COVID-19 Threats and Opportunities: Toward a Circular and Resilient Bioeconomy

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Introduction: COVID-19 Crisis, Setting the Scene

On January 2020 a previously unknown virus, then named SARS-CoV-2, was identified in China. A few weeks after, an outbreak, later defined by the World Health Organization (WHO) as a pandemic, put to test the healthcare systems of both advanced and developing countries. Lockdown measures were enforced to slow down the spread and mortality of the infectious disease. As a result, people have been forced to stay at home, and businesses to shut down (except essential ones). This means that a symmetric shock on both demand and supply occurred, and in some sectors, it is still ongoing, with important disruptions in the world economy.

Due to the emergence of other global issues such as the war in Ukraine, the pandemic seems to be losing relevance; however, COVID-19 is still not over. Even when many countries have reduced or fully removed containment measures, risks derived from the emergence of new variants, new waves of contagion, challenges derived from the first shocks of the pandemic, and the application of zero-COVID policies are still posing pressures on the economies around the world, particularly in terms of global trade.

The pandemic also unfolded in unexpected ways due to different factors such as the emergence of new SARS-CoV-2 variants, the speed of vaccination around the globe, the diverse lockdown regulations, and other public health measures in countries. Although these factors impacted on a different scale in each country, the global economy has been under pressure since the emergence of the virus,

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leaving behind many uncertainties about the economic recovery after the shock. The COVID-19 pandemic caused a contraction of 3.3% in global economic activity in 2020 (International Monetary Fund 2021). The nature of these shocks has been unique, leading primarily to a reduction of labor supply and a curtailment of mobility and social interactions. Workplace closure disrupted supply chains and lowered productivity. On the other hand, consumers' demand has been fluctuating as a result of uncertainty and changes in incomes.

After the contraction of the economy in 2020, the estimated global growth rose 5.5% in 2022. This recovery, however, has not been globally equal as emerging markets and developing economies are going through slower recoveries compared to advanced economies (The World Bank 2022b). With new global challenges such as the Ukraine war, the projections for global growth and economic recovery are still unknown for the upcoming years.

There is yet much uncertainty caused by the pandemic due to the potential long-term repercussions on supply chains, shocks in financial markets, changes in consumption, and other factors. In addition, there are still important risks derived from the pandemic to consider such as the appearance of new variants, and the effects of the implementation of zero-COVID policies in countries like China, which could lead to a reduction in global demand and keep disruptions in supply (Organisation for Economic Co-operation and Development 2022b).

The International Labour Organization (ILO) has reported that for 2020, the global decline in the employment rate was unprecedented; compared to 2019, 2.2% of global working hours were lost, corresponding to 255 million full-time jobs meaning that disruptions in the labor market were greater than those related to the global financial crisis 2009 (International Labour Organization 2021). As a consequence of this decline in incomes, the impact of COVID-19 has been posing challenges to the "ending poverty by 2030" goal of the 2030 Agenda: global poverty has increased from 7.8% to 9.1% according to some estimates (Sánchez-Páramo et al. 2021). The adverse impacts of COVID-19 could result in poverty levels similar to those recorded 30 years ago, in 1990 (Sumner et al. 2020). Furthermore, evidence suggests that the negative effects of the pandemic on the economy will be more severe for emerging economies since data have shown that the recovery of advanced economies has been faster compared to middle- and low-income countries. (The World Bank 2022a).

Available data show how the COVID-19 pandemic has been different from previous pandemics, as they did not involve to such extent as many countries as this one. Considering also that the outbreak started in China, the world's leading manufacturer, disruptions in the supply of intermediate goods in different industries caused further disruptions in production and supply chains (Gopinath 2020). As the virus spread across the world, it heavily affected the world economy. The disruption of supply and demand, manufacturing activities, and exports in large economies also affected all nations. In addition, the manufacturing sector was disrupted in three ways: (i) direct supply disruptions which hindered production, (ii) supply chain contagion which amplified the supply shocks, and (iii) demand disruptions (Baldwin and Di Mauro 2020).

The economy was also affected by disruptions in the private sector. According to Ivanov (2020), 94% of Fortune 1000 companies reported supply chain disruptions at the beginning of the pandemic. These disruptions, although less severe, have been long-lasting and subject to a "ripple effect" propagation and simultaneously affecting supply, demand, and logistics infrastructure. The International Monetary Fund (IMF) suggests that supply disruptions cut approximately in 0.5–1% the global GDP growth in 2021, while adding 1% to core inflation (2022).

In terms of international trade, from the beginning of the pandemic in 2020 until 2022, many fluctuations have occurred, starting with a great decline of 9% of total global trade in the first half of 2020 and followed by a fast recovery in the second half of the same year (United Nations 2022). Even though many countries have eased the COVID-19-related restrictions, the long-lasting effects of these measures are impacting trade activities. The World Trade Organization (2022) still foresees a slower recovery in merchandise trade volume for 2022.

If banks and financial institutions this time did not appear to be at the heart of the crisis, they have been anyway involved in the process of sustaining other firms, which have been hugely affected both in terms of confidence and liquidity (Baldwin and Di Mauro 2020). Firms have to pay wages and debts, whereas families have to pay rents and mortgages: bankruptcies and insolvencies could finally lead to a financial catastrophe. That is why governments, such as the Italian one, intervened with drastic fiscal and welfare measures to alleviate the economic burden that lockdown measures cause, especially in favor of SMEs, which are the most exposed to liquidity issues.

Some studies have shown how small businesses are more financially fragile: larger firms entered the crisis with the capacity of covering expenses for up to 65 days, compared to 50 days for a microenterprise (The World Bank 2022a; Bartik et al. 2020). In addition, some sectors were more vulnerable creating a different expectation of survival depending on the sector: retail, accommodation, food services, arts, and entertainment were among the most vulnerable ones. It is clear, therefore, that this crisis is complex in various ways and that it is leaving a mark in micro- and macroeconomic terms. As Baldwin and Di Mauro pointed out, companies, individuals, and governments experienced disruptions that may eventually lead to deglobalization (2020). Companies are experiencing the risks that global supply chains involve; financial intermediaries and regulators will incorporate pandemic shocks into their future risk assessments and stress tests.

As exposed by a recent study, network interconnectedness, economic openness, and transport integration were key determinants in the early global temporal spread of the pandemic (Tsiotas and Tselios 2022). Hence, countries that are more integrated into the globalized economic structure—those with higher economic openness—were earlier exposed to the COVID-19 outbreak compared to those with lower economic openness.

An additional complexity experienced during the pandemic is the one related to energy sources. Traditional energy resources, such as fossil fuels, were hit hard: the crude oil market was the most affected one. Generally speaking, the collapse in economic activity and transport led to widespread declines in commodity prices, not only in the energy field but also in secondary sectors such as metal and food. This also puts uncertainty on the potential long-term repercussions on clean technologies: in 2009, new venture capital and private equity investments in clean energy companies were down 56% compared to 2008 (Foray et al. 2020). Some countries might even loosen environmental regulations to favor economic recovery (i.e., China). The recalled plunge in the price of a barrel of crude oil could also make renewable energies less profitable, therefore reducing financial incentives for investments.

Since the pandemic-induced crisis could be long-lasting, new economic solutions might have to be considered. The current economic model focused on a linear and globalized production scheme has been put under high stress, as mentioned above. Supply chain disruptions, slower economic recovery in developing regions, and zero-COVID policies in countries like China are evidence that some crises are still being faced by economic systems and that some risks persist.

As the OECD affirms, the spread of COVID-19 raised awareness of the consequences of a lack of resilience and preparedness to deal with pandemics; in the future, climate change, water pollution, deforestation, and illegal wildlife trade may increase the risk of further pandemics. The organization stresses the importance of continued investment in economic transformations and technological innovations, notwithstanding the need for swift economic recovery; the various stimulus packages which States are implementing could be a timely opportunity to favor a more sustainable and environmental-friendly economy—encouraging at the same time a resilient recovery.

Even when the challenges are significant, this crisis creates opportunities to accelerate a transition toward sustainability by implementing changes in current lifestyles, health systems, environmental conservation, and new economic policies to stimulate investments aligned with these objectives. Considering that economic policy is a matter of choice, the current crisis can be overtaken in many ways and with different long-term goals. On the other hand, as the trade-off between economic recovery and sustainable growth might not be aligned, there are risks that can be counterproductive. The European Council, on 26th March 2020, while addressing the response to COVID-19, stressed the need for coordinated action and integration of green transition and digital transformation in the EU recovery plan. As stated by Tjisse Stelpstra, "*the devastating situation created by COVID-19 must bring all policymakers together and be the wake-up call for a new economic model that places social wellbeing and environmental sustainability at the core of the EU's economic recovery*" (European Committee of the Regions 2020). Considering that the circular economy model is gaining momentum in the EU, also being supported by funds, policies, and an increase in related jobs, it can be one pivotal element for this recovery.

COVID-19 as a Sustainability Driver: An Analysis of Emerging Challenges

The debate on the origin of the SARS-CoV-2 is still inconclusive. Some studies state that the virus has a zoonotic origin (Morens et al. 2020), while other views suggest that the virus was engineered (Borsetti et al. 2021; Harrison and Sachs 2022). Although further investigation is needed to clearly understand the origin of the virus, some important lessons can be learned from how the pandemic evolved, how economic and social systems were affected by it, and from the responses to these impacts.

The extent to which humans have transformed and exploited natural resources creates greater risks for the emergence of more frequent and severe animal-to-human zoonosis which can eventually evolve into viral epidemics (United Nations Environment Programme 2020). This risk estimation is based on the fact that more than 70% of infectious diseases that emerged in humans since the 1940s can be traced back to animals, above all wildlife, including SARS and associated coronavirus (Food and Agricultural Organization 2017, 2018; Jones et al. 2008).

One of the catalysts for the emergence of new epidemics is the current food system. On the one hand, current food systems are based on a large-scale production scheme, representing a threat of spillover infections since intensive livestock production amplifies the risk of diseases because large numbers of animals are confined in small spaces, with narrowing genetic diversity and fast animal turnover. On the other hand, habitat destruction, unchecked urbanization, and land grabbing lead to amplified human–wildlife interaction, which eventually causes zoonotic spillover (International Panel of Experts on Sustainable Food Systems 2020). Hence, the COVID-19 pandemic can help to redefine the relationship between humans and wildlife.

Another factor that aggravates the negative effects of COVID-19 and that simultaneously represents a threat to sustainability is urbanization. Thirty-five years ago, more than 60% of the world's population lived in rural areas: it has now dropped to 46%, while the urban population is set to grow up to 68% by 2050 (Food and Agricultural Organization 2017). Cities are already consuming 75% of the world's natural resources (Ellen McArthur Foundation 2017) and 78% of the energy supply (United Nations 2021). Concerning resource demand, some studies have shown how urbanization also impacts food consumption patterns since it increases the demand for processed and animal source foods (Food and Agricultural Organization 2017). As an example, China, the alleged epicenter of this disease, has one of the highest urbanization rates in the world, having doubled its level in the last 40 years, from 22.7% to 54.4% (Wu et al. 2017). This process is strictly linked to rising animal protein consumption (due to higher wages), increased land conversion and livestock production, a higher zoonotic risk (due to closer contact with wild animals), and finally a rapid spread of pathogens through the globalized channels of the world economy.

COVID-19 has also highlighted the negative effects that urbanization represents in terms of health. Cities are frequently places with high levels of pollution. They are responsible for 60–80% of greenhouse gas emissions. Pollution levels have been proven to cause several health issues such as lung and heart damage, which are responsible for seven million early deaths every year; additionally, city inhabitants with pre-existent respiratory conditions became more vulnerable to COVID-19 (Avetisyan 2020). So far, several studies have investigated the relationship between the spread and severity of COVID-19 and air pollution. Although research on this matter is still inconclusive, several studies (Piscitelli et al. 2022; Becchetti et al. 2022) have observed an association between air quality and COVID-19.

The link between pollution and COVID-19 contagion might simply rest in high urbanization and industrialization, where air quality is poorer and everyday human contact is frequent. According to the Italian Superior Health Institute (Settimo et al. 2020), the complexity of the phenomenon, together with inconclusive knowledge of certain factors that have played a role in the transmission and spread of SARS-CoV-2 infection, makes it difficult to establish a direct association between high levels of air pollution and COVID-19 outbreak or its amplifying role in the infection. Nonetheless, some researchers sustain that particulate matter can act as carriers of chemical and biological contaminants, such as viruses. Moreover, particulate matter (PM) could also work as a substratum that keeps the virus in the air for a longer time and as a booster of contagion (Setti et al. 2020). It has been suggested that there is an association between PM and virus spread: pre-existing levels of PM10, PM2.5, and NO2 are positively correlated with COVID-19 contagion and mortality (Becchetti et al. 2022; De Angelis et al. 2021). Finally, other studies observed that chronic exposure to air pollution is associated with COVID-19 morbidity and mortality (Barnett-Itzhaki and Levi 2021).

One more aspect that the COVID-19 pandemic has revealed issues in our current ways of living and our relationship with nature is consumption. The pandemic caused unprecedented changes in consumption habits. It was evident that individual actions can jeopardize the system stability and this was the case for basic goods consumption. As for the immediate reaction to the crisis, when people knew about forced lockdown measures, they rushed to groceries stores to fill their home shelves. In a report dated March 2020, the Institute of Services for the Agri-Food Market (2020) showed that panic buying was the first instinctive reaction. Worldwide supermarket shelves were emptied of key food and nonfood items, such as pasta, rice, canned goods, flour, frozen foods, bottled water, hand sanitizers, hand soap, and toilet paper (Hobbs 2020).

Cities are already responsible for 50% of global waste production (Ellen McArthur Foundation 2017) and even when in 2020 plastic use for large-scale plastics-using sectors—e.g., vehicles, trade, and construction—declined due to the slowdown in economic activities, the production of plastic waste rose significantly in other sectors such as healthcare and packaging (Filho et al. 2021; Organisation for Economic Co-operation and Development 2022a). Changes in habits, such as lockdowns, increased online shopping, and delivery services, increased the plastic waste generation in households (Filho et al. 2021). COVID-19 increased healthcare waste volume in facilities up to 10 times; the volume of waste generated is estimated to be around 87,000 tons only for personal protective equipment (World Health Organization 2022). At the same time, the pandemic caused important disruptions in plastics recycling due to difficulties in separate collection processes, the shift toward single-use plastics, and the low competitiveness of recycled plastics associated with low prices of primary raw materials (Organisation for Economic Co-operation and Development 2022a). Altogether, these factors have exacerbated the already existing pressure on the environment derived from plastic waste pollution.

In the longer run, global consumers might change their habits in two main senses. The first one is the rapid growth of online delivery: while many big companies had already implemented this service, their systems struggled to cope with the sudden expansion in online orders, leaving long time lags before delivery slots were available (Hobbs 2020). From a second stance, local supply chains might also have known a revived interest by consumers. For instance, interest in local consumption is an already established trend as people perceive economic, social, environmental, and health benefits to the higher resilience of local supply chains. Some cities have already developed strategies to promote new businesses to encourage local SMEs during the economic recovery. However, long-lasting effects are still unknown since many goods rely on global supply chains and localized chains, such as food, are still less cost-efficient than globalized ones (Hobbs 2020).

Only time will tell if the many changes induced by this crisis will be long-lasting or not: surely, it exposed the need for a systemic change, putting health at the center of society. Some speak about "Health in All Policies," meaning that besides sustaining the healthcare itself, States should think about promoting health in every aspect of people's life (Mundo et al. 2019). Moreover, policymakers and businesses should reconsider at least some of the foundations of the economic system—putting sustainability at the core of the new economic development model and therefore rethinking global value chains (Rethinking Value Chains Collective 2016) toward a model where workers, small farmers, and communities have access to the social, economic, and environmental resources they require for a decent standard of living while preserving and regenerating natural ecosystems.

Striving for Solutions: An Agenda Toward Circular Bioeconomy in the Post-COVID-19 Era

As discussed in previous sections, the negative effects derived from the still ongoing COVID-19 pandemic have been intensified by our current globalized system, causing alterations in both production and consumption activities, leading to relevant issues such as financial shocks, environmental burdens, and increased levels of inequality and poverty. Hence, from this experience, there are several points to remark to use the COVID-19 pandemic as a turning point to set a path toward sustainability. The need to react to the COVID-19 crisis is a unique catalyst to transition to a more sustainable economy, where wellbeing and Pareto optimality are reconsidered through new lenses. Putting forward a new economic model requires transformative policies, purposeful innovation, access to finance, risk-taking capacity, and new and sustainable business models and markets. But above all, we need to address the past failure of our economy to value nature, because our health and wellbeing fundamentally depend on it (McGlade et al. 2020).

The turning point is necessarily a rethinking of the ruling linear economic model, the so-called "take-make-dispose" system—where resources and product value are not optimized—to a more sustainable one. The problem with this linear economic model is that it causes an irreversible autocatalytic process, where an increase in consumer demand causes an increase in industrial production which results in reduced costs and therefore a lower perceived value of products by consumers (Clark 2017). Once the value of a product is lowered, its usefulness is short-lived, and the desire to dispose of it greatly increases, leading to the widely adopted replacement before redundancy. Therefore, with this model, sustainability can never be achieved, since traditional, fossil-based resources are becoming ever more scarce and expensive, especially as most of the readily accessible fossil-based resources have already been extracted, leading to the need for much more energy-intensive and expensive processes to obtain them. In addition, the disposal of huge volumes of goods has led to a large accumulation of waste in landfill sites and uncontrolled release into the environment, with the worryingly vast quantities of plastics accumulated in the seas and oceans being a prime example of this (Attard et al. 2020).

Pursuing a recovery from COVID-19 based on a circular bioeconomy is possible since it represents a framework to rethink and reform our relationship with the land, food, health, living spaces, and industrial systems to achieve sustainable wellbeing in harmony with nature. After the crisis, we are more aware of the fragility of natural and economic systems. For this reason, the implementation of new ways of development based in more shock-resistant communities needs to be supported by new paradigms such as the circular bioeconomy. All these changes require shared responsibility from governments, financial aid, and the creation of new opportunities for recovery.

With this aim, the *NextGenerationEU* recovery program, released in 2021, aims to support the recovery from the coronavirus crisis to create "a post-COVID-19 EU that is greener, more digital, more resilient and better fit for the current and forthcoming challenges" (European Commission 2021). The program aims to tackle important issues to support the green transition, foster investments, strengthen human capital, advance digital transition, and support an open strategic autonomy. This ambitious agenda requires the cooperation and interaction of multiple stakeholders to reach a sustainable recovery from the COVID-19 pandemic.

The European Union had already laid out strategic plans to implement a circular economy that can continue to help the COVID-19 recovery process. The EU Commission focuses on three phases—production, consumption, and waste—of a product's life. A better design can make products more durable or easier to repair, away from the usual linear pattern of "take-make-use-dispose" which discourages circularity. Indeed, 80% of products' environmental impacts are determined at the design phase (European Commission 2022a). COVID-19 is an example of how unintended waste generation can be dangerous. With the pandemic, there has been a rise in the demand for medical protective equipment, much of this made of plastic. An opportunity for reducing consumption and waste generation of this type of waste can emerge by following the abovementioned principles. Some studies have already indicated the environmental benefits of adopting ecodesign principles for the reduction of environmental impact in this field (Morone et al. 2022) particularly in the masks' use and disposal.

The EU has enacted the "Ecodesign Directive" to enhance sustainability principles such as improving durability, increasing recycled content in products, enabling remanufacturing and high-quality recycling, and incentivizing product-as-a-service or other models where producers keep the ownership of the product or the responsibility for its performance throughout its lifecycles (European Commission 2022b). In addition, the Commission highlights that even when smartly designed, products could lead to the inefficient use of resources and waste generation during their processing. For this reason, it promotes best practices in various industrial sectors through BREFs (Best Available Technique Reference Documents) and by promoting innovative industrial processes.

A first step would be overcoming fossil fuels as the primary resource of our economy and substituting them with biomass: a "bio-based" economy where materials, chemicals, and energy are derived from renewable biological resources (McCormick and Kautto 2013). The linear model involves extracting raw materials from nature, producing the desired products, and disposing of them. Waste generated during the production stage is also treated and discharged to nature. The circular economy involves using this waste for producing energy or raw materials for other products. It also includes the recovery of valuable components from discarded products as well as the regeneration of resources in the case of biomass (Moula et al. 2017).

The second step, consumption, is equally relevant, considering how it can affect businesses' marketing choices. At the same time, consumers' choices are based on the information they can access, the range and prices of existing products, and the regulatory framework. For this reason, the Commission is trying to improve the reliability of "green labels," starting from the EU Ecolabel. In a way, it also intends to "extend" the consumption of products, through reuse and repair thanks to legal guarantees and the compulsory availability of spare parts and repair information as opposed to planned obsolescence. Moreover, the Commission sustains innovative forms of consumption, such as sharing products or infrastructure, consuming services rather than products, and using IT and digital platforms. It also stresses the relevance of public procurement spending (20% of EU GDP), with the promotion of "Green Public Procurement" (GPP), where sustainable criteria are created at the EU level and then applied by national authorities.

Thirdly, waste management plays a crucial role in determining whether (and to what extent) resources are reused or instead are left out of the system. According to the Commission, only around 40% of the waste produced by EU households is recycled (with spikes from 80% to 5% depending on the area). Fields of action include increased recycling targets for packaging materials, raised levels of high-quality recycling, improved calculation of recycling rates, and administrative capacity. The EU is now restricting funds for landfills and incinerators while fighting the illegal transport of waste. When waste cannot be prevented or recycled, recovering its energy content is deemed as the best option.

In addition, the Commission aims at creating a market for secondary raw materials, which might be traded and shipped as any other good; nonetheless, uncertainty on their quality can hinder the market suitability. Recycled nutrients are seen as key secondary raw materials, as they can be returned to soils as fertilizers, reducing the need for mineral-based ones; however, a more comprehensive regulation is needed to ensure uniform quality standards. The Commission Action Plan also focuses on bio-based materials, which can be used for a wide array of products and energy uses such as biofuels. Indeed, the depletion of fossil fuels and the global environmental awareness push towards renewable bioresources and agro-industrial wastes for the production of alternative fuels in a sustainable manner.

Biomass sources are involved in numerous sectors and can provide different products and energy. Sectors of biomass include agriculture, livestock, forestry, pulp and paper, textile, and aquaculture. From the circular economy viewpoint, all these sectors generate waste and by-products useful as raw material for chemical or energy production in another sector, thus being interconnected (Organisation for Economic Co-operation and Development 2009). Circular economy might play a role in the sense that biomass conversion processes can utilize waste and by-products from plants and biomass activities as well as the recycled used products and wastes, thus reducing the environmental impacts of all the involved sectors from harvesting to product end life.

Additionally, within a circular economy model, biorefineries are the key to turning negative-valued waste into a potential renewable feedstock and are thus seen as a powerful alternative to replace petroleum-based refineries. Opposite to traditional refineries, biorefineries see a great opportunity in using biomass of non-edible feedstock or biogenic waste as raw materials to produce biofuels (Venkata Mohan et al. 2016). According to the EU Commission, biorefineries should adopt a cascading approach to the use of their inputs, favoring the highest value-added and resource-efficient products, such as bio-based products and industrial materials, over bioenergy. The principle of cascading use is based on single or multiple materials uses followed by energy use through burning at the end of life of the material, including taking into account the greenhouse gas emissions (GHG) mitigation potential. By-products and wastes from one production process are used to feed into other production processes or for energy. Biorefineries can thus contribute to the principles of a "zero-waste society" (European Commission 2012).

This way, an all-round "circular bioeconomy" could be implemented, overlapping a mere "circular economy" with a "bioeconomy" model: circular economy, indeed, is focused on strengthening resource efficiency and using recycled materials to reduce fossil carbon overuse; bioeconomy aims at substituting fossil carbon with renewable carbon from biomass agriculture, forestry, and marine environment (Carus and Dammer 2018). This is the core of the EU 2018 sustainable Bioeconomy

Strategy, which "*needs to have sustainability and circularity at its heart. This will drive the renewal of our industries, the modernization of our primary production systems, the protection of the environment and will enhance biodiversity*" (European Commission 2018, p. 4).

Circular economy is not complete without the bioeconomy and vice versa. The huge volumes of organic side and waste streams from agriculture, forestry, fishery, food, and organic process waste can only be integrated into the circular economy through bioeconomy processes, while the bioeconomy will hugely profit from increased circularity. New knowledge-based processes (such as biotechnology, algae, or insects for food and feed), new applications, and new links between bioeconomy and other industrial sectors are needed (Carus and Dammer 2018).

The bioeconomy can contribute in several ways to the circular economy, including the utilization of organic side and waste streams from agriculture, forestry, fishery, food, and organic process waste. Also, biodegradable products can be returned to the organic and nutrient circle. And paper, other wood products, natural fibers textiles, and many more materials can be successfully cascaded. Furthermore, innovative additives from oleo-chemicals can help enhance the recyclability of other materials. Once a certain threshold volume of new bio-based polymers is reached, the collection and recycling of bioplastics will become economically attractive (Carus 2017).

In this sense, the bio-based sector is key for the use of renewable biological resources and processes to substitute fossil-based products. Bio-based products go far beyond biomass processing. They capitalize on the unprecedented advances in life sciences and biotechnology (including microbiology, microbiomes, and enzyme technologies) that, coupled with the digital revolution, allow us to use nature's biological assets, its biochemicals and biomaterials, and its biomimetic assets (its functions and processes) to generate significant new sources of economic value and future revenue (Hetemäki et al. 2017).

The bio-based sector has seen huge advances in recent years. The interest in the transition from fossil to bio-based products has revitalized traditional sectors by bringing opportunities to diversify their products. Innovation capitalizes on the skills of making use of various biomass for bio-based production in traditional sectors such as pulp, woodworking, textiles, and wood-based construction. The pulp, paper, and board developed new cellulose-based applications that can replace fossil-based textiles and plastics and boost the use of nanofibril applications in bio-based adhesives, laminates, 3D printing and flexible electronics, and corrugated cardboard for the large-scale packaging business for Internet products. The revitalization of pulp, paper, and board has also brought solutions for the better utilization of their side streams for biofuel production and is also now seen increasingly in markets including fine and commodity chemicals, health care, automotive, consumer goods, construction, etc. Some low-tech products, such as composites, packaging materials, etc., have lower added value but also lower cost and risk; hence they are interesting for their large potential for replication in a diversity of regions and contexts (European Commission 2018). Therefore, advances in bio-based innovation enhance the circularity of the bio-based sector and the whole bioeconomy by enabling the processing of current side streams, residues, and wastes into products.

The technologies also enable biowaste and residues from farms and forest-based sectors, from cities, or from the food sector to be transformed into bio-based products such as chemicals, organic fertilizers, biofuels, and also heat and power, if a more circular use is not possible. The food-processing industries, for instance, are exploring the potential of converting residues into bio-based products such as chemicals and biofuels (Pagotto and Halog 2016; Stegmann et al. 2020) As Sillanpää and Ncibi (2017) highlight, when promoting biofuels, one should bear in mind that a balance with the food industry and world's food needs has to be found. The authors suggest that *"we could cultivate food crops for energy in marginal land and with marginal waters reclaimed from industrial or municipal wastewaters. The ethical issue is limited to the scenario where nonfood crop, with high energy output, are cultivated in arable lands and irrigated with fresh waters. Nowadays, with the threatening climate change impacts on agriculture, the serious shortages of water in many countries, and the recurring starvations and undernourishments in many others, it would be common sense (not to say humane) to prioritize feeding the population"* (p. 80).

New and more efficient ways of biomass processing are key for recovering complex molecules from biomass (e.g., polymers such as cellulose, hemicellulose, and lignin derivatives), for new product value chains, and to avoid the loss of value resulting from breaking complex biomolecules down. Greater value can also be obtained from unavoidable biological wastes and residues through the efficient collection and conversion technologies and systems, as well as through the development of upcycling technologies for them (Attard et al. 2020).

The development and deployment of biorefineries will depend heavily on the profit margins of bio-based products and the successful development and commercialization of new technologies, the availability of local and regional feedstock at competitive prices, suitable infrastructure and logistics, skilled personal, private, and public support services, and financing and permitting and fostered by a supportive policy and regulatory enabling environment (European Commission 2018; Yamakawa et al. 2018). Furthermore, a biorefinery requires a uniform, year-round, cost-efficient, and reliable supply of desired quality biomass feedstocks. The transport, storage, and handling of biomass require careful assessment to minimize investment risk associated with a biorefinery project. There are numerous sources of variability in the biomass supply chain such as weather uncertainty; seasonal seasonality, physical and chemical characteristics, geographical distribution, and low bulk density of biomass feedstocks; structure of biomass suppliers and their willingness to grow biomass crops; local transportation and distribution infrastructure; and supplier contracts and government policies (Sharma et al. 2013; Huang et al. 2010). To address these challenges, companies have to embrace resiliency and responsibility in supply chain management. The pandemic risk is just the last factor that drives the need for sustainable and resilient supply chains, as part of a broader bioeconomy.

Most supply chains are still linear in structure, with increased globalization of business operations meaning that product components are sourced worldwide. As observed during the critical period of the COVID-19 pandemic, global supply chains became fragile and affected a wide range of economic sectors. While closing the loop across global supply chains is still in its early stages and when implemented will involve high-value products, it seems that it is within regional and local loops that the majority of opportunities for the development of “circular supply chains” lie, because of the reduced geographic barriers. This is not surprising considering that circular economy takes its inspiration from the functioning of living systems where cyclical patterns are not only closed and thus waste is turned into food, but they are also local and decentralized (Nielsen and Müller 2009).

In addition, regional and local circular supply chains would be in line with the developing concept of redistributed manufacturing, which consists of reshoring large-scale manufacturing sites to more local, smaller ones. Redistributed manufacturing is crucial for creating a more sustainable manufacturing industry and is intertwined with the CE, with one city-based project analyzing the impact of localized and small-scale manufacturing plants on UK city resilience (Freeman et al. 2016). Circular supply chains expand the range of environmental and economic value that is created beyond those attainable within so-called closed-loop supply chains. Value creation stems from flowing materials across different supply chains. For instance, textiles can be designed without the use of chemical substances and when reuse is no longer possible, natural fibers can be used as secondary raw material serving insulation and filling purposes eventually returning to nature at the end of their useful life. Cascading materials across different supply chains creates additional revenue streams via selling secondary raw materials that can be used for the manufacturing of a different product and thus expanding further downstream a company’s supply chain (Christopher and Peck 2004; Antikainen and Valkokari 2016).

Circular supply chains also require a conceptual shift from products and ownership to access to services. These supply chains are not only closed-loop but also open concerning the opportunity for materials to flow across different supply chains, and within technical and biological cycles. New product development processes therefore should involve suppliers as part of early supplier involvement, looking at new ways to extend product life through additional services and finding different uses for products as they reach the end of the cascade. In the end, the way products and supply chains are designed will reduce the demand for recycling, although a prolonged period of transition involving the accommodation of traditional waste-based thinking is reasonably expected before the full benefits of circular systems can be effective.

Policy Agenda and Final Remarks

The need for a shift in the current world economy, as seen above, is ever more urgent. The COVID-19 crisis might boost the efforts in shifting towards a sustainable economic model aligned with the 2030 Sustainable Development Goals. Hence, circular bioeconomy becomes a good strategy to overcome the challenges that the COVID-19 pandemic has posed in economic, ecological, and societal structures. However, these strategies should not take sustainability as a given, but rather address it explicitly. There have already been concerns about possible side effects of the bioeconomy. Some researchers and NGOs have questioned its environmental sustainability, and have voiced concerns that it could lead to the exploitation of EU forests at the cost of biodiversity or that bioenergy may in the short-term cause more CO2 emissions (European Academies Science Advisory Council 2017).

These views are important to consider, especially given sustainability problems experienced in the past. Science also has mixed views on these issues, and the impacts also depend very much on how bioeconomy development will be advanced and monitored. The objective should be to maximize the synergies and minimize the trade-offs between bioeconomy, biodiversity, and climate mitigation. A circular bioeconomy can help to support biodiversity and climate mitigation, and biodiversity and climate mitigation are necessary for a successful circular bioeconomy.

Research, development, and innovation have to strengthen the foundations of a circular bioeconomy, a goal that requires policymakers' intervention and long-term planning. In what follows we propose a three-bullet-point policy agenda and a final remark on its implementation.

First, funding needs to increase all along the innovation network (basic research, applied research, education, and piloting of new products and services). Green finance investments can have a pivotal role in creating the necessary ecosystem for a shift in the economic development model. The policies include two aspects: the reform and innovation of existing financial tools, an exploration of the type of fiscal policy and the feasible way to raise money for green finance development, and the reform of existing fiscal revenue management and distribution policy, namely the efficiency and direction in the use of fiscal funds (Wang and Zhi 2016; Owen et al. 2018).

Second, policymakers should be reviewing their subsidizing policies, converting environmentally harmful subsidies (EHSs) into environmentally friendly subsidies (EFSs): often incentives, exemptions, and benefits can be counterproductive or unbalanced. A study by the Italian Senate of the Republic reported in 2018 that 16.2 billion Euros were spent on EHSs, while only 15.7 on EFSs.

Third, product eco-labeling should be continuously addressed and updated by policymakers, as consumers' role in the shift towards sustainability is indispensable in both the short and the long run. In recent years, interest in environmental issues has increased, along with the idea that consumer choices can improve the performance of the production system as a whole (Iraldo et al. 2020). Policy and regulatory efforts should reinforce the perception of eco-labels as a signal of quality and value worth paying for, as well as ensure that eco-labeled products are indeed eco-friendly.

Indeed, policymakers and researchers should work closely to improve and enhance sustainability measurement and measurability. To elaborate effective policies, a feasible and reliable quantification of eco-friendliness and sustainability is pivotal. All along supply chains, data on environmental impact should be carefully collected and processed, giving policymakers an affordable picture of their decisions' benefits and inconveniences, and researchers better guidelines for future studies. These are the main fields of action in which policymakers, and all stakeholders in the economic system and society, should be engaged and actively committed to building a world run by sustainable principles and a bio-based circular economy.

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