu, B., Lu, X., Wang, S., Hubacek, K., Gong, P., 2020. Global supply-chain effects of COVID-19 control measures. Nat. Hum. Behav. https://doi.org/10.1038/s41562-020-0896-8.
Herrero, M., Thornton, P.K., D'Croz, D.M., Palmer, J., Benton, G., Bodirsky, B. L., Bogard, J.R., Hall, A., Lee, B., Nyborg, K., Pradhan, P.4, Graham D. Bonnett1, Brett A. Bryan 6, Bruce M. Campbell7,8, Svend Christensen 7, Michael Clark 9, Mathew T. Cook1, Imke J. M.

de Boer10, Chris Downs1, Kanar Dizyee1, Christian Folberth 11, Cecile M. Godde1, James S. Gerber 12, Michael Grundy1, Petr Havlik11, Andrew Jarvis8, Richard King 3, Ana Maria Loboguerrero 8, Mauricio A. Lopes 11, C. Lynne McIntyre1, Rosamond Naylor13, Javier Navarro1, Michael Obersteiner 11, Alejandro Parodi 10, Mark B. Peoples1, Ilje Pikaar 14,15, Alexander Popp4, Johan Rockström4,16, Michael J. Robertson1, Pete Smith 17, Elke Stehfest 18, Steve M. Swain 1, Hugo Valin 11, Mark van Wijk19, Hannah H. E. van Zanten 10, Sonja Vermeulen3,20, Joost Vervoort21 and Paul C. West . 2020. Innovation can accelerate the transition towards a sustainable food system, Nature Food. Vol 1, 266–272.

IBEC, 2020 https://www.ibec.ie/connect-and-learn/media/2020/04/03/covid19-ibec-publishes-proposed-solutions-to-liquidity-crisis (accessed 5th June, 2020).

Interreg Atlantic Area Sharebiotech Project (2012). https://keep.eu/projects/440/ (Accessed 31 July, 2020).

Interreg Atlantic Area Neptunus Project (2018). Water-Energy-Seafood Nexus:Eco-innovation and Circular EconomyStrategies in the Atlantic Area. https://neptunus-project.eu/ (Accessed 31 July, 2020.

Irish Fiscal Advisory Council (2020) – Fiscal assessment report, May 2020. https://fiscalcouncil.ie (accessed 7th June, 2020).

Just Transition Fund, 2020. https://www.gov.ie/en/publication/ed10d-just-transition-fund/ accessed 24th June, 2020.

Koe, T. Chocolate balls for immune health: Singapore firm's new product for kids amid COVID-19. 2020. https://www. nutraingredients-asia. com/Article/2020/04/30/Chocolate-balls-for-immune-health-Singapore-firm-s-new-product-for-kids-amid-COVID-19 Accessed 11 May 2020.

Kuhn, T.S., 1962. The Structure of Scientific Revolutions. The University of Chicago Press, Chicago, IL.

Lauer, M.S., D'Agostin, R.B., 2013. The randomized registry trial – the next disruptive technology in clinical research. N. Engl. J. Med. 369 (17), 1579–1581.

Li, M., Porter, A.L., Suominen, A., 2018. Insights into relationship between disruptive technology/innovation and emerging technology – a bibliometric perspective. J. Food Eng. 220, 20–27.

Liu, X., Steele, J.C., Meng, X.Z., 2017. Usage, residue, and human health risk of antibiotics in Chinese aquaculture: a review. Environ. Pollut. 223, 161–169.

Mankins, J.C., 2009. Technology readiness assessments: a retrospective. Acta Astronauticia 65, 1216–1223.

Masterson, C.H, Murphy, E., Major, I., González, H., O'Toole, D., McCarthy, S., Laffey, J.G., Rowan, N.J. 2019. Purified Beta-Glucan from the Lentinus Edodes mushroom attenuates antibiotic resistant *Klebsiella pneumoniae*-induced pulmonary sepsis. Am. J. Respir. Crit. Care Med. 2019;199:A1222. doi:https://doi.org/10.1164/ajrccm-conference.2019.199.1_MeetingAbstracts.A1222.

Masterson, C.H., Murphy, E.J., Gonzalez, H., Major, I., McCarthy, S.D., O'Toole, D., Laffey, J.G., Rowan, N.J., 2020. Purified β-glucans from the Shiitake mushroom ameliorates antibiotic-resistant *Klebsiella pneumoniae*-induced pulmonary sepsis. Letters in Applied Microbiology https://doi.org/10.1111/lam.13358.

Medical Expo, 2020. Five Major Trends That Will Impact the Food Industry in 2020. http://emag.medicalexpo.com/five-major-trends-will-impact-the-food-industry-in-2020/ (Accessed 31 July, 2020).

Michelini, L., Principato, L., Iseavoli, G., 2018. Understanding food sharing models to tackle sustainability challenges. Ecol. Econ. 145, 205–217.

Mohamed, S., Nadia, S., Hafeedza, H., Rahman, A., 2012. Seaweeds: a sustainable functional food for complementary and alternative therapy. Trends Food Sci. Technol. 23 (3), 83–96.

Murphy, E.J., Masterson, C., Rezoagli, E., O'Toole, D., Major, I, Stack, G.D., Lynch, M., Laffey, J.G., Rowan, N.J. (2020). β-Glucan extracts from the same edible shiitake mushroom Lentinus edodes produce immunomodulatory and pulmonary cytoprotective effects – implications for coronavirus disease (COVID-19). Sci. Total Environ., 732, 25th August 2020, 139330. doi:https://doi.org/10.1016/j.scitotenv.2020.139330.

Nagji, B., Tuff, G., 2012. Managing your innovation portfolio. Harv. Bus. Rev. 90 (5), 66–74.

Naughton, J., Tiedeken, E.J., Garvey, M., Stout, J., Rowan, N., 2017. Pulsed light inactivation of the bumble bee trypanosome parasite Crithidia bombi. Journal of Apiculture Research 56, 144–154.

Naughton, S., Kavanagh, S., Lynch, M., Rowan, N.J., 2020. Synchronizing use of sophisticated wetlaboratory and in-field handheld technologies for real-time monitoring of key microalgae, bacteria and physicochemical parameters influencing efficacy of water quality in a freshwater aquaculture recirculation system: A case study from the Republic of Ireland. Aquaculture https://doi.org/10.1016/j.aquaculture.2020.735377.

O'Neill, E.A., Rowan, N.J., Fogarty, A.M., 2019. Novel use of the alga *Pseudokirchneriella subcapitata*, as an early-warning indicator to identify climate change ambiguity in aquatic environments using freshwater finfish farming as a case study. Sci. Total Environ. 692, 209–218.

O'Neill, E.A., Stejskal, V., Clifford, E., Rowan, N.J., 2020. Novel use of peatlands as future locations for the sustainable intensification of freshwater aquaculture production – a case study from the Republic of Ireland. Sci. Total Environ. 706. https://doi.org/10.1016/j.scitotenv.2019.136044.

Peat Restore (2020). Climate change mitigation by means of rewetting the peatlands. https://life-peat-restore.eu/en/ (Accessed 26th July, 2020).

Peatlands in the EU (2020). Common Agriculture Policy (CAP) beyond 2020. https://www.eurosite.org/wp-content/uploads/CAP-Policy-Brief-Peatlands-in-the-new-European-Union-Version-4.8.pdf (accessed 26th July, 2020).

Power, J. (2020). Coronavirus – sharp rise of cases in meat plants concering. https://www.irishtimes.com/news/ireland/irish-news/coronavirus-sharp-rise-in-meat-plant-cases-concerning-health-officials-1.4257698 (accessed 27th July, 2020).

Recovery Plan for Europe. https://ec.europa.eu/commission/presscorner/detail/en/ip_20_940 (Accessed 31 July, 2020).

Reid, G., O'Beirne, N., Gibson, N. (2020). How companies can reshape results and plan for a COVID-19 recovery https://www.ey.com/en_ie/transactions/companies-can-reshape-results-and-plan-for-covid-19-recovery (accessed 6th June, 2020).

Reuters, 2020. Alphabet soup: how will post-virus economic recovery shape up? https://uk.reuters.com/article/uk-health-coronavirus-economy-graphic/alphabet-soup-how-will-post-virus-economic-recovery-shape-up-idUKKCN21R25J?il=0

Richie, S.C., Hacker, J.C., Yearkey, K.L., Shi, Z., Pak, S.H., Rainwater, C.E., 2018. Unravelling of food production microbiome: concepts and future directions. Food and Feed Safety Systems and Analysis. Academic Press.

Robroek, B.J.M, Jassey, V.E., Payne, R.J., Martí, M., Bragazza, L., Bleeker, A., Buttler, A., Caporn, S.J.M., Dise, N.B., Kattge, J., Zajac, K., Svensson, B.H., Ruijven, J.V., Verhoven (2017) . Taxonomic and functional turnover are decoupled in European peat bogs. Nat. Commun. 8, 1161. doi:https://doi.org/10.1038/s41467-017-01350-5.

Rowan, N., 2011. Defining established and emerging microbial risks in the aquatic environment: current knowledge, implications, and outlooks. International Journal of Microbiology 2011, 462832 15 pages. https://doi.org/10.1155/2011/462832.

Rowan, N., 2019. Pulsed light as an emerging technology to cause disruption for food and adjacent industries – quo vadis? Trends Food Sci. Technol. 88, 316–332. https://doi.org/10.1016/j.tifs.2019.03.027.

Rowan, N., Laffey, J.G., 2020. Challenges and solutions for addressing critical shortage of supply chain for personal and protective equipment (PPE) arising from Coronavirus disease (COVID19) pandemic – case study from the Republic of Ireland. Sci. Total Environ. 725. https://doi.org/10.1016/j.scitotenv.2020.138532.

Rowan, N., Valdramidis, V.P., Gómez-López, V.M., 2015. A review of quantitative methods to describe efficacy of pulsed light generated inactivation data that embraces the occurrence of viable but non culturable state microorganisms. Trends Food Sci. Technol. 44 (1), 79–92.

Ruiz-Salmón, I., Margallo, M., Laso, J., Villanueva-Rey, P., Mariño, D., Quinteiro, P. Dias, A.C., Nunes, M.L., Marques, A., Feijoo, G., Moreira, M.T., Loubet, P., Sonnemann, G., Morse, A., Cooney, R., Clifford, E., Rowan, N. J., Méndez-Paz, D., Parga, X, Anglada, C., Martin, J.C., Rubén-Aldaco, A., 2020. Addressing challenges and opportunities of the European seafood sector under a circular economy framework. Current Opinion in Environmental Science & Health, Volume 13, 101–106.

Saguy, I.S., Roos, Y.H., Cohen, E., 2018. Food engineering and food science and technology: forward looking journey to future horizons. Innovative Food Sci. Emerg. Technol. 47, 326–334.

Sarkis, J., Cohen, M.J., Dewick, P., Schröder, P., 2020. A brave new world: lessons from the COVID-19 pandemic for transitioning to sustainable supply and production resources. Resources, Conservations, Recycling. 159. https://doi.org/10.1016/j.resources.2020.104894.

Scally, D. (2020). Germany imposes local lockdown after meat plant outbreak. https://www.irishtimes.com/news/world/europe/coronavirus-germany-imposes-local-lockdown-after-meat-plant-outbreak-1.4286213 (Accessed 27th July, 2020).

Schuelke-Leech, B.-A., 2018. A model for understanding the orders of magnitude of disruptive technologies. Technol. Forecast. Soc. Chang. 129, 261–274.

Seoane, M., Rioboo, C., Herrero, C., Cid, Á., 2014. Toxicity induced by three antibiotics commonly used in aquaculture on the marine microalga *Tetraselmis suecica* (Kylin) Butch. Mar. Environ. Res. 101, 1–7.

Silva, A.L.P., Prata, J.C., Walker, T.R., Campos, T.R.W., Duarte, A.C., Soares, A.M.V.M., Barceló, D., Rocha-Santos, T., 2020. Rethinking and optimising plastic waste management under COVID-19 pandemic: policy solutions based on redesign and reduction of single-use plastics and personal protective equipment. https://10.1016/j.scitotenv.2020.140565.

StartUS-Insight, 2020. Disrupting The Food Industry: A Breakdown On Startup Driven Innovation. https://www.startus-insights.com/innovators-guide/disrupting-food-industry-breakdown-startup-driven-innovation/ (Accessed 31 July, 2020).

Sousa, M.J, & Rocha, A. (2018). Skills for the disruptive digital business. J. Bus. Res. http://dx.doi.org/https://doi.org/10.1016/j.busres.2017.12.051.

Statista, 2020a. Food - United States. https://www.statista.com/outlook/40060000/109/food/united-states (Accessed 31 July, 2020).

Statista, 2020b. Industry report on food manufacturing. https://www.statista.com/study/15804/industry-report-food-manufacturing/. Accessed date: 23rd April, 2020.

Tahar, A., Tiedeken, E.J., Clifford, E., Cummins, E., Rowan, N.J., 2017. Development of a semi-quantitative risk assessment model for evaluating environmental threat posed by the three first EU watch-list pharmaceuticals to urban wastewater treatment plants – a Irish case study. Sci. Total Environ. 603, 627–638.

Tahar, A., Kennedy, A., Fitzgerald, R., Clifford, E., Rowan, N., 2018a. Full water quality monitoring of a traditional flow-through rainbow trout farm. Fishes 3, 28.

Tahar, A., Kennedy, A.M., Fitzgerald, R.D., Clifford, E., Rowan, N., 2018b. Longitudinal evaluation of the impact of traditional rainbow trout farming on receiving water quality in Ireland. PeerJ 6, 1–22.

Tahar, A., Tiedeken, E.J., Rowan, N.J., 2018c. Occurrence and geodatabase mapping of three contaminants of emerging concern in receiving water and at effluent from waste water treatment plants – a first overview of the situation in the Republic of Ireland. Sci. Total Environ. 616, 187–197.

Taleb, N.N., 2018. The Black Swan: Second Edition: The Impact of the Highly Improbable Fragility. Random House Publishing Group ISBN 0679604189, 9780679604181.

Tiedeken, E.J., Tahar, A., McHugh, B., Rowan, N.J., 2017. Monitoring, sources, receptors and control measures for three European Union watch list substances of emerging concern in receiving waters – a 20 year systematic review. Sci. Total Environ. 574, 1140–1163.

Yongfu, S., Liheng, W., Zontan, S., Kunsheng, W., Liangyan, J.H., Jian, C., et al. (2017).Connotation and selection of disruptive technologies that lead industrial change. Strategic Study of CAR. https:/doi.org/10.153302/J-SSCAE-2017.05.002.