The Bioeconomy and Food System Transformation

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1 Bioeconomy Concepts and Contributions

The most widely and well-recognized definition of bioeconomy was proposed in the framework of the Global Bioeconomy Summit, which was held in 2018, whereby the: "bioeconomy is the production, utilization and conservation of biological resources, including related knowledge, science, technology, and innovation, to provide information, products, processes and services across all economic sectors aiming toward a sustainable economy" (IACGBS 2018). The bioeconomy, as a policy framework and developmental approach, makes use of material and energy found in biodiversity, biomass and genetic resources, which contributes to sustainability initiatives and climate change mitigation targets. Additionally, the knowledge that is generated about biological principles and processes can be replicated in the design of new products (IACGB 2020).

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The concept of bioeconomy as a development approach arises from the context of the current era, driven by the advance of science and technology (S&T) and the need to address new problems and concerns (Patermann and Aguilar 2018). In recent decades, this definition has been boosted not only by the progress in research and developments in the field of biological sciences, but also by its complementarity and convergence with the S&T of materials (especially nanotechnology) and information (e.g., artificial intelligence (AI), digitization, information and communication technologies (ICT), and the Internet of Things (IoT)) (Krüger et al. 2020; Torres-Giner et al. 2020; van Dijk et al. 2021). The emergence of the bioeconomy has also been favored by concerns associated with climate change, since material replacement and the energy base of production processes are essential components of the actions needed to mitigate its impact. This new paradigm is proposed as an important complement to the fossil decarbonization of the economy (Lewandowski 2018). Moreover, interest in the bioeconomy also emerges out of societies' concerns around meeting the increased demand for food through agriculture that more sustainably uses natural resources and reduces the potential for negative environmental impacts (Wesseler and von Braun 2017).

In addition to the above, consumers are moving towards increasingly sustainable lifestyles and are inclined to buy environmentally-friendly products (Sandra and Alessandro 2021). These new demands are an opportunity for the utilization of biomass (agricultural residual and food waste) not only to help reduce pollution, but also as an alternative feedstock for the production of a wide range of materials, from fuels and energy to chemicals, bioplastics and pharmaceuticals, among others (Usmani et al. 2021). Furthermore, future bioeconomic innovations are expected to generate greater positive impacts on sustainability (Biber-Freudenberger et al. 2020), like synthetic biology, novel nitrogen-fixing crops, nanofertilizers, etc. (Herrero et al. 2020a).

The bioeconomy has similarities and differences with concepts of the circular economy and the green economy, which are also currently being discussed as approaches to sustainable development (D'Amato et al. 2017; Kardung et al. 2020). All of them are multi-dimensional concepts that have as goals: the reduction of greenhouse gas (GHG) emissions; the efficient use of energy and material; responsible consumption; and social inclusion through innovation (D'Amato et al. 2019). However, what distinguishes the bioeconomy is its focus on the transformation of the structure of production, because the basis for this is that material and energy are biological resources, as well as the use of knowledge for processing and the creation of value-added chains (Fig. 1).

The bioeconomy makes important contributions to sustainable economic growth from the environmental and social points of view, especially in rural areas (Refsgaard et al. 2021). For example, the European Union (EU) bioeconomy (post-Brexit composition) employed around 17.5 million people and generated €614 billion of added value in 2017 (Ronzon et al. 2020). In that same year, in Latin American countries such as Argentina, the bioeconomy generated 2.47 million direct jobs (Coremberg 2019). Similarly, Nordic countries have experienced bioeconomy-related employment growth of 5–15%, especially in Iceland, Denmark

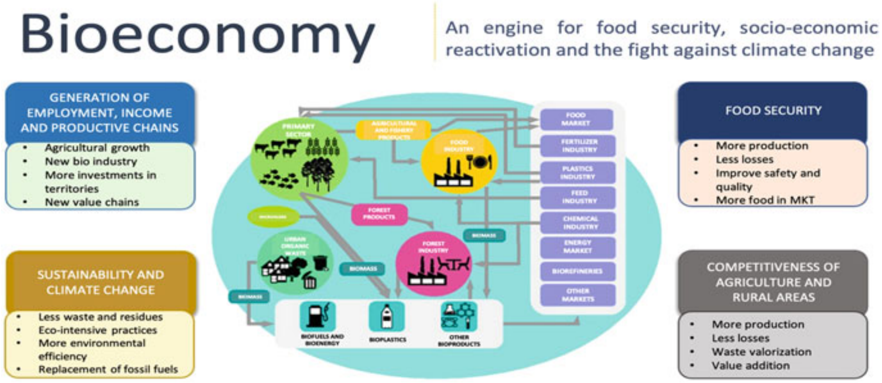
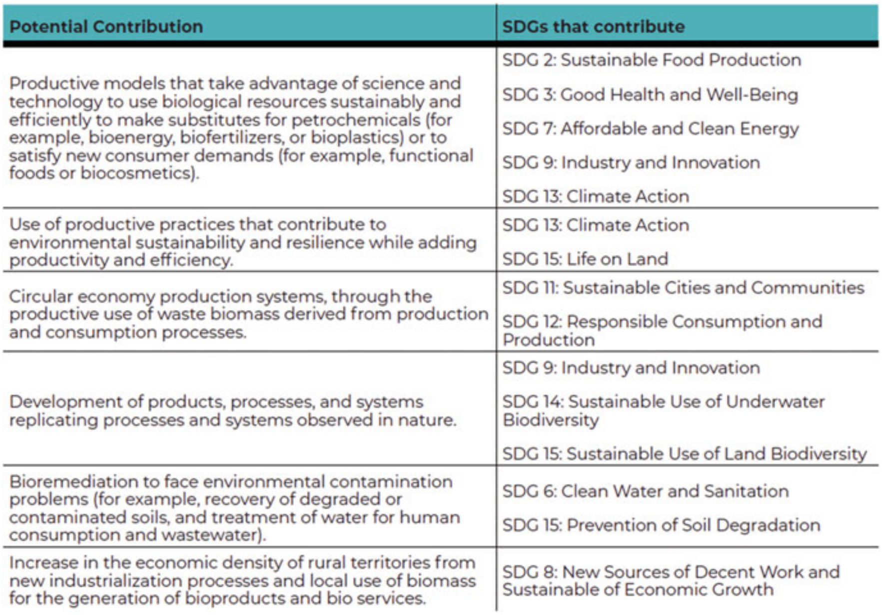


Fig. 1 Sectors and networks of the bioeconomy. (Source: Adapted from the Andalusian Bioeconomy Strategy 2018)

and Sweden (Refsgaard et al. 2021). It is estimated that the bioeconomic development model will have an economic potential of US$7.7 trillion between now and 2030 (WBCSD 2020). Additionally, in 2017, countries such as Italy expected to increase employment by 15% through its bioeconomic strategy (Italian Government 2019). Meanwhile, Colombia plans the generation of 2.5 million new jobs in its bioeconomic sectors (Colombian Government 2020). Previous projections are supported by trends in the bioeconomy markets. While commodities such as vegetable oil, sugar and cereals have a growth rate of less than 4.45%, sectors with higher added value such as biofuels, bioplastics and biofertilizers grew by 25%, 20% and 14%, respectively (Betancur et al. 2018). Using new S&T to add value to biological resources leads to more profitable and sustainable markets.

Finally, links between the bioeconomy and the 2030 Agenda for Sustainable Development have been demonstrated by using the indicators of the United Nation's Sustainable Development Goals (SDGs) for monitoring and evaluating the bioeconomy (Calicioglu and Bogdanski 2021). In an analysis of national bioeconomic strategies carried out by Linser and Lier (2020), it was found that topics related to the SDGs were indirectly related to objectives, planned actions and proposed measurements for policy instruments aimed at promoting the bioeconomy. Fourteen relevant SDGs for the bioeconomy were identified. For example, the bio-based economy can play a fundamental role in the decarbonization of the planet (SDG 13: Climate Action) and the production of agricultural bio-inputs, healthy food and the sustainable intensification of agricultural production (SDG 2: Zero Hunger, SDG No. 3: Good Health and Well-being and SDG No. 15: Life on Land). In addition, the closure of production cycles through the use of residual biomass improves the sustainable production indicators (SDG No. 12: Responsible Consumption and Production and SDG No. 11: Sustainable Cities and Communities). Another important contribution of this new paradigm is the design of biomaterials and production of different types of bioenergy (SDG No. 9: Industry, Innovation and

Table 1 Potential contributions of the bioeconomy to the SDGs



Potential Contribution	SDGs that contribute
Productive models that take advantage of science and technology to use biological resources sustainably and efficiently to make substitutes for petrochemicals (for example, bioenergy, biofertilizers, or bioplastics) or to satisfy new consumer demands (for example, functional foods or biocosmetics).	SDG 2: Sustainable Food Production SDG 3: Good Health and Well-Being SDG 7: Affordable and Clean Energy SDG 9: Industry and Innovation SDG 13: Climate Action
Use of productive practices that contribute to environmental sustainability and resilience while adding productivity and efficiency.	SDG 13: Climate Action SDG 15: Life on Land
Circular economy production systems, through the productive use of waste biomass derived from production and consumption processes.	SDG 11: Sustainable Cities and Communities SDG 12: Responsible Consumption and Production
Development of products, processes, and systems replicating processes and systems observed in nature.	SDG 9: Industry and Innovation SDG 14: Sustainable Use of Underwater Biodiversity SDG 15: Sustainable Use of Land Biodiversity
Bioremediation to face environmental contamination problems (for example, recovery of degraded or contaminated soils, and treatment of water for human consumption and wastewater).	SDG 6: Clean Water and Sanitation SDG 15: Prevention of Soil Degradation
Increase in the economic density of rural territories from new industrialization processes and local use of biomass for the generation of bioproducts and bio services.	SDG 8: New Sources of Decent Work and Sustainable of Economic Growth

Source: Chavarría et al. (2020)

Infrastructure and SDG No. 7: Affordable and Clean Energy), which help generate new jobs (SDG 8: Decent Work and Economic Growth).

The approach and application of the bioeconomy as a development model, contributing towards the achievement of the SDGs related to food security and nutrition, health and well-being, and clean water and sanitation, among others, is presented and analyzed in Table 1.

2 Bioeconomic Contributions to Food System Transformation

The transformation towards more sustainable and equitable food systems seeks to provide healthy and nutritious food for all, while creating livelihood opportunities and reducing negative impacts (von Braun et al. 2020). To achieve this goal, the UN Food Systems Summit has established five Action tracks, which are related to the bioeconomy as follows: **Action Track 1** seeks to ensure the availability of safe and nutritious food for everyone. This will require increasing crop and livestock yields through sustainable intensification activities in multifunctional landscapes, the diversification of production and good soil management (Hendriks et al. 2020). Another engine for the transformation of food systems is the shift to healthy and sustainable consumption patterns (**Action Track 2**). In this case, the bioeconomy can strengthen local value chains, promoting the reuse and recycling of food resources (Herrero et al. 2020b). **Action Track 3** aims to optimize the use of natural resources in food production, processing and distribution as pollution, soil degradation and loss of biodiversity are reduced. For this, the bioeconomy proposes strategies focused on value chains with integrated cycles, which increase efficiency and recycling through products and co-products in different biological systems (Hodson et al. 2020). These strategies for integrating chains and adding value to products at the local level contribute to poverty reduction through the creation of new rural jobs (**Action Track 4**) (Neufeld et al. 2020). Finally, **Action Track 5** seeks to promote resilience in the face of vulnerabilities, impacts and stresses in food systems (Hertel et al. 2020). Resilience can be strengthened by a growing bioeconomy based on the diversification of agricultural commodity production, the increased use of bio-based inputs in agriculture and the diversification of rural incomes into rural production of bioenergy, bio-based industry and environmental services. The current contingency caused by COVID-19 and recent natural disasters highlights the importance of innovations to prepare food systems for future pressures.

2.1 Advantages of Scientific and Technological Developments

Advances in the fields of biology, ICT and engineering are repositioning the role played by biological resources and improving our ability to understand and take full advantage of the opportunities they offer. In recent decades, advances in biology have accelerated, with new research tools such as genome editing contributing new knowledge of plant, animal and microbial genomes and big data. The increases in knowledge are being used to enhance the efficiency of crops, animals, biofuel, bioplastics and bioenergy production. The new tools have highlighted the full potential of the intrinsic value of natural and biological processes (IACGB 2020). The impact of these trends, which are transformative in themselves, is augmented by the interaction among them, what is beginning to be referred to as ‘technological convergence.’ By interacting with each other, different disciplines – biology, biotechnology, chemistry, nanotechnology, data science, ICT, engineering, etc. – are driving the progress of each specific field, blurring the traditional boundaries between sectors of the economy and changing the competitive advantages of countries and their businesses (MIT 2005; Park 2017).

Information and communication technologies and digitalization are becoming important determinants of the organization and competitiveness of economies. Widespread connectivity, satellite technologies, data science and artificial intelligence mechanisms, robotics, autonomous systems, electronic and biological sensors, virtual and augmented reality, the IoT and blockchain applications are increasing the efficiency of agriculture, food and biomass supply chains, which reduce waste and resource use while increasing the quality of food and biomass. It is also becoming increasingly possible to predict climate phenomena, foresee their consequences and generate risk management programs to better deal with the consequences and monitor climate impact, all of which will undoubtedly reduce farm management costs (Draca et al. 2018).

Through the use of such groundbreaking S&T, the bioeconomy makes it possible to improve the productivity and sustainability of biological resources by developing more productive, disease-resistant and environmentally-friendly varieties of plants and animals. S&T increases the productivity of biomass (including waste and residues), developing new bioproducts with high added value, such as nutraceuticals, bioenergy and other biological materials used by the cosmetic, pharmaceutical, chemical and other industries. Furthermore, it generates a range of new services and attaches greater value to biodiversity (Lokkoa et al. 2017; Malyska and Jacob 2018), for example, integrated pest management based on biological pesticides and fertilizers (Akutse et al. 2020).

Technological convergence is one of the trends making the biggest contribution to the renewed, modernized vision of agriculture and food systems, value-added chains and international trade. Convergence is especially important because of young people's technological skills – which far exceed those of previous generations – and the need to halt the migration of young people from rural territories to more urbanized areas. These new technological scenarios are already beginning to be reflected in agriculture, agribusiness and the rural regions, and are increasingly perceived as offering the basis for the development of 'sustainable intensification.' Furthermore, they are expected to have significant effects on the ways in which agricultural production is organized, improved rural employment opportunities and equity in rural territories.

Technological advances and convergence support SGDs: 3 (Good Health and Well-being); 8 (New Sources of Decent Work and Sustainable of Economic Growth); 9 (Industry and Innovation) 11 (Sustainable Cities and Communities); 12 (Responsible Consumption and Production); and 15 (Sustainable Use of Land Biodiversity).

2.2 Transforming Rural Environments, Generating Income and Employment Opportunities

One of the key issues around the bioeconomy comes from the implications of moving from fossil- to bio-based value chains. Fossil raw materials are relatively homogenous, are globally extracted in high volumes from only a few highly productive deposits of limited area, and come out almost completely ready to be transformed into products predominantly for the energy sector, but also for the multi-stage chemical sector and the construction sector, through large-scale industrial and logistical infrastructures. The defining attributes of the associated value chains are that they are global and large-scale. In contrast, biological carbon – biomass – comes from a highly decentralized context because of the diverse nature of agriculture and forestry and 'does not travel well.' Due to its large volumes, limited shelf-life and low energy and carbon density, it is not economical to transport biomass long distances before processing it, an issue that calls for biorefineries – integrated biomass processing facilities – to also be organized in a decentralized way in locations close to the areas producing the raw materials.

It is these characteristics of bio-based value chains that open up opportunities for significant transformations of the rural landscape and the way rural areas integrate into the economy. These bio-based value chains can significantly increase the economic 'density' of the territories. In the first place, bio-based value chains bring new activities – biorefineries and other industrial and logistical infrastructures – into the rural landscape, diversifying sources of income and the nature of employment opportunities. Greater economic density will generate greater opportunities for Latin American and Caribbean (LAC) territories that have high unemployment, informal jobs (76% of those employed), poverty (45%; two to three times higher than urban rates) and exclusion. The use of biomass for new industries will increase economic opportunities for both the agricultural and non-agricultural sectors, as the non-agricultural sector in LAC generates 58% of the income of rural territories (ILO 2020).

Bioeconomic value chains can address one of the common concerns in rural communities around the world: out-migration to urban centers and aging populations due to the lack of interest among young people to remain in farming vis-a-vis the promise of a more 'attractive' future in non-agricultural jobs. There is no possibility of success in achieving better livelihoods in the context of a decaying rural space. According to an Organisation for Economic Co-operation and Development (OECD) study that included 24 developing countries around the world, only 45% of rural youths are satisfied with their employment (OECD 2018). Among the reasons for seeking a new job, rural youths mentioned: a better income (36.7%); greater stability in contracts (20%); better working conditions (17%); and an increase in skills (13%).

A second strategic component of the impact of bioeconomic developments on transforming rural environments is the implications of improved energy availability in terms of attracting other economic activities beyond the bio-based value chain activities proper. In this sense, there is considerable evidence that rural electrification stimulated local business development (Riva 2020), which suggests that bioenergy options could not only significantly lower the cost of energy through the decentralization of costly energy grids – a continuing hurdle for many rural areas, particularly in the poorer countries – but also improve environmental performance by using residual biomass and waste (Tamburini et al. 2020). This should be especially important for a region like LAC, where forest biomass is equivalent to half of its land area (and 25% of the world's forests), and its agriculture represents 12% of world agricultural production and contributes to the 16% of the world export of agricultural products. Furthermore, it is a region where more than 120 million tons of food are wasted annually (55% of fruits and vegetables, 40% of roots and tubers, 25% of cereals, meats and dairy products) (ECLAC et al. 2019).

Energy – in affordable, stable supply – is a critical restriction to economic development, and the bioeconomy is increasingly offering it through options that are not competitive with food production (Gabashwediwe et al. 2019). Furthermore, in an increasingly interconnected world, the emerging bioeconomy networks (i.e., value adding, energy diversification) are a viable strategy for reversing the conditions that have been fueling rural out-migration, making the rural areas more competitive spaces for social and economic development (Hartley et al. 2019). In 2018, bioenergy generated 3.18 million jobs – equivalent to 30% of all jobs in the renewable energy sector. Moreover, the employment generated by the biofuels sector worldwide is highly concentrated in the western hemisphere. Latin America and the Caribbean accounts for 50% of liquid biofuel jobs worldwide, while North America accounts for 16%. Brazil leads among countries as the largest employer in biofuels, employing 832,000 persons (Torroba 2020a).

Improved rural economies through bioeconomy and bio-based energy contribute to supporting SDGs: 3 (Good Health and Well-being); 7 (Affordable and Clean Energy); 8 (New Sources of Decent Work and Sustainable of Economic Growth); 9 (Industry and Innovation); 11 (Sustainable Cities and Communities); and 15 (Sustainable Use of Land Biodiversity).

2.3 Improving Food Chain Resource Use

The diversification and efficient use of biomass to produce biofuels contributes to GHG reduction, generates added value and employment, and can contribute to safer and more efficient agri-food systems. From the point of view of the economy of the industry, biomass utilization gives rise to various co-products, among which are a series of biomaterials of different added value. The energetic biomaterials are liquid, solid and gaseous biofuels, which, aggregated under the term ‘bioenergy,’ represent the production of 10% of the world’s primary energy supply (IEA 2019). In an associated way, a wide range of products linked to animal and human food (flour proteins, expeller, bagasse, distiller’s dried/wet grains with solubles, etc.) and other high value-added products linked to the pharmaceutical, alcohol chemical and oleo chemical industries are also produced.

In this way, the efficient and integral use of biomass gives rise to an industry categorized as ‘multi-product’ (Baumol et al. 1982), in which the production of co-products allows for diversification and complements the production of food, facilitating better distribution in the production costs of raw materials, which makes the system more efficient. In addition, a safer agri-food system is generated, since diversified uses make up a reserve or buffer of raw materials that can be used as food in case of a food crisis. Moreover, the production of biofuels has generated a more stable demand for raw materials (especially of those multi-annual crops), generating an additional sales channel that allows for expansion in the supply of raw materials involved in the process. According to Torroba (2020b), 16% of corn production worldwide, 20% of sugar, 19% of soybean oil and 16% of palm oil were destined towards biofuels. When the prices of related commodities are not attractive, the redirection of raw material derived from crops, especially multi-annual ones, can be particularly beneficial to farmers. It generates more stable demand for raw materials. The more stable demand for raw materials, and the potential positive impact this has on prices, can benefit a neglected group in LAC: family farmers, of whom there are 60 million working in the sector.

The productivity of the bioeconomy sectors has significantly improved over time, reflecting learning-by-doing and ongoing technological updating. The processing costs of US corn ethanol declined by 45% between 1983 and 2010, while production volumes increased seventeen-fold; learning-by-doing and economies of scale played an important role in reducing these processing costs. Similarly, the cost of producing sugarcane ethanol in Brazil declined by 70% between 1975 and 2010 (Chen et al. 2015). With advances in biotechnology to enhance the productivity of feedstock crops, the efficiency of refining and the use of residue, the cost of biofuels and their environmental impacts will decline while the added value is enhanced (Debnath et al. 2019).

Finally, the use of biomass residues to produce alternative biofuels (e.g., biogas, advanced biofuels, etc.) lends a higher degree of efficiency to the system, allowing for the transformation of losses of raw materials or waste into energies of biological origin. The potential of residues originating from forestry, agriculture, and other sources is estimated to amount to 40–170 exajoule/year, with a mean estimate of around 100 exajoule/year by 2050 (IPCC 2012). For comparison purposes, annual energy consumption in the US amounts to 94 exajoules. The use of biomass could amount to a considerable percentage in the total generation of bioenergy, however, adoption of biomass as a source of bioenergy will vary widely, depending on supply availability and cost.

Enhancing the utilization of resources in supply chains supports SGDs: 7 (Affordable and Clean Energy); 9 (Industry and Innovation); and 13 (Climate Action).

2.4 *Improved Nutrition and Health*

The growing interest of consumers in products with natural ingredients can promote new value chains associated with tropical biodiversity. Agroforestry systems with native fruit trees and traditional forest foods can provide the necessary macro- and micro-nutrients needed to improve nutrition and food security (Chamberlain et al. 2020). Simultaneously, food innovations have helped diversify diets, especially with new protein sources such as those based on micro-algae (Melgar-Lalanne et al. 2019; Ordoñez-Araque and Egas-Montenegro 2021) and insects. Micro-algae possess a high nutritional value, containing protein, polyunsaturated fatty acids, bioactive carbohydrates and antioxidants, including pigments such as carotenes and chlorophylls phycobiliproteins (Fernández et al. 2021). Moreover, other technologies under development, such as cultured meat products, promise to be a sustainable protein source (Post et al. 2020).

On the other hand, innovations in plant breeding technologies, such as those used to create genetically modified (GM) crops, have made significant contributions towards addressing the SDGs, in particular, goals one (reducing poverty) and two (reducing hunger). While increased yields have contributed to higher household incomes, which reduces poverty, the increased yields have also enhanced household food security (Klümper and Qaim 2014; Subramanian and Qaim 2010; Smyth 2022). Biofortified GM crops have been adopted, increasing micro-nutrient availability (Hefferon 2014). Research to improve the nutritional quality of food includes protein increases (canola, corn, potato, rice, wheat); improved oils and fatty acids (canola, corn, rice, soy); improved carbohydrates (corn, potato, sugar beet, soy); increased vitamins (potato, rice, strawberry, tomato); and increased mineral availability (lettuce, rice, soy, corn, wheat) (Newell-McGloughlin 2014). Nutritionally enhanced foods improve an individual's nutrient intake, preventing and/or treating leading causes of death such as cancer, diabetes, cardiovascular disease and hypertension. Improving the nutritional content of daily food consumption certainly has day-to-day effects, but of significant importance are the long-term effects that extend for decades over the course of an individual's lifetime.

In many instances, improving macro-nutrients (e.g., proteins, carbohydrates, lipids, fiber) and micro-nutrients (e.g., vitamins, minerals, functional metabolites) results in significant childhood health improvements, such as reducing blindness due to the lack of vitamin availability (Wesseler and Zilberman 2014; Dubock 2014). Improved food nutrient content, especially the increase in mineral availability, contributes to improved immunity systems and reduces stunting (Wesseler et al. 2017). In many developing countries, plant-based nutrient intake accounts for 100% of an individual's nutrient diet, further highlighting the importance of nutritionally enhanced crop-derived foods. Health benefits are extended into adulthood through reductions in cancer-causing mycotoxins, as is the case with GM corn, in which the presence of these mycotoxins is 30% lower (Pellegrino et al. 2018). As the later-in-life benefits from improved childhood nutrition become better understood, the full value of nutritionally enhanced crops and foods may not be realized for several decades.

One quality of life improvement that has resulted from the small land-holder adoption of GM crops is the reduction in drudgery (Gouse et al. 2016). The majority of weed control in developing countries is done, as it has been for thousands of years, through back-breaking manual labor. Manual weeding is labor commonly assigned to women. The assessment of GM corn adoption impacts on female manual weeding by Gouse et al. (2016) found that this task was reduced by three weeks over the course of a year. This reduction in the amount of time spent manually weeding corn fields allowed these women to have larger vegetable gardens, as they had more time to haul water and be with their children. Another human health benefit from GM crops is the reduction in the incidence of pesticide poisoning following GM cotton adoption. In an assessment of the impacts of GM cotton adoption in India, Kouser and Qaim (2011) estimated that there were between 2.4 and 9 million fewer cases of pesticide poisoning annually. With GM cotton first adopted in India in 2003, the cumulative reduction in the number of pesticide poisonings can be estimated to be in excess of 100 million cases (Smyth 2020).

Innovative research in the agriculture and food sectors is transforming food systems through both the increased provision of food and more nutritious and healthy food. The increased provision of safe, nutritious food has life-long health benefits, thereby contributing to reduced healthcare system expenses.

Improved biofortification of food and health benefits from biotechnology support SDGs: 1 (End Poverty); 2 (Sustainable Food Production); and 15 (Sustainable Use of Land Biodiversity).

2.5 Improved Environmental Sustainability and Climate Resilience

Investments in the bioeconomy and biotechnology have made substantial environmental improvements and offer tremendous potential to be a leading strategy in the efforts to mitigate climate change. It is estimated that biomass could save 1.3 billion tons of carbon dioxide (CO_2) equivalent emissions per year by providing 3,000 terawatt-hours (TWh) of electricity by 2050 (Zihare et al. 2018). Concerning biofuels, their performance shows different emission reductions according to multiple factors, including considering the product's life cycle, and is closely linked to agricultural yield and the technologies applied during the primary and industrial production process. According to the IPCC (2011), the "good use of bioenergy can significantly reduce greenhouse gas emissions compared with alternative fossils." In this sense, it is necessary to establish national instruments of measure for GHG emissions throughout the life cycle of biofuels according to the different raw materials used to corroborate the environmental advantages. Besides, bio-based products release fewer GHG emissions compared to fossil carbon commodities (Antar et al. 2021). For example, since bioplastics consume less energy during their production than plastics derived from petroleum, they tend to emit less carbon dioxide in their life cycle (Yadav et al. 2020).

Another contribution of the bioeconomy towards sustainability is the reduction and use of food waste. In the agro-industrial sector in LAC, food waste is around 127 million tons per year, enough to satisfy the nutritional needs of 300 million people (Macias et al. 2018). Thanks to the advances in S&T, multiple technologies allow for the reduction of waste and its use to produce new bioproducts (e.g., for the food, energy, chemical, pharmaceutical, and construction industries). Food waste can be considered as a cheap feedstock for producing value-added products such as biofertilizers, biofuels, biomethane, biogas and value-added chemicals (Hassan et al. 2018). These new industries have the potential to contribute to the mitigation objectives of climate change and the environmental sustainability of productive commercial activities thanks to the switch from products of fossil origin with a high carbon footprint to inputs (waste) that had a high generation of carbon dioxide emissions and to the change in the energy matrix.

The commercialization of GM herbicide tolerant canola, corn and soy in the mid-1990s revolutionized land management practices, resulting in tens of millions of acres being transitioned to zero tillage. The additional commercialization of GM insect-resistant corn, cotton and soy has resulted in millions of fewer pesticide applications. The reduction in tillage and chemical applications has produced a significant environmental benefit, with 2.4 billion kg fewer carbon dioxide emissions and 775 million kg fewer chemically active ingredients being applied (Brookes and Barfoot 2020). It has been estimated that the commercialization of insect-resistant crops has reduced global pesticide use by 37% (Klümper and Qaim 2014). Not only are there fewer GHG emitted during the production of crops, the continuous cropping of fields with no tillage is increasing the soils' sequestration and storage of carbon dioxide (Sutherland et al. 2021). Conventional agricultural practices that require the use of tillage for weed control are estimated to have a net global warming potential that is 26–31% higher than zero-tillage land (Mangalassery et al. 2014).

The adoption of GM crops is driving the movement to sustainable crop production by removing tillage as the leading form of weed control. The environmental benefits from this are significant for sustainability, as, in one analysis, 86% of farmers reported decreased soil erosion and 83% reported increased moisture conservation (Smyth et al. 2011). A further benefit from the removal of tillage is that the rate of herbicide resistance development in weed populations has declined following the wide adoption of GM crops (Kniss 2018). The adoption of GM technology in corn, soybean and cotton reduced agricultural land and input use and saved 0.15 Gt of GHG emissions, equivalent to roughly one-eighth of the emissions from automobiles in the US (Barrows et al. 2014).

One emerging and vital area of innovative bioeconomy research is the use of innovative breeding technologies, including genome editing, to improve the abilities of plants to sequester increased amounts of carbon dioxide, allowing agricultural food production to make significant contributions to reducing the impacts of changing climates (Ort et al. 2015). Changes in a plant's ability to photosynthesize can have additional yield-enhancing benefits (Baslam et al. 2020). Bioeconomy photosynthesis research that results in plants sequestering greater volumes of carbon dioxide and higher yields will ensure that crop production levels do not decline in the face of changing climates.

Plant breeding involving biotechnology and genome editing is also providing additional sustainability benefits by developing new varieties that are resistant to diseases that threaten to destroy species. Fungal diseases and viruses have had devastating impacts on the production of coffee, for which an estimated 60% of all production is threatened (Davis et al. 2019). Similar circumstances exist regarding the production of bananas (FAO 2020), oranges (Nelson 2019) and cocoa (Ploetz 2007). The technology is also being applied to reintroduce species into regions where they were previously made extinct due to disease, such as the case with the American chestnut tree (The American Chestnut Foundation 2015).

The environmental benefits from GM crops are making substantial contributions to improving the sustainability of agriculture and food production. The reduction in GHG emissions, increased carbon dioxide sequestration and improved photosynthesis provide a leading solution for the mitigation of changing climates.

The application of biotechnologies that improve environmental sustainability and climate resilience supports SDGs: 2 (Sustainable Food Production); and 3 (Good Health and Well-being).

2.6 Upscaling Biotechnology Innovations

Humanity is facing major challenges, including climate change, food security and rural development. The bioeconomy is poised to play a central role in addressing these challenges. New technologies in the life and information sciences, combined with practical knowledge of production practices and ecosystems, can unleash the bioeconomy's potential. This requires significant investment in basic and applied research, training highly skilled professionals and fostering a fluid relationship between academia and industry. Zilberman et al. (2013) suggest that the 'educational industrial complex' has been essential in establishing the biotechnology and information technology sectors in the US and throughout the world. In the educational industrial complex, publicly supported basic research within universities and other research institutions leads to discoveries and innovations that are transferred to and expanded by startups and other private sector actors. Their development efforts lead to products that are produced and marketed by the private sector and transferred to final users. The educational industrial complex has already led to the establishment of supply chains of new products, including biofuels and oils, fine chemicals, pharmaceuticals and foods. University researchers have led some of these new ventures and the exchange between universities and the private sector in clusters like the Bay Area, St. Louis, Davis, Sao Paolo, San Diego, Austin, Mendoza, Santiago, etc.

The supply chains that emerge from these industrial clusters provide direct employment in the production of technological devices and even greater opportunities in the industries resulting from these technologies. The resulting bioeconomy industries are more likely to be concentrated in rural regions, alleviating rural poverty. For example, biofuel and fine chemical production can transfer rents from owners of non-renewable resources like fossil fuels to the expanded agri-food sector. The success of the educational industrial complex depends on maintaining academic and research excellence. The pioneering knowledge produced by EMBRAPA was key to the emergence of Brazil as an agricultural powerhouse, suggesting that support for outstanding research institutes linked with industry is a sound social investment.

The three main obstacles to the development of the bioeconomy sector are regulatory uncertainty, high transaction costs and financial constraints (Zilberman et al. 2013). Upscaling and applying new knowledge requires a science-based regulatory environment that aims to reduce regulatory burden and accelerate the development and application of new, safe technologies. The emergence of entrepreneurial startups is more likely when venture investors and capital markets are established to support new industries and when regulatory procedures are streamlined to reduce the cost and time needed to establish the venture.

Greater efficiencies in the commercialization and adoption of innovative biotechnological techniques and products contribute to SDGs: 7 (Affordable and Clean Energy); 9 (Industry and Innovation); and 15 (Sustainable Use of Land Biodiversity).

3 The Path Forward

Food systems, the "activities involved in producing, processing, transporting and consuming food" (UN 2021), are an integral part of the bioeconomy concept as a development approach. New developments in the biological sciences allow countries to address the many challenges society is facing. We have summarized the many opportunities the biological sciences have to offer. The translation of these opportunities into practice will not be trivial. There are a number of institutional factors that delay or prevent full exploitation of the opportunities that the bioeconomy has on offer. To move forward, these constraints must be addressed. First, research capacity at universities and government institutes that can turn these opportunities into technical and social innovations must be developed. Second, the growth-supporting industries based on these innovations and the supply chains that generate employment and economic growth should be supported. Third, regulations of innovations that protect society, but do not disrupt the application of these opportunities in production, transportation, and consumption and unnecessarily restrict sustainable growth, jobs and resilience, are needed. The differences in regulations and support for innovations and the industries that can spread them in different countries often reflect different societal norms and values. These institutional barriers are difficult to solve by one country alone. The UN Food Systems Summit brought together many countries and many people to discuss the removal of institutional barriers.

Our overview has shown that a lot can be achieved by building research capacity and reducing institutional barriers. The impacts will go beyond the food systems and affect other sectors of national economies as well. An open discussion will be needed that takes differences in norms and values into account without discriminating one against another. The UN Food Systems Summit provided the opportunity. The results depend on us.

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