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Innovations and technology disruptions in the food sector within the COVID-19 pandemic and post-lockdown era

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ABSTRACT

Background: COVID-19 pandemic has caused a global lockdown that has abruptly shut down core businesses and caused a worldwide recession. The forecast for a smooth transition for the agri-food and drink industry is, at best, alarming. Given that COVID-19 shutdown multiple core services (such as aviation, food services, supply chains, and export and import markets), there is an enormous deficiency in critical information to inform priority decision making for companies where this uncertainly is likely to impact negatively upon recovery.

Scope and approach: The current article investigates potential innovations within the era of the COVID-19 crisis after framing them within the four issues of the food sector (food safety, bioactive food compounds, food security, and sustainability) that are directly affected by the pandemic. The prospect of foreseen innovations to disrupt the food sector during lockdown periods and the post-COVID-19 era is also discussed.

Key findings and conclusions: Internet and Communication Technologies, blockchain in the food supply chain and other Industry 4.0 applications, as well as approaches that redefine the way we consume food (e.g., lab-grown meat, plant-based alternatives of meat, and valorization of a vast range of bioresources), are the innovations with the highest potential in the new era. There is also an equally pressing need to exploit social marketing to understand attitudes, perceptions, and barriers that influence the behavior change of consumers and the agri-food industry. Subsequently, this change will contribute to adapting to new norms forged by the COVID-19 pandemic, where there is a significant gap in knowledge for decision making.

1. Introduction

The COVID-19 pandemic led to millions of infections and deaths worldwide, changing dramatically what we perceived as norms and impacting society, health systems, governmental policies, and businesses. The food sector is no exception, as the consequences of this "*Black Swan*" socio-economic event (Reid et al., 2020) has changed the way we think, buy and consume food by accelerating pre-existing innovation trends (Askew, 2020f), marking a "before" and "after" period. In the short term, the pandemic affected the sector by causing labor problems (e.g., lack of workers due to illness and quarantine measures), the shutdown of factories, food shortages on shelves, and some cases stress of cash flow for the active businesses (Reid et al., 2020). We are also on the verge of a significant global recession (Guan et al., 2020), lacking critical information for recovery. The role of mapping trends and predicting consumer behavior towards new technologies, services, and products for transitioning beyond COVID-19 will be highly beneficial as per approaches described previously by Busse and Siebert (Busse & Siebert, 2018) and Suanda et al. (Suanda et al., 2018). On a long term basis, the pandemic affects the whole food sector into four main domains: food safety, bioactive food ingredients, food security, and sustainability (Galanakis, 2020).

Overcoming the pandemic's obstacles will not be achieved through austerity but by strong leadership, inspiration, and ambition. Even though vaccination to protect against COVID-19 has begun, the second pandemic wave has affected many countries. Thus it is impossible to

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exclude the possibility of repeated infection and lockdown waves, as the pandemic might continue up to the end of 2021, establishing further uncertainty to the food sector (Rowan & Laffey, 2020).

Subsequently, the pandemic's most significant impact may be from the changes induced during the following recovery period (Askew, 2020f). Today, it is uncertain with any degree of confidence what specific impact the global recession will have on the economy, as it relates to particular opportunities and needs encountered by emerging technologies in the food sector.

Through a long reflective lens, lessons have been learned from previous catastrophic global events, such as the Spanish Flu or Black Death, where inspiration has led to paradigm shifts in disruptive technologies. Subsequently, there is an increasing focus on innovative technologies to make the food sector sustainable to meet the opportunities arising from the COVID-19 pandemic (Munekata et al., 2020). The current perspective article explores relevant innovations within the era of the COVID-19 pandemic and post-lockdown era. The foreseen innovations are framed as two more dimensions within the boundaries of the four domains above (Fig. 1) before discussing their prospects of being implemented during expected lockdown periods and eventually to disrupt the food sector after the end of the pandemic crisis.

1.1. *Implications of the pandemic in the food sector*

As a '*Black Swan*' socio-economic event occurring extremely rarely, the COVID-19 pandemic resulted in catastrophic consequences. In this kind of crisis, companies would not have predicted and planned accordingly (Reid et al., 2020). Food and food supply chain safety was the first emergent issue under consideration, requiring an increasing number of precautionary measures as long as we move from farm to fork (Rizou et al., 2020). Sustaining food production through COVID-19 brought challenges, including clustering of cases in agricultural food production, slaughterhouses, and food processing industries (Ecdc, 2020). . This fact revealed operational issues of the food industry new era trying to maintain food supply balanced with social distancing. Likewise, the unified social solidarity to protect frontline workers from fighting COVID-19 has resulted in the abrupt mass closure of services and businesses globally, which has prompted governments to launch commensurate 'staggering' economic recovery packages to support a beleaguered industry (Govie, 2020; IBEC, 2020). COVID-19 pandemic has reset the new norm for society, with the frenzy of uncertainty fueling many companies to scramble to maintain functionality within their marketplace (Guan et al., 2020). Work practices have changed in terms of remote operation, including working from home and digital communication platforms and Internet and Communication Technologies (ICT) (Del Rio & Malani, 2020). What became evident during this crisis is that advanced and more digital traceability is a powerful tool in comprehending the implications of the supply chain in the case of a public health emerging event (Hahn, 2020).

Over the last year, boosting the immune system was a priority for consumers. This trend has accelerated within the COVID-19 era, and consumers' interest in sustainable, healthy, organic, and functional foods has been increasing rapidly (Askew, 2020a, 2020d; Galanakis, 2015, 2021; Zinoviadou et al., 2015). Moreover, products that are considered by consumers to boost their immune system (e.g., camomile, kombucha) have experienced a 3- to 4-fold increase in sales (Askew, 2020f). A recent survey of 23,000 European shoppers indicated that 72% of consumers would change their eating habits in the post-lockdown era to follow more healthy patterns (Fmcggurus, 2020). Following consumers' needs, food companies are commercializing products with bioactives, creating a trend towards seeking recognition of food bioactives as immune-boosting agents (Galanakis et al., 2020) (Daniells, 2020) that encompass forging more collaborations between governmental bodies and academic institutions to address this need (Koe, 2020a, 2020b).

On the other hand, the pandemic led to an instantaneous lack of critical information about consumers' preferences, attitudes, and bottlenecks in the post-lockdown period (Rowan & Laffey, 2020). The

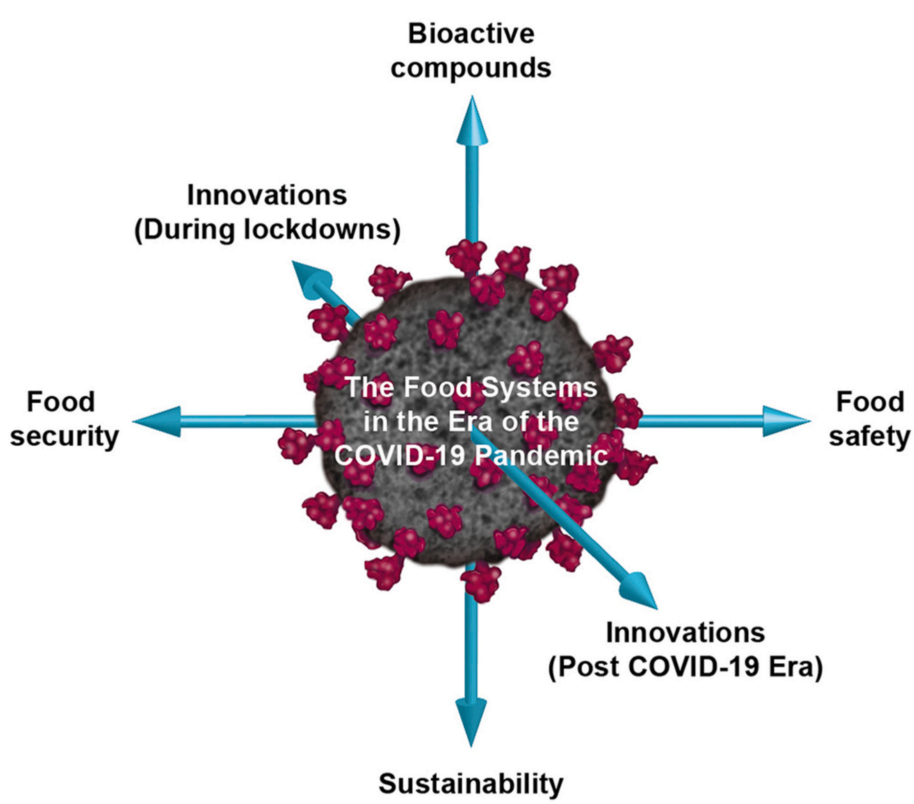

Fig. 1. The food systems in the era of the COVID-19 pandemic and the prospect of implementing innovations during lockdowns and post COVID-19 era.

induced disruptions in the food supply chain have increased the risk for food fraud, whereas finding convincing evidence about the real health benefits of nutraceuticals and functional foods became critical. This gap also highlighted the emerging role of digitization using data analytics and Artificial Intelligence (AI) to support the real-time needs (e.g., remote monitoring and management decision tools) of the food industry, smart agriculture, supply chain, and food security (Bacco et al., 2019). Moreover, the proliferation of new technologies helped digitize the food supply chain and increased traceability systems' investments to mitigate risk, improve efficiency, and underpin sustainability initiatives (Kennedy et al., 2020).

Sectors benefiting from the current challenges of COVID-19 include companies producing non-perishable foods and processed food companies. For example, panic buying during the lockdown has driven consumers to develop new habits and taste products that they have not purchased before, e.g., freeze-dry ready meals. Since consumers have tasted rehydrated products and compared them with fresh food, it is expected that the demand for this kind of product will grow over the next years (Askew, 2020b). Companies are also experiencing a rapid increase in the need for plant-based ready meals (Askew, 2020e) and alternative protein sources to meat and dairy products (Foodnavigator, 2019). Direct-to-consumer services have rapidly increased, whereas many traditional grocery brands try to develop an easy route to market and become online first brands (Askew, 2020f). The online food trade has witnessed an explosive increase in demand, whereas there is a warning for sustainable packaging solutions due to the rapidly increased need for packaged food. Although the measures needed to ensure food safety, security, and sustainability converge more than ever before, it is essential to avoid hazardous and illegal food products reach the market due to shortages, false claims, or other reasons (e.g., economic). For example, food recalls due to authenticity concerns are likely to be reduced (Everstine, 2020). Since the online order of nutraceuticals has rapidly increased, attention should be given to these products' adulteration and safety (Bullimore, 2020). The second wave of infection that has already been witnessed worldwide will create additional opportunities for innovators and services such as online retail and deliveries (Rowan & Laffey, 2020).

2. Innovations and disruptions in the new era

COVID-19 pandemic has accelerated innovation all around the world. This change has already been seen in places where the virus hit first (e.g., in China), where large companies such as Huawei have increased their expenses for research and development activities. There is also reasoning behind this trend as companies that invested in the 2008 economic crisis (instead of just cutting costs) grew fast during the recession (Davey, 2020). On the other hand, defining and forecasting what constitutes a disruptive technology is complicated as the impact is more likely to be measured from a retrospective downstream perspective. Since the 1990s, researchers have referred to disruptive technologies as whirlwind, ground-breaking, game-changing, earth-quake, and emergent technologies that typically cause a substantial disturbance in established market structure and prominent companies. This disturbance is generated by producing highly efficient products and services that are more competitively priced, less complicated, and more accessible than established innovations (Christensen, 1997; Christensen & Bower, 1996; Schuelke-Leech, 2018). Disruptive technologies can substantially cause localized change within a market or industry (e.g., first-order disruption) or cause ground-breaking changes across many cross-cutting domains (e.g., second-order disruption) over a period that substantially influences societal norms. The challenges for technological forecasters and investors are those disruptive technologies are by their nature nascent – meaning that they can only be proven as disruptive in hindsight based upon demonstrating evidence-based impact. The uncertainty arising from COVID-19 will shape future disruptive technologies that may emerge from entrepreneurs, start-ups, small and medium-sized enterprises (SMEs), and larger established companies. These companies are willing to integrate new solutions at providing smaller, lighter, more flexible, cheaper, and more convenient products (Rowan, 2019).

Fig. 2 illustrates the different innovations within the COVID-19 pandemic era and their application's field(s). The chord diagrams of Fig. 3 demonstrate the prospect of implementing the foreseen innovations in the food sector within the era of the COVID-19 pandemic and respective applications during lockdown periods and within the post-COVID-19 era. The chords start from the potential innovations during the lockdowns and end up in the post-COVID-19 era. The thicker the chords are, and the higher are the prospects of the new era's innovations. These innovations may be enhanced by adjacent industries and services dealing with digitization, using meteorological data linked with climate modeling (Ruiz-Salmón et al., 2020). Overall, it is challenging to predict the holistic consequences of this COVID-19 pandemic and at what time point we will emerge from it, and which innovations and technologies will disrupt the food sector.

2.1. Bioactive compounds

The pandemic generated opportunities and challenges for the commercialization of innovative functional foods and nutraceuticals containing target bioactive compounds (e.g., Vitamins and antioxidants) and highlighted the advances of personalized nutrition to boost consumers' immune system and improve their overall health (Galanakis et al., 2020). These prospects are expected to remain high within the post-lockdown and post-pandemic era due to the increased interest of health-conscious individuals. Subsequently, companies will seek new information and knowledge about consumer needs toward these products to address the pandemic's challenges. Nowadays, the development of these kinds of products are proposed with the simultaneous valorization of bioresources, e.g., the recovery of high added-value compounds from food waste (Galanakis, 2012, 2018; Galanakis et al., 2018; Nagarajan et al., 2019; Roselló-Soto, Barba, et al., 2015; Ruiz-Salmón et al., 2020; Wong et al., 2015), and the utilization of microalgae and plant foods (Ananey-Obiri et al., 2018; Bursać Kovačević et al., 2018;

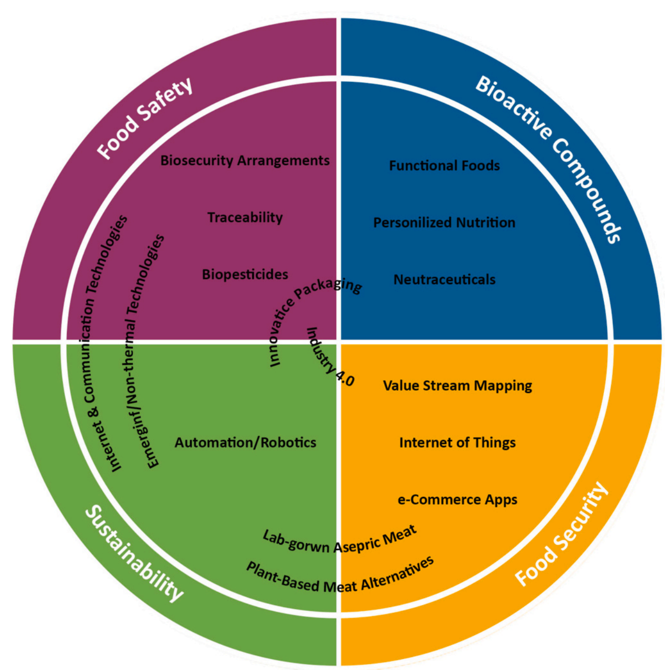

Fig. 2. Foreseen innovations and disruptive technologies to tackle challenges of the four directions affected by the COVID-19 pandemic: food safety, bioactive compounds, food security, and sustainability.

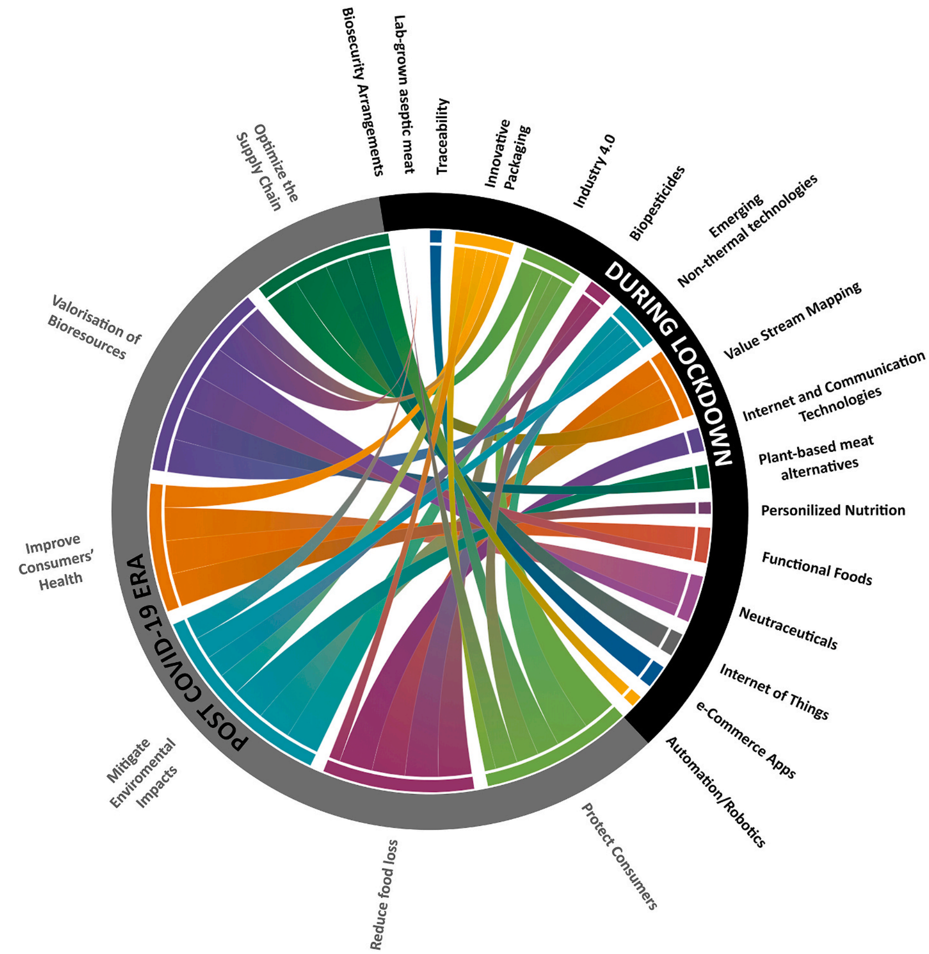

Fig. 3. The prospect of implementing the foreseen innovations in the food sector within the era of COVID-19 pandemic and respective applications during lockdown and post-COVID-19 periods.

Galanakis, 2013; Roselló-Soto, Galanakis, et al., 2015). Adjacent advances will also be made in immune-boosting animal feed products such as recently reported by Taufek and co-workers (Taufek et al., 2020), who described the performance of mycelial biomass and exopolysaccharide from Malaysian edible mushroom *Ganoderma lucidum* for the fungivore red hybrid Tilapia (Oreochromis sp.) in Zebrafish embryo. Carballo and co-workers (Carballo et al., 2019) also reported on the use of β-glucans from yeast combined with microalgae extracted digest to improve the health of gut microbiome of high-value fish that prevented bacterial infection.

2.2. Food safety

On the other hand, innovations such as smart and active packaging, advanced traceability systems (e.g., using blockchain technology), new biosecurity arrangements (e.g., promoting a food safety culture in food processing facilities and farms), the application of biopesticides to agriculture and industry 4.0 (e.g., blockchain technology) are expected to grow substantially in the new era. The ultimate goal is to protect consumers by ensuring the food and food supply chain's safety and reduce food loss and the environmental impact of the food sector. These innovations may lead to new business models that could disrupt the food supply chain and the market of food products in a techno-socioeconomic way. By achieving international consensus on datasets, priority should be given to reliable processing and critical information for clinical trials (Rowan, 2019) by promoting open access to findings.

For instance, the FDA is planning to release a relevant blueprint targeting the development of traceable food systems and safer, more digital, and more secure food supply (FDA, 2020). Technologies such as artificial intelligence, blockchain, the Internet of Things (IoT), and sensor technology would allow the direct tracking of foods and commodities from farm to fork. The combination of advanced traceability systems with modern analytical and smart tools (e.g., remote or virtual inspections, root cause analyses) would reduce the response in food-borne outbreaks by using data streams. The latest could make the supply chain more visible, reducing the time between tracking the contamination origin of food and responding with mitigating actions.

These kinds of technologies would also assist in imbalances caused by panic buying and spot shortages due to extreme events and help comprehend the causes of food contamination and interpret predictive analytics. The latest use data to predict the contamination possibility and ultimately reduce food loss and waste, e.g., when lockdowns temporarily disrupt the chain of producers and customers in public places (e.g., schools and restaurants). New biosecurity arrangements will help to promote a food safety culture in food processing facilities and farms. There is also a pressing need for education and social enterprise to support the community transitioning to emerging changes and embrace new approaches for food sustainability and security that will accelerate consumer acceptance of green innovation.

2.3. Sustainability

With the changing lifestyle and rapid urbanization of the global population that has been accelerated by behavior changes arising from COVID-19, there is an increased generation of food waste from various industrial, agricultural, and household sources (Sharma et al., 2020).

From price spikes and panic buying to the acceleration of food waste, sustainability, and other economic implications, the COVID-19 crisis (as a real exercise) has reminded us that the current food systems are fragile. Thus, they should become more resilient, ensuring food security in future crises such as new pandemics and extreme events due to climate change. Two overarching priorities are to ensure that producers and processors can continue to operate effectively and keep supply lines open and that most services can work as effectively as possible during the pandemic. These are on top of the pressing need to develop innovative means to increase food production to meet growing populations internationally informed by digital technologies. Priorities also include the likely consolidation of significant industries with secure packaging and capacity for research and innovation that will potentially flourish during and post COVID-19 era, when socio-economic norms have been reset and countries quickly deploy economic recovery plans.

The dominant linear economy system, which is mainly based on increasing production to address increased consumption, has proved inefficient for the sustainable management of our resources (Hetemäki et al., 2017; Stegmann et al., 2020). On the other hand, the transition of the current development model to a circular bioeconomy approach could enhance resilience by converting biomass into various biobased products (Farcas et al., 2020; Mak et al., 2020). Thus, a more exceptional drive for innovations in this direction will balance the food supply chain's impact on the environment with the emergence of less-energy intensive, eco-friendly processes, products, and services (O'Neill et al., 2019). For instance, the traditional approaches for managing food waste include land-filling and incineration that generate toxic gases, causing severe environmental and human health hazards. The circular bioeconomy provides opportunities to valorize food waste utilizing biorefineries that produce biofuels, electrical energy, biosurfactants, biofertilizers and so forth (Mordorinelligence, 2020; O'Neill et al., 2019; Rahmanian et al., 2014). The use of biobased packaging materials and non-thermal disinfection technologies for packaging, such as pulsed light (Rowan, 2019), are two examples that could accelerate green innovation in the new era. Biobased materials have been developed to mitigate the complications instigated by conventional plastics. The bioplastic packaging market has been driven by the increasing awareness of traditional plastics' adverse effects, which has steered both consumers and regulatory bodies to opt for biobased materials in place of conventional plastic. The bioplastics packaging market was valued at USD 14.85 billion in 2019 and is expected to reach USD 39.37 billion by 2025 (Mordorinelligence, 2020).

Seafood and aquaculture sectors of Europe, are encounter also significant challenges concerning environmental threats (climate change, marine debris, resource depletion), social development (worker rights, consumer's awareness), or economic growth (market and nonmarket goods and services, global competitiveness). These issues are pressuring all stakeholders, from policy-makers to citizens and industries, to adopt more sustainable policies, practices, and processes. For example, O'Neill (O'Neill et al., 2020) reported Trout and Perch's organic fish farm production on the Irish peatlands using an aquaculture recirculation system (powered with wind energy) where water quality and waste remediation are controlled naturally by using indigenous microalgae and bacteria. Moreover, collaborations among different parties and beyond borders should be improved, aiming to create more efficient networks along the seafood and aquaculture sectors' supply chain. To achieve this, a "nexus thinking" approach (i.e., the analysis of actions in connected systems) combined with a life cycle thinking appears like an excellent opportunity to facilitate the transition to a circular bioeconomy. The emergence of centers of research excellence linked to enterprise and education with a global orientation that seeks to exploit added value to products derived from food waste will increasingly come to the fore. Future research would consider the impact of climate change on food supply chains, including circular bioeconomy, as recently demonstrated by O'Neill et al. (O'Neill et al., 2019), who showed the use of naturally occurring biological indicators to assess the environmental impact of sustainable periods of drought on Irish freshwater aquaculture.

Besides, aquaculture is an emerging high-protein low carbon emission process that is of interest globally for intensive food sustainability (Tahar et al., 2018a, 2018b). The generated opportunities will be met in part by advances in the digitization of food technologies, innovation in manufacturing (e.g., emerging non-thermal technologies), and services for a diversity of markets and commensurate sustaining disruptive innovation in the adjacent manufacturing and materials sectors. Although most innovations (e.g., lab-grown aseptic meat, plant-based meat alternatives, biobased packaging, automation of food production, and robotics) targeting the sustainability of the food sector are today in a nascent development stage, they are expected to disrupt the food industry in the years to come (Galanakis, 2020). Also, exploiting advanced manufacturing (such as digitization, big data, ICT, blockchain, artificial intelligence, non-thermal technologies, robotics, augment and virtual reality, and 3D food printing) will address sustainability and security qualitative standards, and traceability along the entire food supply chain.

2.4. Food security

Disruptive innovation in digitization is transforming the pace and scale of the food and drinks industry globally, ensuring food safety and increasing food sustainability and food security applications. For instance, advanced digital solutions (e.g., IoT, blockchain in the supply chain) to ensure 24/7 order taking are expected to grow, whereas companies will have to promote their values and brand and their quality commitments (Askew, 2020c). The adaptation to new business models that allow the modernization of retail would also contribute to this direction. These models include, e.g., IoT and ICT (e.g., online delivery for supply chain), or e-commerce that utilizes mobile apps for shopping purposes, helping smallholders and producers to find different customers in small city centers (Askew, 2020f) (FDA, 2020; Galanakis, 2020). To this line, Naughton et al. (S. Naughton et al., 2020) demonstrated the need for real-time digitization and ICT in aquaculture to connect complex laboratory data analysis with in-field physicochemical measurements. These tools should determine optimum feeding rates at a fish farm or conditions' adjustments for disease mitigation.

The application value stream mapping is also expected to grow fast in the new era. This digital tool allows the proper management of the supply chain from agricultural production to processing, retail, and consumption. Likewise, it reduces food loss and mitigates environmental impacts (Wesana et al., 2019). Use of potential disruptive non-thermal technologies, such as pulsed light, for food packaging disinfection that also has potential for second-order disruption in areas of waste effluent treatment and critical ecosystem service management such as treatment of pollen frequently contaminated complex parasites and viruses for farmed bumblebees used in buzz pollination of soft fruits and crops across Europe (Garvey & Rowan, 2019; I. M. T. Murray et al., 2018; J. Naughton et al., 2017; Rowan, 2019). Disruptive technologies for promoting pollination security can be extended to commercial electron beam or x-ray treatments for large scale throughput, where the benefits of these emerging solutions have been comprehensively reviewed by (McEvoy & Rowan, 2019). MacFadden and co-workers (Mcfadden et al., 2016) also reported comparing the efficacy of using commercial electron beam and pulsed light for novel sterilization of Irish retailed infant milk formulae to further enhance safety and security from a non-thermal processing perspective. Traditional and emerging technologies were also comprehensively reviewed to help future-proof food systems contaminated with complex foodborne parasites (Franssen et al., 2019; Gérard et al., 2019; Herrero et al., 2020).

There is also a growing potential to exploit immersive Industry 4.0 advances (e.g., virtual and augmented reality) to advance remote workforce training that can embrace the need for social distance to prevent transmission of COVID-19 (N. Murray et al., 2019). Training and competence development remains mostly grounded in traditional practice methods against a backdrop of highly innovative processes and technology advancements (N. Murray et al., 2019; Rowan, 2019). Likewise, the provision of specialist training in the agri-food workforce merits innovative approaches using technology as a tool in competence development. In the context of specialist training and educational programs, Immersive Multimedia (I.M.) technologies such as virtual reality are emerging as potential platforms based on their delivery of 360° visuals, spatial audio, and allowing the learner to move beyond the passive mode towards an active participant in their learning experience (Braga Rodrigues et al., 2020). In conjunction with wearable sensor technologies (capturing different user physiological metrics), task performance, and user interaction, these technologies facilitate a right "human-in-the-loop" system that supports adaptive, personalized while maintaining context-based learning. Combined educational (such as Cognitive Load Theory) and immersive training capture, at the individual level, critical abilities of the learner, which then informs how the presentation system challenges the learner, thus optimizing the learner experience (Braga Rodrigues et al., 2020; N.; Murray et al., 2019).

3. Conclusion

The COVID-19 pandemic has led to historical changes in our society's norms and the way people interact. It also showed direct and high impacts on the food sector, affecting mainly bioactive compounds, food safety, food security, and sustainability. The lockdown of billions of people during the last winter and spring and the lockdown waves that are expected to come in the next months/years led to different innovations in the food sector. Among them, Industry 4.0 applications (IoT, ICT, and blockchain technology) and innovations that disrupt the way we consider and consume food (e.g., lab-grown meat, plant-based alternatives of meat, and valorization of a vast range of bioresources) are the ones with the highest potential in the new era. Niche applications such as the development of nutritional and immune-boosting products to support the health and recovery of COVID-19 patients will become popular. There is also a trend towards intensive sustainable food production systems (such as digitization, AI, and automation in smart agriculture) with future-proofing for the potential impact of security risks and climate change through the supply chain to mitigate critical needs embrace opportunities. Education and training for the next generation of workforce in emerging technologies and accelerating initiatives that will foster behavior change of consumers to the merits of these new business services, technologies, and products will be becoming increasingly important. Globally, there will be a pressing focus on food security regionally and nationally to mitigate against challenges presented by the potential occurrence of future viral pandemics such as that caused by SARS-CoV-2 to protect vulnerable critical supply chains.

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References

Ananey-Obiri, D., Matthews, L., Azahrani, M. H., Ibrahim, S. A., Galanakis, C. M., & Tahergorabi, R. (2018). Application of protein-based edible coatings for fat uptake reduction in deep-fat fried foods with an emphasis on muscle food proteins. In *Trends in food science and technology* (Vol. 80, pp. 167–174). Elsevier Ltd. https://doi.org/10.1016/j.tifs.2018.08.012

Askew, K. (2020a). COVID-19 crisis accelerates mainstreaming of immune boosting beta glucans. https://www.foodnavigator.com/Article/2020/04/20/COVID-19-crisis-accelerates-mainstreaming-of-immune-boosting-beta-glucans.

Askew, K. (2020b). European freeze dry looks beyond COVID-19 boost: 'We will continue to see repeat purchase. https://www.foodnavigator.com/Article/2020/05/07/European-Freeze-Dry-looks-beyond-COVID-19-boost-We-will-continue-to-see-repeat-purchase.

Askew, K. (2020c). Organic alliance CEO on COVID-19: 'This epidemic will mark a before and after for society. https://www.foodnavigator.com/Article/2020/05/13/Organic-Alliance-CEO-on-COVID-19-This-epidemic-will-mark-a-before-and-after-for-society.

Askew, K. (2020d). Organic food gets coronavirus boost. https://www.foodnavigator.com/Article/2020/05/06/Organic-food-gets-coronavirus-boost.

Askew, K. (2020e). Plant-based ambient brand fiid's strong growth during coronavirus: 'There is a silver lining for our category. https://www.foodnavigator.com/Article/2020/04/29/Plant-based-ambient-brand-Fiid-s-strong-growth-during-coronavirus-There-is-a-silver-lining-for-our-category.

Askew, K. (2020f). The FoodNavigator Podcast: What does Coronavirus mean for the future of food?. https://www.foodnavigator.com/Article/2020/05/15/The-FoodNavigator-Podcast-What-does-Coronavirus-mean-for-the-future-of-food.

Bacco, M., Barsocchi, P., Ferro, E., Gotta, A., & Ruggeri, M. (2019). The digitisation of agriculture: A survey of research activities on smart farming. *Array, 3–4*, 100009. https://doi.org/10.1016/j.array.2019.100009

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), Article e0230570. https://doi.org/10.1371/journal.pone.0230570

Bullimore, S. (2020). COVID-19: Nutraceutical players respond. https://www.nutraceuticalbusinessreview.com/news/article_page/COVID-19_Nutraceutical_players_respond/163975.

Bursać Kovačević, D., Barba, F. J., Granato, D., Galanakis, C. M., Herceg, Z., Dragović-Uzelac, V., & Putnik, P. (2018). Pressurized hot water extraction (PHWE) for the green recovery of bioactive compounds and steviol glycosides from Stevia rebaudiana Bertoni leaves. *Food Chemistry, 254*, 150–157. https://doi.org/10.1016/j.foodchem.2018.01.192

Busse, M., & Siebert, R. (2018). The role of consumers in food innovation processes. *European Journal of Innovation Management, 21*(1), 20–43. https://doi.org/10.1108/EJIM-03-2017-0023. Emerald Group Publishing Ltd.

Carballo, C., Pinto, P. I. S., Mateus, A. P., Berbel, C., Guerreiro, C. C., Martinez-Blanch, J. F., Codoñer, F. M., Mantecon, L., Power, D. M., & Manchado, M. (2019). Yeast β-glucans and microalgal extracts modulate the immune response and gut microbiome in Senegalese sole (Solea senegalensis). *Fish & Shellfish Immunology, 92*, 31–39. https://doi.org/10.1016/j.fsi.2019.05.044

Christensen, C. M. (1997). *The innovator's dilemma: When new technologies cause great firms to fail* (M. H. B. S. P. Boston (ed.)).

Christensen, C. M., & Bower, J. L. (1996). Customer power, strategic investment, and the failure of leading firms. *Strategic Management Journal, 17*, 197–218. https://doi.org/10.2307/2486845. Wiley.

Daniells, S. (2020). 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. https://www.nutraingredients-usa.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.

Davey, R. (2020). Now is the time to accelerate innovation - Clarivate. https://clarivate.com/article/now-is-the-time-to-accelerate-innovation/.

Del Rio, C., & Malani, P. N. (2020). COVID-19 - new insights on a rapidly changing epidemic. *JAMA - Journal of the American Medical Association, 323*(14), 1339–1340. https://doi.org/10.1001/jama.2020.3072. American Medical Association.

Ecdc. (2020). *COVID-19 clusters and outbreaks in occupational settings in the EU/EEA and the U.K*.

Everstine, K. (2020). *COVID-19 and food fraud risk | FoodSafetyTech*. https://foodsafetytech.com/column/covid-19-and-food-fraud-risk/.

Farcas, A. C., Galanakis, C. M., Socaciu, C., Pop, O. L., Tibulca, D., Paucean, A., Jimborean, M. A., Fogarasi, M., Salanta, L. C., Tofana, M., & Socaci, S. A. (2020). Food security during the pandemic and the importance of the bioeconomy in the new era. *Sustainability, 13*(1), 150. https://doi.org/10.3390/su13010150

FDA. (2020). *new era of smarter food safety*. FDA. https://www.fda.gov/food/new-era-smarter-food-safety.

Fmcggurus. (2020). *The impact of COVID-19 in 2020 & beyond*. https://fmcggurus.com/covid-19/.

Foodnavigator. (2019). A matter of taste. Your protein - proudly green!. https://www.foodnavigator.com/Product-innovations/A-matter-of-taste.-Your-protein-proudly-green.

Franssen, F., Gerard, C., Cozma-Petruţ, A., Vieira-Pinto, M., Jambrak, A. R., Rowan, N., Paulsen, P., Rozycki, M., Tysnes, K., Rodriguez-Lazaro, D., & Robertson, L. (2019). Inactivation of parasite transmission stages: Efficacy of treatments on food of animal origin. *Trends in Food Science & Technology, 83*, 114–128. https://doi.org/10.1016/j.tifs.2018.11.009. Elsevier Ltd.

Galanakis, C. M. (2012). Recovery of high added-value components from food wastes: Conventional, emerging technologies and commercialized applications. *Trends in Food Science & Technology, 26*(2), 68–87. https://doi.org/10.1016/j.tifs.2012.03.003. Elsevier.

Galanakis, C. M. (2013). Emerging technologies for the production of nutraceuticals from agricultural by-products: A viewpoint of opportunities and challenges. *Food and Bioproducts Processing, 91*(4), 575–579. https://doi.org/10.1016/j.fbp.2013.01.004

Galanakis, C. M. (2015). Separation of functional macromolecules and micromolecules: From ultrafiltration to the border of nanofiltration. *Trends in Food Science & Technology, 42*(1), 44–63. https://doi.org/10.1016/j.tifs.2014.11.005. Elsevier Ltd.

Galanakis, C. M. (2018). Phenols recovered from olive mill wastewater as additives in meat products. *Trends in Food Science & Technology, 79*, 98–105. https://doi.org/10.1016/j.tifs.2018.07.010. Elsevier Ltd.

Galanakis, C. M. (2020). The food systems in the era of the coronavirus (CoVID-19) pandemic crisis. *Foods, 9*(4). https://doi.org/10.3390/foods9040523. MDPI Multidisciplinary Digital Publishing Institute.

Galanakis, C. M. (2021). Functionality of food components and emerging technologies. *Foods, 10*(1), 128. https://doi.org/10.3390/foods10010128
Galanakis, C. M., Aldawoud, T. M. S., Rizou, M., Rowan, N. J., & Ibrahim, S. A. (2020). Food ingredients and active compounds against the coronavirus disease (COVID-19) pandemic: A comprehensive review. *Foods, 9*(11), 1701. https://doi.org/10.3390/foods9111701
Galanakis, C. M., Tsatalas, P., & Galanakis, I. M. (2018). Implementation of phenols recovered from olive mill wastewater as U.V. booster in cosmetics. *Industrial Crops and Products, 111*, 30–37. https://doi.org/10.1016/j.indcrop.2017.09.058
Garvey, M., & Rowan, N. J. (2019). Pulsed U.V. as a potential surface sanitizer in food production processes to ensure consumer safety. *Current Opinion in Food Science, 26*, 65–70. https://doi.org/10.1016/j.cofs.2019.03.003. Elsevier Ltd.
Gérard, C., Franssen, F., La Carbona, S., Monteiro, S., Cozma-Petruţ, A., Utaaker, K. S., Režek Jambrak, A., Rowan, N., Rodríguez-Lazaro, D., Nasser, A., Tysnes, K., & Robertson, L. J. (2019). Inactivation of parasite transmission stages: Efficacy of treatments on foods of non-animal origin. *Trends in Food Science & Technology, 91*, 12–23. https://doi.org/10.1016/j.tifs.2019.06.015. Elsevier Ltd.
Govie. (2020). Roadmap for reopening society and business. https://www.gov.ie/en/news/58bc8b-taoiseach-announces-roadmap-for-reopening-society-and-business-and-u/.
Guan, D., Wang, D., Hallegatte, S., Davis, S. J., Huo, J., Li, S., Bai, Y., Lei, T., Xue, Q., Coffman, D. M., 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. *Nature Human Behaviour, 4*(6). https://doi.org/10.1038/s41562-020-0896-8
Hahn, S. (2020). *Pandemic challenges highlight the importance of the new era of smarter food safety*. FDA. https://www.fda.gov/news-events/fda-voices/pandemic-challenges-highlight-importance-new-era-smarter-food-safety.
Herrero, M., Thornton, P. K., Mason-D'Croz, D., Palmer, J., Benton, T. G., Bodirsky, B. L., Bogard, J. R., Hall, A., Lee, B., Nyborg, K., Pradhan, P., Bonnett, G. D., Bryan, B. A., Campbell, B. M., Christensen, S., Clark, M., Cook, M. T., de Boer, I. J. M., Downs, C., … West, P. C. (2020). Innovation can accelerate the transition towards a sustainable food system. *Nature Food, 1*(5), 266–272. https://doi.org/10.1038/s43016-020-0074-1
Hetemäki, L., Hanewinkel, M., Muys, B., Ollikainen, M., Palahi, M., & Trasobares, A. (2017). *Leading the way to a European circular bioeconomy strategy*. European Forest Institute. https://efi.int/publications-bank/leading-way-european-circular-bioeconomy-strategy.
IBEC. (2020). *COVID19 Ibec publishes proposed solutions to liquidity crisis*. https://www.ibec.ie/connect-and-learn/media/2020/04/03/covid19-ibec-publishes-proposed-solutions-to-liquidity-crisis.
Kennedy, A., Stitzinger, J., & Burke, T. (2020). Food traceability. In A. Demirci, H. Feng, & K. Krishnamurthy (Eds.), *Food safety engineering, food engineering series*. Springer Nature Switzerland.
Koe, T. (2020a). *COVID-19 and nutra research: Where does the industry need to focus its scientific endeavours?*. https://www.nutraingredients-asia.com/Article/2020/04/01/COVID-19-and-nutra-research-Where-does-the-industry-need-to-focus-its-scientific-endeavours.
Koe, T. (2020b). *Immunity innovation: Gencor to study PEA's immune boosting effects via human trial*. https://www.nutraingredients-asia.com/Article/2020/03/19/Immunity-innovation-Gencor-to-study-PEA-s-immune-boosting-effects-via-human-trial.
Mak, T. M. W., Xiong, X., Tsang, D. C. W., Yu, I. K. M., & Poon, C. S. (2020). Sustainable food waste management towards circular bioeconomy: Policy review, limitations and opportunities. *Bioresource Technology, 297*, 122497. https://doi.org/10.1016/j.biortech.2019.122497
McEvoy, B., & Rowan, N. J. (2019). Terminal sterilization of medical devices using vaporized hydrogen peroxide: A review of current methods and emerging opportunities. *Journal of Applied Microbiology, 127*(5), 1403–1420. https://doi.org/10.1111/jam.14412. Blackwell Publishing Ltd.
Mcfadden, E., Ramos, A.-L. C., Bradley, D., Vrain, O., Mcevoy, B., Rowan, N. J., & Student, P. (2016). Comparative studies on the novel sterilization of Irish retailed infant milk formulae using electron beam and pulsed light treatments. *International Journal of Science, Environment and Technology, 5*(6), 4375–4377.
Mordorinelligence. (2020). *Smart waste management market | growth, trends, and forecast (2020 - 2025)*. https://www.mordorintelligence.com/industry-reports/smart-waste-management-market.
Munekata, P. E. S., Domínguez, R., Budaraju, S., Roselló-Soto, E., Barba, F. J., Mallikarjunan, K., Roohinejad, S., & Lorenzo, J. M. (2020). Effect of innovative food processing technologies on the physicochemical and nutritional properties and quality of non-dairy plant-based beverages. *Foods, 9*(3). https://doi.org/10.3390/foods9030288. MDPI Multidisciplinary Digital Publishing Institute.
Murray, N., Buckley, J., Seery, N., & Rowan, N. J. (2019). *Blending immersive and educational technologies to inform sustainability and diversification of workforce training through machine interface learning using sterilization technologies as model - quo vadis?*. https://research.thea.ie/handle/20.500.12065/3280.
Murray, I. M. T., Rowan, N. J., McNamee, S., Campbell, K., & Fogarty, A. M. (2018). Pulsed light reduces the toxicity of the algal toxin okadaic acid to freshwater crustacean Daphnia pulex. *Environmental Science and Pollution Research, 25*(1), 607–614. https://doi.org/10.1007/s11356-017-0472-6
Nagarajan, J., Krishnamurthy, N. P., Nagasundara Ramanan, R., Raghunandan, M. E., Galanakis, C. M., & Ooi, C. W. (2019). A facile water-induced complexation of lycopene and pectin from pink guava byproduct: Extraction, characterization and kinetic studies. *Food Chemistry, 296*, 47–55. https://doi.org/10.1016/j.foodchem.2019.05.135
Naughton, S., Kavanagh, S., Lynch, M., & Rowan, N. J. (2020). Synchronizing use of sophisticated wet-laboratory 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, 526*, 735377. https://doi.org/10.1016/j.aquaculture.2020.735377
Naughton, J., Tiedeken, E. J., Garvey, M., Stout, J. C., & Rowan, N. J. (2017). Pulsed light inactivation of the bumble bee trypanosome parasite Crithidia bombi. *Journal of Apicultural Research, 56*(2), 144–154. https://doi.org/10.1080/00218839.2017.1289668
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. *The Science of the Total Environment, 692*, 209–218. https://doi.org/10.1016/j.scitotenv.2019.07.243
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. *The Science of the Total Environment, 706*, 136044. https://doi.org/10.1016/j.scitotenv.2019.136044
Rahmanian, N., Jafari, S. M., & Galanakis, C. M. (2014). Recovery and removal of phenolic compounds from olive mill wastewater. *JAOCS, Journal of the American Oil Chemists' Society, 91*(1), 1–18. https://doi.org/10.1007/s11746-013-2350-9
Reid, G., O'Beirne, N., & Gibson, N. (2020). *How to reshape results during the COVID-19 crisis | E.Y. - Ireland*. https://www.ey.com/en_ie/transactions/companies-can-reshape-results-and-plan-for-covid-19-recovery.
Rizou, M., Galanakis, I. M., Aldawoud, T. M. S., & Galanakis, C. M. (2020 Aug). Safety of foods, food supply chain and environment within the COVID-19 pandemic. *Trends in Food Science & Technology, 102*, 292–299. https://doi.org/10.1016/j.tifs.2020.06.008
Roselló-Soto, E., Barba, F. J., Parniakov, O., Galanakis, C. M., Lebovka, N., Grimi, N., & Vorobiev, E. (2015). High voltage electrical discharges, pulsed electric field, and ultrasound assisted extraction of protein and phenolic compounds from olive kernel. *Food and Bioprocess Technology, 8*(4), 885–894. https://doi.org/10.1007/s11947-014-1456-x
Roselló-Soto, E., Galanakis, C. M., Brnčić, M., Orlien, V., Trujillo, F. J., Mawson, R., Knoerzer, K., Tiwari, B. K., & Barba, F. J. (2015). Clean recovery of antioxidant compounds from plant foods, by-products and algae assisted by ultrasounds processing. Modeling approaches to optimize processing conditions. *Trends in Food Science & Technology, 42*(2), 134–149. https://doi.org/10.1016/j.tifs.2015.01.002. Elsevier Ltd.
Rowan, N. J. (2019). Pulsed light as an emerging technology to cause disruption for food and adjacent industries – quo vadis? *Trends in Food Science & Technology, 88*, 316–332. https://doi.org/10.1016/j.tifs.2019.03.027. Elsevier Ltd.
Rowan, N. J., & 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. *The Science of the Total Environment, 725*, 138532. https://doi.org/10.1016/j.scitotenv.2020.138532
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., Méndez-Paz, D., Iglesias-Parga, X., … Aldaco, R. (2020). Addressing challenges and opportunities of the European seafood sector under a circular economy framework. *Current Opinion in Environmental Science and Health, 13*, 101–106. https://doi.org/10.1016/j.coesh.2020.01.004
Schuelke-Leech, B. A. (2018). A model for understanding the orders of magnitude of disruptive technologies. *Technological Forecasting and Social Change, 129*, 261–274. https://doi.org/10.1016/j.techfore.2017.09.033
Sharma, P., Gaur, V. K., Kim, S. H., & Pandey, A. (2020). Microbial strategies for bio-transforming food waste into resources. *Bioresource Technology, 299*, 122580. https://doi.org/10.1016/j.biortech.2019.122580
Stegmann, P., Londo, M., & Junginger, M. (2020). The circular bioeconomy: Its elements and role in European bioeconomy clusters. *Resources, Conservation and Recycling X, 6*. https://doi.org/10.1016/j.rcrx.2019.100029. Elsevier B.V.
Suanda, J., Cawley, D., Brenner, M., Domegan, C., & Rowan, N. (2018). Identification of behavioural change strategies to prevent cervical cancer among Malay women in Malaysia. *Social Marketing*, 555–566. https://doi.org/10.4324/9781315648590-34. Routledge.
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*(3), 28. https://doi.org/10.3390/fishes3030028
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*, (7), Article e5281. https://doi.org/10.7717/peerj.5281
Taufek, N. M., Harith, H. H., Abd Rahim, M. H., Ilham, Z., Rowan, N., & Wan-Mohtar, W. A. A. Q. I. (2020). Performance of mycelial biomass and exopolysaccharide from Malaysian Ganoderma lucidum for the fungivore red hybrid Tilapia (Oreochromis sp.) in Zebrafish embryo. *Aquaculture Reports, 17*, 100322. https://doi.org/10.1016/j.aqrep.2020.100322
Wesana, J., Gellynck, X., Dora, M. K., Pearce, D., & De Steur, H. (2019). Measuring food losses in the supply chain through value stream mapping: A case study in the dairy

sector. *Saving Food*, 249–277. https://doi.org/10.1016/b978-0-12-815357-4.00009-2. Elsevier.

Wong, W. H., Lee, W. X., Ramanan, R. N., Tee, L. H., Kong, K. W., Galanakis, C. M., Sun, J., & Prasad, K. N. (2015). Two level half factorial design for the extraction of phenolics, flavonoids and antioxidants recovery from palm kernel by-product. *Industrial Crops and Products, 63*, 238–248. https://doi.org/10.1016/j.indcrop.2014.09.049

Zinoviadou, K. G., Galanakis, C. M., Brnčić, M., Grimi, N., Boussetta, N., Mota, M. J., Saraiva, J. A., Patras, A., Tiwari, B., & Barba, F. J. (2015). Fruit juice sonication: Implications on food safety and physicochemical and nutritional properties. *Food Research International, 77*(77), 743–752. https://doi.org/10.1016/j.foodres.2015.05.032