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Bioeconomy and green recovery in a post-COVID-19 era

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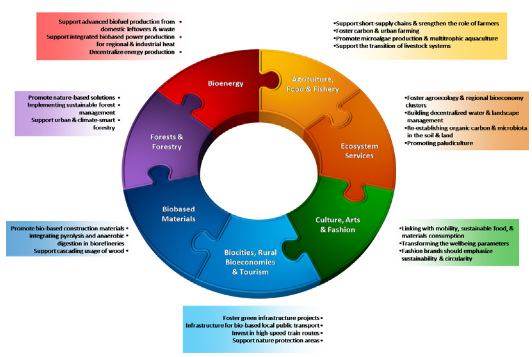
HIGHLIGHTS

- Explores how the bioeconomy can enhance the resilience of bio-based, food, and energy systems in the post-COVID-19 era
- Integrates innovations, environment, ecosystem services, "biocities", food, rural economies, and tourism
- Integrating culture, arts, and the fashion industry is underlined towards building a better bioeconomy
- Food systems should become more resilient to allow adapting rapidly to severe crises

GRAPHICAL ABSTRACT



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ABSTRACT

The spread of the COVID-19 pandemic has generated a health crisis and repetitive lockdowns that disrupted different economic and societal segments. As the world has placed hope on the vaccination progress to bring back the socio-economic "normal," this article explores how the bioeconomy can enhance the resilience and sustainability of bio-based, food, and energy systems in the post-COVID-19 era. The proposed recovery approach integrates technological innovations, environment, ecosystem services, "biocities," food, rural economies, and tourism. The importance of integrating culture, arts, and the fashion industry as part of the recovery is underlined towards building a better bioeconomy that, together with environmental safeguards, promotes socio-cultural and economic innovations. This integration could be achieved supporting communities and stakeholders to diversify their activities by combining sustainable production with decarbonization, stimulating private investments in this direction and monitoring the resulting impact of mitigation measures. Food systems should become more resilient in order to allow adapting rapidly to severe crises and future shocks, while it is important to increase circularity towards the valorization of waste, the integration of different processes within the biorefinery concept and the production of bio-based products and biofuels.

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Contents

1. Introduction

The COVID-19 outbreak in early 2020 has caused a devastating health crisis and global socio-economic disruption due to the repetitive lockdowns that restricted humans' activities. People, public authorities, and enterprises worldwide were not prepared for the sudden impacts of this rare "*Black Swan*" event (Rowan and Galanakis, 2020) in different sectors such as food, raw material provision, tourism, and others (Table 1). In particular, the pandemic affected the various actors in the production and distribution of food value chains, accelerating domino effects, e.g., scarcity of products due to panic buying, business bankruptcy due to lack of liquidity, cascading effect of restaurants' lockdown, and others (Fritsche et al., 2021). The drastic increase of teleworking combined with the shutdown of cultural activities (e.g., closure of cinemas, theatres, and stadiums) and numerous conferences and exhibitions restricted the food delivery substantially through restaurants and canteens. Simultaneously, people turned to home cooking, consumption patterns and amounts of food waste changed, leading to disruptions in the food supply chains (HLPE, 2020; CCRI, 2020). Some food factories and processing facilities (e.g., Germany, the US, and other countries) closed temporarily due to COVID-19 spread among workers (HLPE, 2020; Rizou et al., 2020).

The pandemic also had direct and indirect effects on bio-based products and the bioenergy sector, clearly linked to the fossil sector and the market disruption generated by COVID-19. For instance, the demand for alcohols and textiles increased rapidly due to the urgent need for disinfectants, facemasks, and sterile medical clothing manufacturing (Fritsche et al., 2021). A significant disruption in forest management and forestry sector activities has also been observed in some areas (Fritsche et al., 2020). Besides, the need for single-use packaging materials, wrappings, and plastics, which have already started to increase before the pandemic, shows a steady demand highlighting the dynamic for bio-based plastic alternatives in the future (Fritsche et al., 2021). Due to the restricted mobility and transport, the respective demand for fuels decreased and, in civil aviation, almost collapsed, though air freight increased. The pandemic's first wave reduced oil price even to negative values, triggered by projections that oil demand would fall by 8.4 mb/d up to the end of 2020 compared to 2019. This trend led to a lack of inland storage availability and led to almost 50 billion € write-downs during the second trimester of 2020 (IEA, 2020). US and EU oil majors have so far adopted different strategies. US companies sustain the conventional business (under Trump's Administration), while the European are more active in reducing fossil fuel consumption. Moreover, investments in innovative technologies for the bioenergy sector declined within 2020 due to the lower fossil fuel prices and the challenging economic environment (e.g., lower cash flows, reduced demand, higher debts, and decreased profits) (Fritsche et al., 2021).

Up to January 2021, the economies' transition in the post-COVID-19 era remains uncertain as the pandemic has not been controlled yet. By the end of the autumn of 2020, the so-called 2nd pandemic wave has reached most countries, causing a new cycle of horizontal lockdowns. Given the present uncertainties in distribution, acceptance, and efficiency of COVID-19 vaccination programs, the pandemic might continue up to the end of 2021, and a 3rd wave cannot be ruled out. Subsequently, the resilience of our food, energy, and material supply systems is at stake, and mitigation measures are widely debated. The experiences obtained from the previous "*Black Swan*" events of the last two centuries (e.g., the Spanish Flu of 1918–1920, and World War II) indicate that the societies resolve respective consequences with enormous creativity, adaptation to innovative pathways, and massive changes to tackle austerity (Rowan and Galanakis, 2020). The crisis had occurred when the flaws of the current systems of production, transformation, and consumption were already evident (Gerten et al., 2020). The exceptional measures taken to recover our economies from the crisis can be turned into opportunities for 'building back better' and fostering the transition to a new economic system (OECD, 2021). The pandemic has revealed the need to redesign the global systems to minimize their vulnerability and build on local self-sufficiency. This is vital to prepare for future crises in flows of food, energy, and other goods, and above all, place citizens' wellbeing and the planet at its heart (EC, 2020a).

We believe that the 'circular bioeconomy' concept can be a crucial component of this transition, based on a mix of disruptive social and technological and social innovations. The current article discusses how the bioeconomy can provide an outlet to the global economies to recover from the pandemic, increase resilience, and prepare for new "Black Swan" events in the future.

2. The role of bioeconomy for green recovery and resilience in the post-pandemic era

As nations organize vaccination plans to tackle the pandemic and apply recovery measures to foster their economies, society should focus on building resilience and maintaining ambitions for zero-carbon futures. This direction reinstates the circular bioeconomy and biobased products and services on the cornerstone of strategic decision making. This trend has been long pursued by the US Biopreferred program to spur economic development, create new jobs and provide new markets for farm commodities. The Program was designed by the 2002 Farm Bill and reauthorized and expanded as part of the Agriculture Improvement Act of 2018 (USDA, 2021). Just a couple of months before the COVID 19 outbreak, the European Union announced the European Green Deal's for a climate-neutral economy by 2050 (EC, 2019), which also acknowledges the shift from a linear bioeconomy to a circular bioeconomy and promotes changes in policy frames. China, Japan, and the Republic of Korea also announced similar climate-neutral economy plans within 2020 (Schiermacher, 2020). The US's new administration has also declared its intention to rejoin the Paris climate agreement immediately after the 2020 presidential election (Newburger, 2020).

A transition towards a circular bioeconomy could enhance resilience by valorizing domestic biomass resources and waste. However, although many researchers claim that the bioeconomy is circular by nature (Stegmann et al., 2020), it is of high importance to underline the "circularity"

Table 1
Impacts of the COVID-19 pandemic on the food systems, bio-based products, and bioenergy.

Sector	Impacts	References
Production and processing	• Lack of labor leading to production loss • Disruption of demand due to the lockdown of catering • Increased waste of perishable commodities that could not be stored for a long time • Loss of income for the farmers and unemployment of workers in the food industry	Galanakis, 2020 HLPE, 2020 CCRI, 2020
Food supply, logistics, and retailing	• Reduced input capacity and food availability • Reduced transportation routes and international trade flows • Disruption of wholesale markets and local availability • Rapid increase of e-commerce and bankruptcy of small retailers	Galanakis, 2020 HLPE, 2020 CCRI, 2020
Catering and Consumption	• Lockdown, forced inactivity leading disruption of demand and unemployment of workers • Loss of consumers' income and widening of inequalities • Panic buying • Price spikes and food insecurity for the most vulnerable citizens • Rapid increase in food delivery services • Direct communication of farmers with consumers • Change of dietary habits	Galanakis, 2020 HLPE, 2020 CCRI, 2020
Bioenergy supply	• Decreased demand for electricity • Slightly increased demand for renewable energy • Significantly reduced demand for diesel, gasoline, and biofuels in transportation • Reduced investments in the energy sector	Bioenergy Europe, 2020
Wood supply and forest management	• Delivery of wood only to major industries • Reduced or collapsed wood construction during the lockdown • Increased demand for "niche" products such as garden decking and furniture due to renovations during the lockdown • Significant increases in small roundwood paper and pallet production due to increased online shopping. • Restricted workforce activities due to reduced mobility of workers and social distancing during tree planting • Delayed responding to forest fires or disease outbreak	Fritsche et al., 2021 CEPF, 2020 Scottish Forestry, 2020
Chemicals and textiles	• Rapid increase of ethanol and alcohols demand used in disinfectants • Rapid rise in textiles (for facemasks) and sterile medical clothing demand • Rapid increase of demand for single-use plastics for wrappings and packaging materials	Fritsche et al., 2021 Berardi et al., 2020 Rowan and Laffey, 2021
Waste	• Increased demand for the recycling of clothes and furniture • changes in reuse and reduction practices, changes (increase and decrease in other cases) in waste flows from households,	Fritsche et al., 2021 Fan et al., 2021
Tourism	• Diminution of activities providing holiday • Disruption of recreation services	Fritsche et al., 2021 Rousseau and Deschacht, 2020

principles if we want to avoid business-as-usual. A circular economy requires minimizing waste, maintaining the value of products, materials, and resources for as long as possible (EC, 2015). Stegmann et al. defined circular bioeconomy as giving emphasis "*on the sustainable, resource-efficient valorization of biomass in integrated, multi-output production chains (e.g., biorefineries) while also making use of residues and wastes and optimizing the value of biomass overtime via cascading.*" (Stegmann et al., 2020). To ensure a rapid and simultaneously efficient transition, a combination of actions, multi-stakeholder collaboration, and increased financial resources must complement the already provided significant amounts of public and private funds worldwide mobilized through stimulus packages, promoting the sustainable circular bioeconomy (Fritsche et al., 2020). Moreover, supporting the small-scale local biorefineries should be a priority as they comply with rural development, and exploit opportunities for resource-efficient repayment chains and leverage, specific strengths within their respective, and settings (Panoutsou and Singh, 2020).

To facilitate the efficient green economic recovery, these should be sustained and further enriched with other nature-based solutions such as reforestation, agroecology, and interventions for low-carbon development, as recommended in most of the studies among the 130 ones revised by Burger et al. (2020). The additional stimulus can facilitate improvements in agricultural value chains that promote biodiversity and sustainable food systems. These include incorporation of artificial intelligence (AI) and Internet and Communication Technologies (ICT) in production, construction of low-energy buildings and protection of natural assets, and off-grid rural electrification, among others. New business models, new production and consumption patterns, new social norms, and new governance schemes could emerge. Emerging innovations could also support manufacturing and food industries in production (e.g., carbon farming, climate-smart forestry) and processing (e.g., automation of food production with robotics) systems (Fritsche et al., 2020). Besides, the decentralization of food systems and biorefineries (e.g., by utilizing smart specialization funding schemes that promote the model of "biocities") could secure smallholders, enterprises, farmers, and customers (Fritsche et al., 2020). Fig. 1 illustrates opportunities for the transformation of the bioeconomy in the post-COVID-19 era.

2.1. Agriculture, food & fishery

After controlling the pandemic waves, matching local demand and consumers' requirements with shorter food supply chains and active food assistance policies will be a fundamental challenge to eliminate uncertainties obtained by the exposure to systemic risks and the growth of the urban population (Pulighe and Lupia, 2020). Strengthening farmers' position in the value chain should become a priority, and policies that emphasize their inclusiveness must be implemented (EC, 2020b; U.S.Farm Bill, 2018; Agriculture and Agri-food Canada, 2019).

Agroecological practices should become usual practices among farmers and a key for transition to sustainable food systems. From rooftop agriculture to community gardening and vertical farming, urban agriculture could improve lives and contribute to green recovery by reducing urban areas' dependency on long-distance supply chains and enhancing consumers' education (Fritsche et al., 2020). The diversification of distribution systems and support of logistic infrastructures to keep added value on-farm will lead to a partial re-territorialization of food systems, providing local communities with a higher governance degree of the distribution system (Maréchal et al., 2020). Education, nutritional guidelines, and public procurement could also be mobilized to support the consumption of locally produced food and ensure sustainable and healthy diets.

Livestock farming systems use approximately 40% of the agricultural land (Mottet et al., 2017). Their transformation into integrated crop-livestock systems can play an essential role in the farming system's circularity since animals are fed with grass (biomass), which cannot be utilized in alternative ways, and improve soil fertility via manure (Van Zanten et al., 2019). The reform of the agricultural supply chains should promote "One Health" principles to eliminate the risks related to antibiotic resistance, control diseases that spread between animals and humans like (COVID-19 or flu), secure food safety, and reduce greenhouse gas (GHG) emissions (WHO, 2017). Besides, start-ups and existing businesses developing innovative products that redefine our consumption norms (e.g., plant-based proteins and other meat alternatives) are expected to grow their market shares over the next years (Galanakis et al., 2021). The fortification of foods with bioactive ingredients to consumers' immune system could also be a great opportunity (Galanakis, 2020), and the recovery of these compounds is nowadays conducted in the context of bioeconomy, valorizing

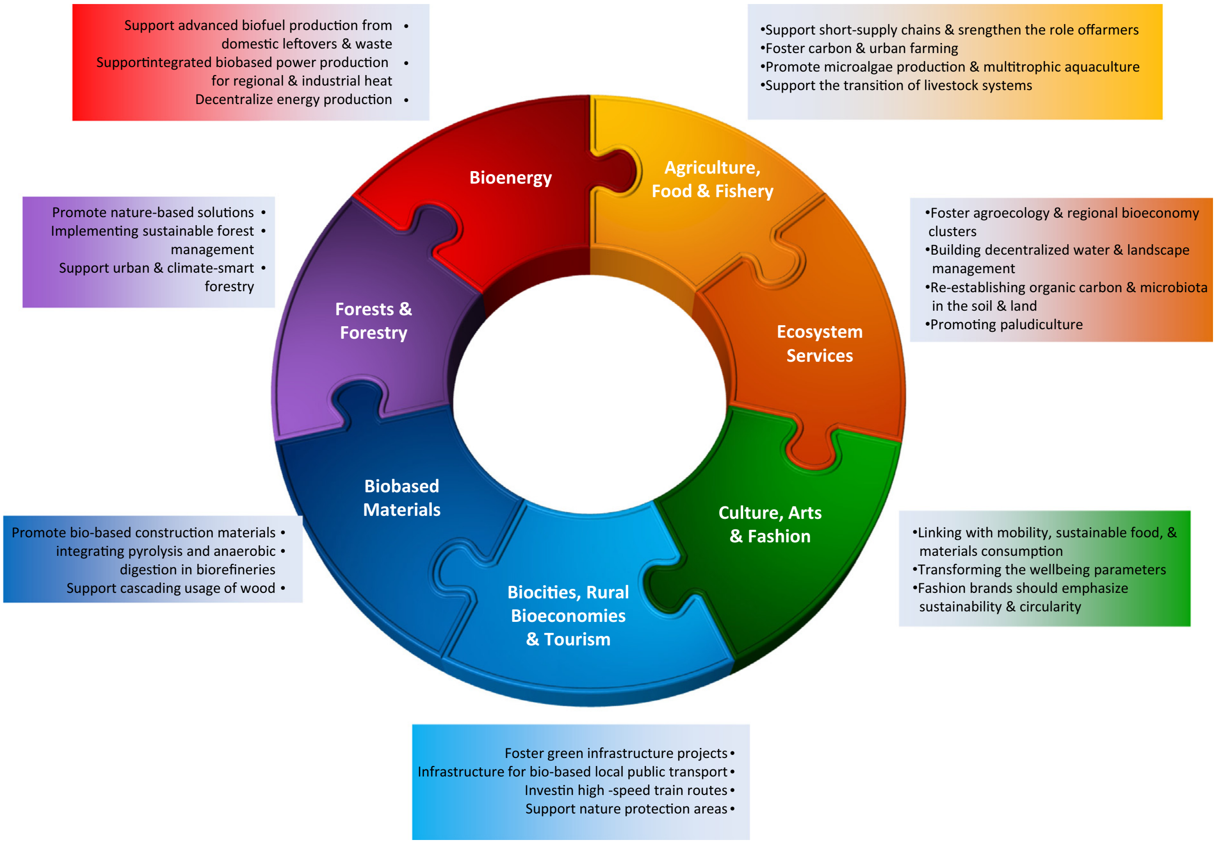

Fig. 1. Bioeconomy opportunities to support green recovery and enhance system resilience in the post-COVID-19 world.

sources like food processing by-products, fungi, and yeasts[1]. The "blue bioeconomy" could comprise a vital alternative to land-based animal feed and food. As the possibility of expanding the current fish supply remains limited, a sustainable "intensification" could come from aquaculture, e.g., microalgae cultivation and the development of multitrophic systems (Rowan and Galanakis, 2020; Fritsche et al., 2020).

2.2. Bioenergy

The current energy system mostly depends on fossil fuels, having an enormous impact on the environment and global economies. European countries are significantly dependent on energy imports (mainly oil, natural gas, and coal) as 58% of EU-28 energy was imported in 2018 compared to 47% imported in 2000 (Fritsche et al., 2021). Subsequently, the need for energy security and local resilience through low carbon solutions is prominent. Renewable energy from solar power and wind are intrinsically variable in time and available. Although it cannot replace thoroughly conventional fuels, bioenergy can provide stand-alone energy generation that will smooth the peaks related to the other forms of variable renewable energies. Through bioliquids and biofuels, it is nowadays strongly regarded as an ideal alternative for aviation, marine, and heavy-duty transports, sectors with fewer decarbonization options (Panoutsou et al., 2021) and offers system energy balancing services, as in district heating and electricity systems (Arasto et al., 2017). Moreover, facilitating energy security within the framework of the circular bioeconomy can be achieved through investments that prioritize local bio-based value chains (e.g., biofuel production processes) and promote supply from domestic regions (Lange et al., 2020).

The circular bioeconomy offers excellent possibilities to integrate biochemical and thermo-chemical processes in local biorefineries that can valorize residues and co-products of upstream routes, produce multiple biobased products, energy, and fuels; thus improving circularity[6]. This strategy would mitigate climate change and contribute to local resilience and rural socio-economic development (Panoutsou and Chiaramonti, 2020) by delivering higher biomass shares within target sectors, creating new permanent jobs, and mitigating raw material competition (Burger et al., 2020). Besides, biofuel's role in the markets can be even more critical if a higher penetration of electricity in transportation is achieved in the future. The EU Renewable Energy Directive II (REDII) addresses several of these issues but do not fully encompass the relevance of strategic storage and EU-based supply chains as probably needed to push the most-needed EU economic recovery (Chiaramonti and Goumas, 2019; Chiaramonti and Maniatis, 2020).

2.3. Bio-based materials

Despite the promotion of circular economy over the last years, industrial production remains too linear and mostly based on non-renewable resources. On a global scale, only a small percentage (12%) of the materials is derived from recycling. In contrast, non-metallic minerals such as sand or gravel account for around half of the extracted resources (IRP, 2019). Scalable innovations and viable technologies could be deployed to produce resource-efficient, circular, and low carbon solutions based on renewable energy and sustainability sourced bio-based materials. A good example is a first-ever car made of nanocellulose, a biomaterial five times lighter and stronger than steel, produced in Japan in 2019. New biomaterials, including bioplastics, hold tremendous promise due to their lower carbon footprint and biodegradability than petrochemical products (Panoutsou and Singh, 2020).

Wood-based products (e.g., wood-based textiles, nanocellulose, and bioplastics) represent a reservoir of sequestered carbon that could be used for textiles, furniture, fiber, and construction. An approach towards green recovery, climate change mitigation, and resilience in the post-pandemic world is valorizing woody biomass to produce a wide range of bio-based materials (Fritsche et al., 2020). New wood-based textiles have been reported to have a climate mitigation effect of 5 kg CO_2 per kg of product used compared to polyester (IPCC, 2019). Moreover, a shift to biomaterials (based on engineering wood or bamboo) could substantially reduce the number of materials used and our cities' carbon footprint while creating durable carbon pools (EC, 2015; Churkina et al., 2020). Using wood in construction has a climate mitigation effect of 2.4–2.9 kg CO_2 per kg of wood contained in products used compared to concrete (EFI, 2017) while also storing 1 ton of CO_2 in each m^3 of products. Building with wood is also more resource-efficient: It can reduce the total amount of materials used in construction by 50% (IPCC, 2019) and be a key priority in green recovery. However, the growth of biomaterial demand should not create additional pressure on natural resources. Cascading the use of biomass – which is a fundamental part of a circular bioeconomy – will contribute to reducing additional pressure on land for biomass (Fritsche et al., 2020).

The COVID-19 pandemic presented an opportunity to accelerate innovations for 3D-printed foods and relevant disposable objects, bio-based packaging, and composite wood materials (Rowan and Galanakis, 2020). Bio-based materials can also be generated by valorizing the organic fractions of waste and leftovers with different biorefinery approaches. These include biomass refining into bio-crude and ethanol through chemical or hydrothermal fragments rich in lignocellulosic components (Miliotti et al., 2019) and integrating pyrolysis and anaerobic digestion in cascading facilities to generate biochar and biomethane, respectively (Casini et al., 2019). Biomass cascading includes also preferring the utilization of wood to manufacture durable products that live longer, prioritizing the utilization of sawdust and chops (leftovers from the wood industry) for useful recycling purposes, such as the production of innovative products, and energy generation with combustion. This approach requires optimal forest management for wood processing, the utilization of wood products in service, and leftovers' valorization (Fritsche et al., 2021).

2.4. Forests and forestry

Terrestrial vegetation systems, particularly forests, stand at the crossroads between the three critical bioeconomy pathways of utilizing more biomaterials, better use of bioenergy, and securing ecosystem services, notably including terrestrial carbon sequestration. This presents risks and opportunities. Necessarily, harvesting in forests to meet demands for biomass must not be a driver for deforestation and must not exceed those forests' capacity to grow more biomass and so renew the losses. Sustainable forest management (SFM) also recognizes requirements to maintain soil and water quality, conserve biodiversity, protect habitats, and respect for local/indigenous communities. However, even meeting the highest SFM standards cannot necessarily address all the goals of bioeconomy development. An increased intensity of harvesting in forests can negatively impact forest carbon stocks and sequestration, effects which may be temporary or may last for centuries, depending on the specific circumstances (Camia et al., 2021). As part of optimizing forest management, such negative impacts need to be avoided or their consequences minimized or rapidly ameliorated. Climate Smart Forestry (CSF) (Verkerk et al., 2020) places the aim of increasing wood supply alongside adapting forest ecosystems to reduce their vulnerability to climate change risks and the overall aim of reducing GHG emissions. The potential of CSF has been demonstrated in a few case study areas in Europe. Still, much more work would be needed to embed CSF into everyday forestry planning and practice across a wide range of forest ecosystems and national or regional circumstances.

Calls for Nature-Based Solutions (NBS) go further than CSF, applying to all land uses and stressing the importance of all the services provided by ecosystems besides biomass supply. Concerning forests, NBS emphasizes protecting, restoring, and extending forests and wooded landscapes, alongside management for adaptation and wood production. As with CSF, practical approaches and frameworks need to be further developed to enable their general adoption.

Restoring and creating forests and increasing trees' presence in the landscape will be particularly relevant as part of the post-COVID-19 recovery. In rural areas, this could create locally accessible sources of biomass (Fritsche et al., 2020) and could contribute to the diversification of agricultural systems and rural regeneration. In urban and peri-urban areas, trees and forests could contribute similar benefits and also provide more opportunities for recreation, retreat, and engagement with nature. This is in addition to other recognized services of trees in urban areas, notably for moderating climate extremes. More generally, bio-based materials production could be coupled with "nature-based solutions" in the forest sector, contributing to urban greening and rural areas' revitalization (Hirst and Lazarus, 2020) as well as the deployment of cascading facilities to utilize locally produced biomass resources (Fritsche et al., 2020).

The emerging picture suggests that forests and forestry could make a significant contribution towards bioeconomy development, with potentially cross-cutting benefits for climate change and ecosystem services and even greater relevance as part of the recovery from the post-COVID-19 pandemic. However, there are evident constraints on forests' capacity to supply more biomass without compromising the delivery of the broader benefits of forests. Hence, a sophisticated policy response is required to support forest protection, restoration, and extension in conjunction with the mobilization of woody biomass resources.

2.5. Ecosystem services

Ecosystem services can offer significant prospects for agriculture, forestry, tourism, culture, health, and wellbeing. '*An ecosystem services perspective provides a useful framework to consider the use of biomass resources for various goals, provided that utilization is realized within the boundaries of sustainability*' (Pfau et al., 2014). A sustainable, circular bioeconomy recognizes the added value of ecosystem services for the environment, the economy, and society. Thus, it ensures they are safeguarded and improved through local co-creative decision planning and implementation. The circular bioeconomy offers a unique opportunity for building decentralized energy production and water and landscape management. It supports the natural capital and improves biodiversity by promoting agroecological farming (Tamburini et al., 2020), re-establishing organic carbon and microbiota in the soil and land, recycling nutrients, and contributing to climate mitigation. For example, the deployment of biochar should be promoted as it can permanently remove carbon dioxide from the atmosphere and fight land abandonment due to desertification: more than 8.5 Mha in the Mediterranean region under risk of marginalization (IPCC, 2019; Chiaramonti and Panoutsou, 2019). Promoting paludiculture could also be another suitable option for other areas, as peatlands play a significant role in offsetting CO_2 emissions through sequestration. They account for ca. 3% of the earth's surface, storing 1.4 trillion tonnes of carbon, which is equivalent to 75% of all atmospheres' carbon (Rowan and Galanakis, 2020).

2.6. "Bio-cities," rural bioeconomies, and tourism

Cities have a critical role in developing and implementing the circular bioeconomy due to the large population, high intensity of economic activities, and increased consumption of goods. Urban livelihoods are affected by different choices concerning infrastructures, education, commerce, and healthy mobility. The pandemic has dramatically affected mobility in urban settlements, and recovery plans could restructure urban environments through smart mobility instead of unsustainable, horizontal lockdown (Acuto et al., 2020). Lockdown vehicle restrictions could be relevant interventions in the post-pandemic era leading to cleaner air and healthier cities (Li et al., 2019). Urban living has entered a new generation where cars' mobility and subsequent carbon emissions could be minimized. For instance, at the beginning of 2021, Saudi Arabia announced "The Line," a revolutionary city of 170 km in length to be built around nature with zero cars, zero streets, and zero carbon emissions (Arab News, 2021). However, current and modern cities' active mobility networks and public transportation infrastructures must be expanded to ensure all citizens' affordability and accessibility (including those living in suburban neighborhoods) (Daniels et al., 2020). Rebound effects in urban/peri-urban and non-urban mobility can also be reasonably expected due to consumers' reduced confidence in public transportations' health and safety. This trend could change consumers' behavior even well beyond the pandemic and should be very carefully monitored.

The tourism industry should also transform by changing the current practices that promote the continuous consumption of resources to a model that favors the decarbonization of transport systems and eco-tourism. Revealing green spaces and promoting healthy activities such as cycling and walking instead of just encouraging them as climate mitigation measures may increase public support of the transition (Acuto et al., 2020).

Finally, it is essential to develop urban agriculture and forestry to provide local feedstock and fresh vegetables, biodiversity gains, green infrastructure, and nature-based solutions to rebuild cities and retrofit biomass supply chains (Rousseau and Deschacht, 2020). Fostering regional development in rural areas requires citizens' training on business models and technical aspects (Chateau and Mavroeidi, 2020). This process will lead to green employment opportunities that will boost post-COVID-19 recovery and facilitate a green transformation to a low carbon economy.

2.7. Culture, arts and fashion

The transformation of the circular bioeconomy towards sustainability requires expanding its social dimension by linking mobility, sustainable food, and materials consumption with culture, arts, and fashion (Hanspach et al., 2020). During the political discussions about the financial packages to recover pandemic-related economic losses, there is a sense that the cultural dimensions have not been taken into account or left behind. The acute reaction to operate remotely and "go virtual" the pandemic by promoting take away, distance learning, and digital environments led to the shutdown of arts performing and closing museums and restaurants. This transformation also concerns leisure time and entertainment (social media, gaming, etc.). The practice of spending more time online has, on the one hand, reduced the spread of the COVID-19, but on the other, has created a significant gap in real-world social interaction and allowed manipulation of public opinions via populism, "bubbles," and fake news. These risks to social cohesion should be seriously considered and included in the overall planning to transition to a sustainable bioeconomy. People will have more green public spaces and increased opportunities to get involved with and inspired by nature. Culture, arts, and relevant social practices (e.g., rental, resale) could also support this transition by replacing material consumption, reducing exposure to fake news, and creatively promoting the bioeconomy wellbeing. Fashion brands have already set the pace by emphasizing sustainability and circularity (McKinsey and Company, 2020) e.g., using recycled (e.g., organic instead of regular cotton) and bio-based textiles that could lower and bio-based textiles that could lower GHG emissions.

3. Conclusions

Table 2 presents a collection of bioeconomy solutions to support green recovery and enhance system resilience in the post-COVID-19 world derived from Fritsche et al. and the authors' further work (Fritsche et al., 2021). Food systems' resilience and mitigation strategies that allow adapting rapidly to inevitable crises should become a priority, ensuring that future shocks and extreme events will minimally affect food chains and vulnerable people. It is also vital to increase circularity and integration of biochemical and thermochemical processes for waste's valorization targeting, the production of bio-based products and biofuels. The integration can be achieved using biorefinery processes to extract critical raw materials, e.g., as identified and listed by the EC. In a more general view, it is time and an excellent opportunity to develop a transformative, circular, inclusive, and sustainable bioeconomy that includes all citizens, fosters innovation and provides at least partial economic recovery solutions post-COVID-19 world. It is vital to swift the well-known slogan of "no one left behind" to "leaving no one out." This change could be achieved in practice by promoting short- and long-term strategies and actual measures supporting communities, stakeholders, and operators to preserve and diversify economic activities, keep jobs, and ultimately build the required resilience to overcome the crisis. These actions should be combined with sustainable production and decarbonization and stimulate private investments in this direction and monitor the resulting impact of mitigation measures.

Table 2
Bioeconomy solutions to support green recovery and enhance system resilience in the post-COVID-19 world.

Sector	Solutions
Agriculture	• Digitize agriculture-related activities and administration • Support creation of open big data platforms and Agricultural and Rural Knowledge and Innovation Systems (ARKIS) focused on data-driven farming • Promote and deploy the potential of carbon farming and agroecology • Develop sustainable livestock and fisheries, and organic nutrient recovery • Learn from success policies implemented in different countries • Develop crisis management plans that predict potential threats, and prevention and emergency response tools
Food	• Promote community marketing channels for local commodities to ensure their distribution at primary and secondary markets • Intensify efforts on reducing and valorizing food waste via integrated biorefineries • Support the establishment of food councils at municipal or provincial levels
Energy	• Stimulate local supply chains and securing investments in renewable fuels by stable policies and dedicated financial instruments • Improve energy resilience through balancing the grid, developing smart infrastructures, and enhancing digital capacities to recalculate potential bioenergy role in the post-COVID-19 era • Account for changes in urban environments (e.g., teleworking, consumer behavior) to re-adjust planning and market uptake of bioenergy carriers within the circular bioeconomy
Forestry	• Develop tools and support forest practitioners to implement the principles of climate smart forestry • Demonstrate relevant forest areas adapting these principles • Cooperate the mobilization of wood resources, while maintaining forest carbon stocks and carbon sequestration
Finance	• Increase funding for circular bioeconomy by mobilizing private investments • Stimulate biobased products and services through tax rebates and other subsidies promoting their usage
Cross-cutting	• Promote the "BioWEconomy" and the industrial symbiosis concepts • Support innovations and technological disruptions • Promote decentralized biorefineries Establish sustainability criteria for production • Support the optimal utilization of biomass • Ameliorate negative impacts on carbon stocks and sequestration in agricultural and forest systems

Further, recent studies and programs suggest that governments around the world should learn from this distressing experience and avoid rolling back current environmental standards and business-as-usual approaches (Fritsche et al., 2021). Therefore, a detailed investigation is needed to understand how the circular bioeconomy can address the pandemic effects and improve rural and urban areas' sustainability and its implications and achieve the Sustainable Development Goals. Together with the recovery of economies and industrial sectors, it is essential to recover other sectors such as tourism. Finally, revealing the role of socio-culture practices from fashion and culture to arts, which are vital components of societal change and need recovery support, should also become a priority.

CRediT authorship contribution statement

All authors contributed equally to the scientific part and the edition of the review article.

Declaration of competing interest

All authors declare that they have no conflict of interest.

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