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An economic perspective of the circular bioeconomy in the food and agricultural sector

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Transforming the agri-food system from a "take-make-waste", or linear production system, to a circular bioeconomy that reduces, recycles, recovers, reuses, and regenerates wastes and transitions from fossil to biobased fuels and products is being hailed as critical for meeting a growing population's food and fuel needs in environmentally sustainable ways. While a transformation towards a circular bioeconomy is an appealing strategy to achieve multiple environmental goals, we argue that this strategy needs to go beyond a techno-centric focus and adopt an economic value-based lens to balance the desire for circularity with its costs, benefits, and distributional effects on society. This perspective analyzes the mechanisms that sustain the existing linear economy and proposes a novel social cost-benefit framework to determine the optimal level and path to circularity. We present five critical pathways to achieve a sustainable circular bioeconomy in a market economy consisting of decentralized decision-makers.

Global food production has tripled since the mid-20th century, growing faster than human population and agricultural land. Technological advances, primarily induced by the objectives of enhancing productivity and profitability, have driven this intensification of agriculture. However, a large portion of inputs, including irrigation water, nutrients, and herbicides, that are applied for crop production are not taken up by the crop; this low input use efficiency results in environmental contamination and runoff that degrades soil and water quality[1–4]. Agricultural processing firms release additional nutrients into wastewater streams as they convert agricultural commodities into consumer goods. Much of the agricultural biomass produced with these inputs is wasted. Of the biomass that is consumable, losses during pre-harvest, post-harvest, and post-consumer stages add to organic waste[5]. Managing agricultural wastes is a challenge for both developed economies and developing countries, as it is often burnt or landfilled, contributing to GHG emissions and air pollution[6,7]. Agricultural pollution is the largest cause of degradation of surface and groundwater quality, loss of soil health, hypoxic zones, and biodiversity loss. Agriculture, forestry, and land use contributed to 22% of global emissions in 2019[8], 30% of energy consumption, 70% of groundwater extraction, and 75% of deforestation[9].

This existing agri-food production system is referred to as linear because it relies on a one-directional process of using extracted inputs, producing outputs and generating residues that become polluting wastes. Recognizing the limitations of relying on this approach to meet growing demands for agri-food products[2,10] has led to a call for a paradigm shift towards a circular bioeconomy[11,12]. Definitions of a circular bioeconomy vary across studies but have a common emphasis on reducing the use of virgin materials, recycling and reusing materials, restoring, and regenerating natural systems, and converting the unavoidable wastes and other biological resources into bioenergy or bioproducts to substitute for fossil fuels[13–17].

There are various existing and emerging technological pathways to enable the transition of the agri-food sector to circularity for any product supply chain and across the multitude of products in an economy (Fig. 1a). These include scientific developments in digital precision farming and artificial intelligence technologies for crop management which can reduce nutrient loss on the field, nutrient recovery and recycling at the edge of the field[18,19]. Similarly, there are multiple types of applications of synthetic biology, gene editing and biotechnology, and precision fermentation to convert and upcycle agricultural wastes and perennial energy crops to plant-based proteins, bioproducts, and bioenergy, that are substitutes for chemical and fossil energy-based products[20] (Fig. 1b). Other examples, include redesigning landscapes to include leguminous crops that necessitate fewer chemical treatments, pasture for grass-fed animals, converting organic waste generated at all stages ranging from crop residues to food scraps into compost and biochar for nutrient-rich soil amendments or into renewable natural gas can improve soil health and crop productivity and reduce need for fossil fuels[21,22].

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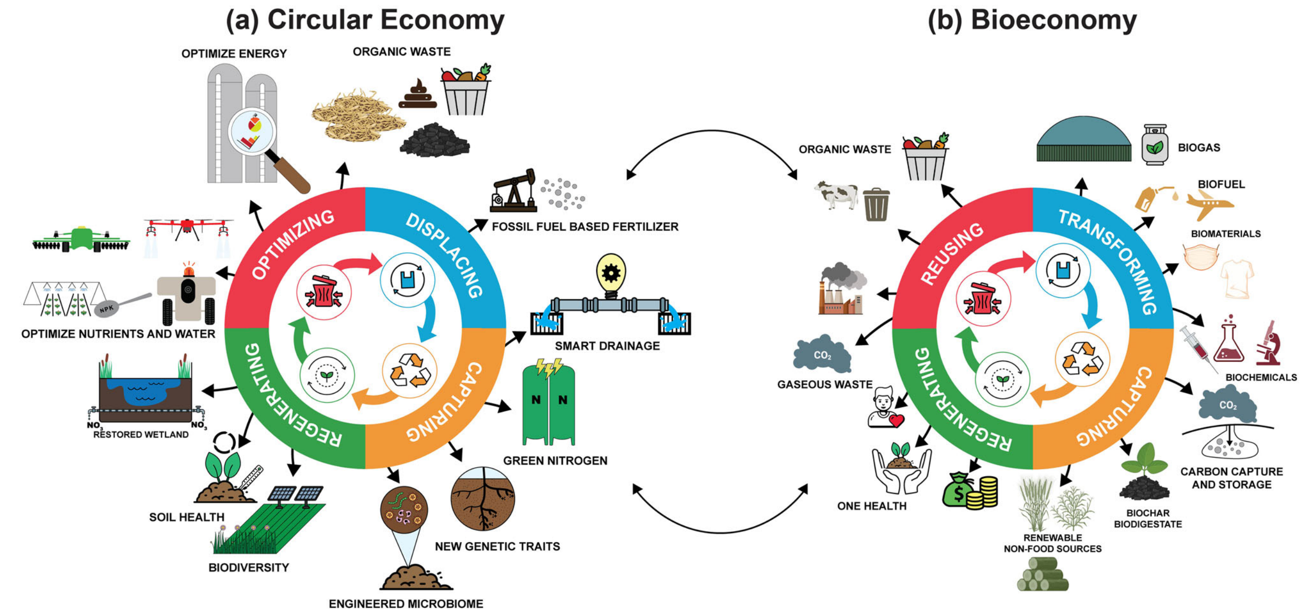


Fig. 1 | Multiple pathways to a circular bioeconomy. a represents multiple pathways to reduce, recyle and reuse waste in a circular economy; **b** represents multiple pathways to produce inputs, food and energy products in a bioeconomy. Together, the two panels show the interconnections among the pathways to reduce, recycle and reuse waste and to convert unavoidable waste and other biological resources to bioproducts that displace fossil fuels.

These pathways may vary in their environmental outcomes and impacts on GHG emissions, water quality, biodiversity, and land use, which may be synergistic or conflicting. These technologies can differ in their costs, pollution-reduction effectiveness, and impacts on productivity and trade-offs. A key complexity in charting a path to a circular bioeconomy is selecting the mix of technologies and the desired extent of circularity to be achieved with this transition; this will affect the costs of achieving a circular bioeconomy and other societal outcomes. The availability of technologies is necessary–but not sufficient–to guarantee a transition to a circular bioeconomy. Consumers and businesses throughout the agrifood supply chain make decentralized decisions guided by their private objectives. Even technologies with high readiness for deployment are often not adopted for economic, behavioral, and social reasons. Thus, a strategy for the transformation to a circular bioeconomy needs to combine technology availability with market-driven mechanisms, regulations, and other incentives for guiding individual consumer and producer choices among the various potential pathways.

Interest in a circular bioeconomy started primarily in environmental, agricultural, and biological engineering and the ecological sciences. There is a large literature on the imperative for transitioning to a circular bioeconomy across developed and developing countries[3,8], identifying barriers, opportunities, and recommendations for the transition and describing the technological pathways for specific sectors[23]. The concept of a circular bioeconomy has not drawn much attention from economists, who are largely unfamiliar with this terminology[24]. Economists have contributed to analyzing the economics of non-point pollution control and other agri-environmental policies[25], designing incentives for technology adoption[26], and developing approaches for quantifying food loss and waste[27] and the environmental impact of reducing food waste[5,28]. They have also noted the need for bundling technical innovations with policies, knowledge, social institutions, and cultural norms to reduce the land and water footprint of agri-food systems[29]. However, there has been no holistic analysis of the economics of transitioning to a circular economy, the optimal mix of the various dimensions of reducing, recycling, recovering, and reusing wastes to displace fossil fuels and the design of mechanisms for incentivizing a circular bioeconomy.

This perspective aims to present an economic lens to determine the optimal level of circularity, the mix of circular strategies, the optimal amount of waste disposal, and the acceptable trade-offs between higher economic costs for consumers and producers and the societal benefits from avoided environmental costs. Economics provides a framework to identify optimal strategies that balance private and social objectives while recognizing that resources are scarce and that trade-offs need to be made. This framework can be applied to design incentives and science-based regulations that price externalities and put a value on public goods to achieve the optimal balance between competing objectives. We describe the institutional, regulatory, and market structures that sustain the existing linear economic system and the need for their transformation to create a demand-pull for the technological advances for a circular bioeconomy.

Determining this optimal choice of pathways and the mix of carrots and sticks policy approaches to achieve it requires sound interdisciplinary collaborations among economists, other social and environmental scientists, biologists, engineers, and others. In addition to economic drivers, the transition to a circular bioeconomy will also depend on social norms and cultural barriers and have implications for social justice that need to be considered. We conclude by presenting five critical pathways to achieve a circular bioeconomy that is sustainable in a market economy consisting of decentralized consumers and producers.

Concept of a circular bioeconomy: its appeal and limitations

The concept of a circular bioeconomy unites two complementary alternatives to the existing linear agricultural production system. The first is the notion of circularity in resource use that emphasizes reducing, recycling, and reusing chemical and other inputs to increase resource use efficiency, maintain products, materials, and resources as long as possible, and minimize the amount of polluting waste released to the environment (Fig. 1a). The second is the concept of a bioeconomy, which consists of sectors of the economy that produce goods and services using renewable natural resources and biological resources as inputs (Fig. 1b)[30]. Bioeconomy can be viewed broadly as encompassing the use of biotechnology and biological resources from various sources to create an economic system in which bio-based products displace fossil fuel-based value chains. These two concepts are highly interconnected and emphasize waste reduction and re-use of wastes and other biological resources to displace fossil fuels.

The notion of a circular bioeconomy is appealing for various reasons. First, it recognizes that a key source of pollution and environmental degradation is waste generation during production, which typically does not use inputs efficiently, both technically and economically. Second, it emphasizes the importance of reducing waste generation at the source, recycling and reusing waste, and converting waste into useful final products to meet consumer demand. Third, it draws attention to the role that biological resources can play in displacing fossil fuels and mitigating changing climate. Lastly, a circular bioeconomy provides an operational and techno-centric path to environmental sustainability.

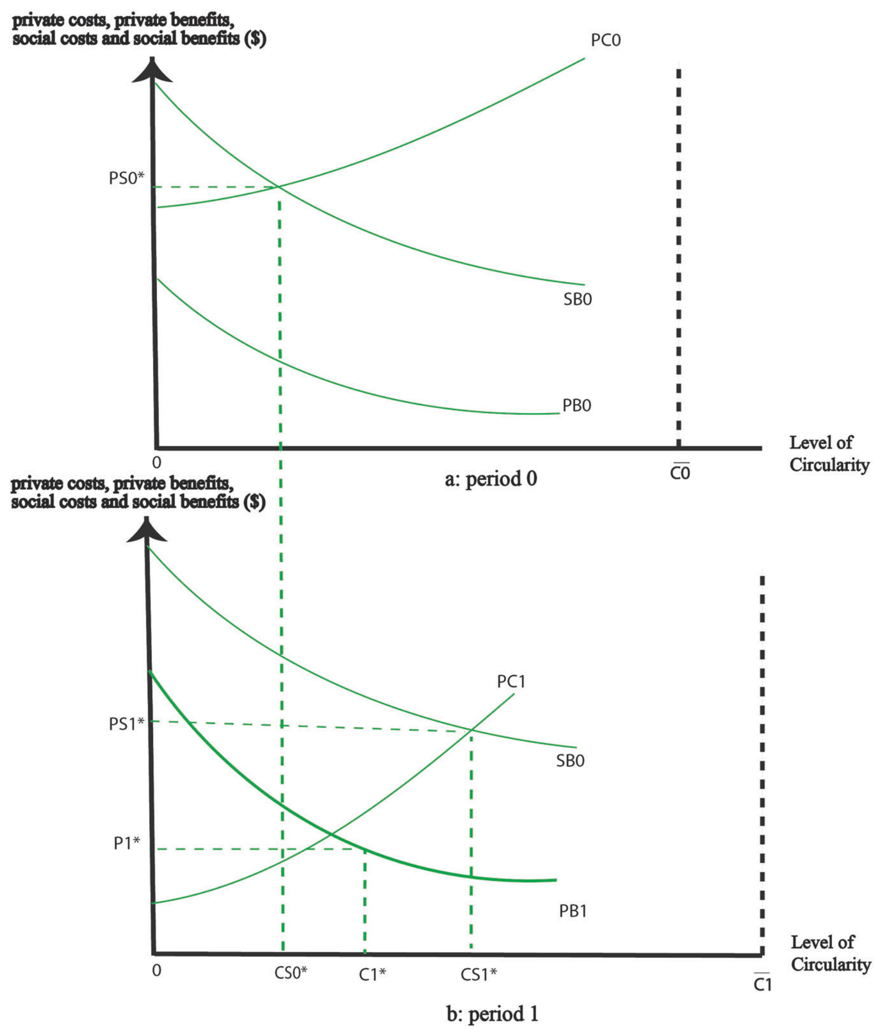
However, a techno-centric approach to sustainability may not be economically or socially sustainable, particularly if it views zero waste and replacement of fossil fuels as end goals rather than a means to an end which is improved human well-being. By itself, the circular economy framework does not provide a mechanism to determine the optimal level of circularity for a product supply chain, sector, or economy, as discussed below and shown in Fig. 2. Higher levels of circularity are likely to increase the cost of production and create trade-offs between the economic costs of circularity, environmental benefits, and social justice. Transitioning to a circular bioeconomy will involve movement along a continuum from a linear economy towards one that is more circular. Solutions that balance a mix of approaches that reduce, recycle, reuse, and dispose of waste with the costs for producers and consumers may enhance environmental and economic well-being.

The concept of a circular bioeconomy sets a single-minded goal of waste minimization and conversion to bio-based products. It does not consider the interconnected role that economic conditions, equitable distribution of resources, and environmental protection jointly play in the well-being of individuals and societies. More specifically, the vision for a circular bioeconomy does not articulate a mechanism for considering questions such as: What is the optimal level of waste and the mix of reducing, recycling, reusing and disposing it? How large are the costs of circularity, and how do they compare to the environmental benefits it leads to? Who pays for a and who benefits from a circular bioeconomy? Can we rely on voluntary approaches and corporate social responsibility to achieve the optimal level of circularity? What types of policy incentives are needed to achieve this optimal level cost-effectively and equitably?

Furthermore, the articulated vision of a circular bioeconomy is based on the implicit belief of "build it and they will come" and that the availability of technologies that reduce waste and increase resource efficiency will naturally make them desirable to adopt by producers. However, the availability of existing and emerging biological and technological solutions is insufficient to transform into a circular bioeconomy unless farmers, businesses, and consumers adopt them. Explicit and hidden costs of adopting circular technologies can limit incentives for adoption and one may need regulatory and market-based incentives to induce the optimal level of a circular bioeconomy.

This technology-push view must be supplemented with a "demand-pull" perspective that recognizes the need to incentivize farmers, businesses, and consumers to adopt circular practices, processes, and products. Lastly, the technology-centric approach to a circular bioeconomy overlooks the need for demand-side conservation efforts as another approach to

Fig. 2 | A social cost-benefit approach to determining the optimal level of circularity. Panel (**a**): A privately optimal linear economy; Panel (**b**): Private and socially optimal levels of circular economy.



environmental sustainability. Overconsumption of products that generate pollution arises because pollution damage is not included in the price of these products.

To design a sustainable circular bioeconomy, policymakers, government and non-government organizations and national and international development agencies need to adopt a normative, nuanced, and systems-view of the circular economy and an approach to determine the sustainable level of circularity – based on consideration of the synergies and trade-offs among costs and benefits of a circular bioeconomy along with the value of environmental benefits obtained and their incidence across society. These organizations frequently rely on cost benefit analysis and environmental impact analysis to examine if a policy or project is financially and environmentally sound.

Why do linear systems persist?

A common linear approach for crop production relies on tillage and nutrient intensive, monoculture crop production practices, and results in post-harvest crop losses, unused crop residues after harvest, and animal waste that could be converted to energy through anaerobic digestion, lack of recycling and reuse of chemicals during the production process, reliance on fossil fuels, single-use plastics, other disposable products as well as post-consumer food loss and waste. There is a large literature examining the factors that prevent the adoption of technologies that could be considered win-win because they are efficiency-enhancing, waste-reducing, and re-using technologies, which should save input costs while reducing nutrient loss, improving soil health, and increasing yield[31]. Despite the potential savings from reducing and reusing waste, circular and bio-based technologies may have higher costs (capital, labor, learning, and search costs), risks, uncertainties, and inconvenience, which can adversely affect the private economic well-being of producers and consumers[32]. Reluctance to implement circular methods may also arise due to a lack of infrastructure, disruption to existing jobs, limited scalability, and uncertainty about government policies[33]. Constraints on financing, access to credit and a short planning horizon (or high discount rates) limit investment in technologies that may take a few years to generate a payback through regeneration of soil health, savings in input costs, and development of markets for circular products[34–36]. Institutional factors, such as declining number of owner-operators on the farmland and lack of crop insurance for new agricultural practices, lack of extension services, technical assistance and infrastructure as well as behavioral drivers, such as attitudes, information, peers, and networks, affect producers' adoption of technologies[37,38].

In a decentralized market-based economy, individual consumers and producers make production and consumption choices based on self-interest. Individual decision-makers have minimal incentives to engage in costly activities to prevent problems such as climate change, hypoxia, and groundwater depletion; products such as certified organics that provide both private and public benefits are likely to be adopted voluntarily to the extent of their perceived private benefits but to levels that may be socially sub-optimal (as discussed below and shown in Fig. 2). Lack of awareness or education about the planetary benefits of circular products can lead to an unwillingness to pay a premium for such products, which can limit markets for these products. Most agricultural lands produce annual commodities like corn, soybean, wheat, and rice, which have long supply chains as feed for livestock and processed ingredients for food products.

Differentiating these commodities for the final consumer, based on the circularity of the methods used to produce them, is challenging due to the current supply chain infrastructure and technology that is designed to blend grain from millions of farms and transport them to wholesale markets and consumer packaged goods (CPG) companies. It is, therefore, difficult to credibly differentiate products sold to consumers based on their methods of production and charge premium prices from environmentally conscious consumers willing to pay for products with lower environmental impacts. CPG companies, however, can have vertically integrated supply chains that are circular for their products and differentiate their brand to appeal to environmentally conscious consumers. While buyers benefit from the availability of a variety or products to serve their differing preferences, product differentiation can become a source of market power. This can lead to increasingly concentrated sectors and affect the market efficiency of agri-food systems. This can affect market prices and social welfare and shift economic surplus from consumers to CPGs[39].

Pollution generated at various stages of the agri-food production process differs in its potential to be measured, monitored, attributed to a polluter, and verified at a reasonable cost; this has implications for the type of policy and behavioral interventions needed to induce circularity[40]. Pollution generated on the farm and food waste is non-point source while pollution generated by processing and CPG firms is point-source pollution. On-farm agricultural pollution is rarely subject to the polluter-pay principle and has not been directly priced. Instead, efforts to reduce pollution generated on the farm have taken the form of conservation programs that offer payments to farmers who voluntarily agree to adopt conservation practices that reduce pollution. These programs offer uniform payments that are practice-based rather than performance-(pollution-outcome)-based because of the non-point nature of agricultural pollution and challenges with measuring, tracking, and attributing pollution to sources at a reasonable cost. The voluntary, practice-based conservation payments approach to pollution control has had limited effectiveness at reducing major environmental problems such as hypoxic zones, impaired water quality in water bodies, groundwater depletion and contamination, and rising costs of waste-water treatment. Current approaches for inducing the adoption of environmentally friendly practices by farmers through conservation payments are limited by fiscal budget constraints, the inability to target participation by farmers that are causing the greatest environmental harm, and to link payments to the extent of ecosystem services provided. Agrifood processing firms are typically subjected to command-and-control air and water quality regulations which require end-of-pipe pollution control technologies and do not incentivize pollution prevention, recycling, or reuse of pollution. Food waste at the retail and household level is not directly priced or taxed and, in part due to lack of data and quantitative information on where it is being generated, stakeholder resistance to approaches that would raise the cost of food and the potential for illegal dumping.

Despite evidence of the potential of modern biotechnology to increase agricultural and biofuel yields, reduce chemical and land use, and thereby reduce biodiversity loss[41,42], public sentiment towards a bioeconomy has been mixed. Concerns about genetically modified crops' environmental and health impacts have led several countries to ban or restrict their production and use. Agricultural biotechnologies are widely used for fiber and animal feed production and less for food. The capacity of agricultural biotechnologies is expanding with innovations like CRISPR[43] and there is a need for regulatory reform for biotechnology to reach its potential. Early efforts at relying on food crops to produce biofuels in the US and EU and the accompanying spike in commodity prices have created a perception of competition between the traditional agricultural economy and the bioeconomy because they rely on the same land base. Concerns about the implications of a bioeconomy for converting non-cropland to crop production with adverse implications for carbon stocks in that land and for biodiversity have led to public skepticism about the net benefits of a bioeconomy. Efforts at switching from food crops to non-food dedicated energy crops that diversify agriculture, reduce nutrient leaching and regenerate soil organic matter have been hampered by high costs of producing advanced biofuels and bioproducts and lack of adequate incentives for investment and commercial-scale production.

Numerous alternatives to linear-based production methods exist, as described above. However, there are several failures in current markets, including subsidies, exerting downward pressure on prices for inputs (such as energy and water) and distorting incentives in production. Government subsidies have been a major form of policy support for agriculture and amounted to $817 billion per year worldwide in the 2019–2021 period[44]. While some forms of subsidies have boosted agricultural productivity, they have also raised serious concerns about introducing distortions and exacerbating the adverse environmental impacts of agri-food systems[45].

Many large farming operations and major agricultural corporations dealing in seeds, fertilizers, herbicides, pesticides, and large CPGs, are hesitant to embrace these alternatives due to concerns about reduced profit margins that could negatively impact shareholder returns. An increasing number of large corporations have voluntarily established net zero carbon, net zero waste and other sustainability goals to reduce waste to landfills, to water bodies and to increase efficiency, reuse, and recycling. The efforts are effective under restrictive conditions, in which firms set numerical goals, timelines for achieving them and their performance can be monitored, measured and tracked with public disclosure of environmental information[46]. While efforts such as private sustainability standards and information disclosure requirements are growing and can help improve the sustainability of production processes under certain conditions, these efforts are often difficult to scale and are not widely prevalent[47]. Moreover, the use of different methodologies and information reporting requirements can lead to a lack of clarity and credibility in the signals to consumers and producers[48].

Agricultural lobbying efforts by large conglomerates and farm associations significantly sway political decisions, hindering reforms to the prevailing systems and preserving the status quo, including crop insurance programs, policy support for production instead of conservation and biofuel mandates that incentivize the use of food crops for biofuel, from which they benefit substantially. The structure of institutions shapes the constituents whose interests are served by policymakers and constrains the potential for reforming agricultural support policies to lead to a more circular and diversified cropping and agri-food system. There are several explanations for the observed technology lock-in and persistence in agri-food systems even when preferred alternatives exist; the entrenchment of skills and knowledge with existing crops and technologies, policy and institutional settings that support the use of these technologies and the infrastructure and production systems that build around them and create reinforcing forces that favor their continued use[49,50].

Public concerns about climate change and environmental degradation have not led to legislation in most countries due to a lack of political will to implement policies that will impose immediate costs but would improve the well-being of the people, land, and the planet in the long run. Despite awareness of the benefits of preventing problems rather than fixing them later, governments with short time horizons fail to take preventive actions that impose short-term economic costs but provide long-term environmental benefits. The presence of multiple and diverse interest groups that vary in their gains and losses contributes to the complexity and challenges of crafting effective environmental regulations.

We now describe a framework to guide the transition to a circular bioeconomy that is sustainable in a market economy.

A framework for transitioning to a circular bioeconomy

Welfare economics offers a conceptual, social cost-benefit framework that determines optimal choices of consumption, production, and technology, and also the prices of market goods and non-market environmental goods that would maximize net benefits (for consumers and producers net of the environmental damages caused by those choices). A stylized representation of this framework is shown in Fig. 2, with circularity represented on the horizontal axis by a scale from 0 to $\bar{C}_0$<1, with *0* representing no efforts at waste reduction beyond what is in the private interests of producers in the absence of any market or regulatory incentives and $\bar{C}_0$ representing a technologically feasible extent (less than 100%) to which waste disposed to the environment can be reduced in the initial time period (Fig. 2a). This level is expected to shift to the right, with technological development, as shown by $\bar{C}_1$ (Fig. 2b). The incremental private cost of reducing waste is expected to be upward-sloping but could be linear, non-linear, or U-shaped. The high fixed costs of scaling up technology could initially result in declining incremental costs due to economies of scale. It is expected to increase, possibly at an increasing rate, as the marginal cost of waste reduction increases and becomes steeper as the theoretical maximum is approached. Monetized values of the benefits of reducing the multiple environmental externalities caused by human activities (based on individual willingness to pay for reducing environmental damages) represent a "demand" for circularity. This is expected to decline as circularity increases but may have an inverted U-shape as the marginal benefits of the first few units of waste reduction can be expected to be low and to increase as waste reduction increases up to a point after which there could be diminishing marginal returns to waste reduction. For simplicity, we represent the private marginal cost of circularity by PC_0 and the private marginal benefit of circularity by the PB_o at time $t = 0$. The social marginal benefit of circularity is represented by SB_o; it can also be considered as the inverse of the social cost of waste generation. Based on economic theory, the privately optimal level of circularity is the point where $PB_o = PC_o$, while the socially optimal level of circularity is represented by the point where $SB_o = PC_o$.

Figure 2(a) represents the case where the private demand for circularity PB_0 is low (because the environment has a large capacity to absorb waste, public awareness of the damages due to a linear economy is low, and incomes are low leading to low demand for environmental quality). In contrast, the incremental cost of circularity represented by curve PC_o is high. In the absence of political will and environmental regulations that price waste or set standards to reduce waste to C_{so}^*, the level of circularity chosen by a market economy is zero (representing a linear economy), because there is no intersection between the PC_o and PB_o curves in Fig. 2a. The socially optimal level of circularity is represented by C_{so}^* with an implicit social cost of waste of P_{so}* (Fig. 2a).

Over time, as environmental damage increases with growing economic activity and the private value placed on environmental quality grows, the private benefits to producers of being socially responsible increase. Suppose that the private demand for circularity shifts to the right to PB_1, at a future time period, $t = 1$ (Fig. 2b). At the same time, technological change reduces the private cost of increasing circularity and shifts the supply of circularity to PC_1. The privately optimal level of circularity is now C_1* with an implicit willingness to price waste at P_1^*. This represents the effects of corporate socially responsible efforts by large firms, such as CPGs, to reduce waste and increase efficiency through their supply chains that can also lead to on-farm efforts to adopt low carbon intensity practices, increasing nutrient use efficiency and soil carbon sequestration. Although, the level of circularity achieved through the socially responsible efforts of producers and consumers is higher than before but still likely to be less than the socially optimal level C_{s1}* with full internalization of externalities by consumers and producers.

With self-interested decision makers, government intervention in the form of penalties for waste generation (such as a carbon or pollution tax) or subsidies for waste removal, recycling, or carbon credits, priced at the social cost of waste, P_{s1}*, or regulatory limits on waste are needed to move towards a socially optimal level of circularity. The magnitude of these taxes will decrease with the availability of low-cost circular technologies and increase as the urgency, magnitude, and value of environmental damages increases. Further shifts in the demand for circularity to the right and reduction in the private cost of circularity, which shift the supply to the right, can result in higher levels of circularity becoming optimal over time.

This framework takes a systems view of the economy. It defines a linear economy as generating a significant amount of waste because it does not internalize the environmental damages from human activities. It recognizes the dynamic nature of technological innovation and evolution of consumer preferences for environmental quality that make a higher level of circularity optimal over time. By incorporating environmental damages in the accounting of social welfare, this framework can determine the optimal mix of technologies, pollution reduction, recycling, reuse, and disposal, and the extent of circularity that maximizes social net benefits. This framework can be extended to consider the social costs of the multiple environmental impacts and trade-offs involved in transitioning from a linear economy to a circular bioeconomy.

Figure 2 shows that the transition to a circular bioeconomy will involve imposing a social cost of waste on the production and consumption of agri-food products. This is expected to raise costs and prices of these products for producers and consumers. This social cost may decrease over time with technological improvements and a greater willingness to internalize the environmental damages of production and consumption decisions. The costs of efforts towards circularity may be disproportionately borne by smaller, low-income producers who cannot bear the costs of participation in sustainability certification program, and lack access to credit, insurance, and technical assistance. While the transition to a circular bioeconomy is socially optimal, this transition does not imply that it will result in a Pareto superior outcome for all, in fact, it may have notable adverse impacts on equity outcomes.

The framework described here can provide the price of various pollutants that need to be imposed, either in the form of pollution taxes or pollution reduction subsidies on carbon emissions, nutrient losses, and other pollutants, to achieve the optimal extent of transformation to a circular bioeconomy in a market economy. The application of this conceptual framework to a product supply chain, sector, or region to determine the optimal level and pathways to circularity requires interdisciplinary collaborations to develop a range of empirical analyses to quantify the costs and benefits of circularity under various technological, market and demand conditions. Economic and social science frameworks need to be integrated with agricultural, biological, and environmental engineering to understand the technological options for reducing, recycling, recovering, and reusing waste generation at each stage of the product from the cradle to the grave for each agri-food commodity. They also need to be integrated with environmental sciences to assess the impacts of alternative pathways for multiple environmental outcomes[51]. To incentivize applied economists and other social scientists to collaborate with agricultural scientists in interdisciplinary research, academic institutions should value publications in interdisciplinary journals, editors of mainstream interdisciplinary journals should prioritize publications that include social scientists, professional social science associations should showcase interdisciplinary research and funding agencies should emphasize interdisciplinary research with social scientists in their allocation decisions. Transition to a circular economy can be expected to involve trade-offs with low costs of food, energy, and water, at least in the short run, till low-cost alternatives to fossil fuels, plastics, and synthetic chemicals are available at scale. Reducing food loss and waste can also have food safety risks that need to be considered. These trade-offs are expected to be mitigated in the long run with technological advances and regulatory incentives that induce innovation. In the near term, the transition to a circular bioeconomy could have a negative consequence for equity within and across countries by raising prices of sustainably produced and differentiated agri-food products and leading to higher costs of energy and clean water to prevent waste. As a result, while the transition to a circular economy may increase the sum of welfare to all groups, it may not be "win-win" for each group. Equity considerations need to be incorporated in the design of policy incentives to mitigate the adverse impacts of a circular bioeconomy on the socially vulnerable groups and to wider acceptance of this transition.

This framework suggests that transforming a linear economy to a circular bioeconomy will depend on the following five pathways that can mitigate trade-offs between competing objectives and strengthen synergies.

Pathways to transition to a circular bioeconomy

Technological advances through investment in research and development are crucial for lowering the costs of circular and bio-based technologies[52]. Public investment in research and development from basic science to commercialization is key to making such technologies commercially available and competitive with conventional technologies, increasing their effectiveness, and thereby mitigating the trade-offs between private economic well-being and social benefits associated with this transition[53]. Emerging digital twin and artificial intelligence technological advances combined with high temporal and spatial resolution data that the field equipment will automatically gather has the potential to convert agriculture from a source of nonpoint pollution to a point source by documenting management practices implemented by farmers, lowering the cost of monitoring practices and using digital twin technology to determine the impact of those practices on the environment and enabling individualized agriculture and supply chain traceability[54,55]. These advances can enable causal attribution of the impacts of production systems on environmental outcomes[56]. This is critical for incentivizing a market-based transformation of the existing linear systems to a circular bioeconomy and implementing performance-based, "polluter pays" policies in the agri-food sector.

Regulatory incentives and institutional change

These transformations require regulatory changes that go beyond the existing voluntary conservation programs for farmers, technology mandates, and command-and-control regulations on businesses to market-based policies that price waste generation, processes, and products based on their social costs of production which include their external (environmental effects) and consumer valuation of those environmental damages. Market-based policies, such as a carbon tax, nitrate taxes, or nonpoint pollution trading schemes, provide the flexibility that is needed for the optimal mix of technologies, demand side conservation, and combination of reduce, recycle, reuse, and regenerate strategies to emerge. A circular bioeconomy also requires institutional transformations that reduce the riskiness of circular production practices through crop insurance programs, loan guarantee programs, environmental reporting, disclosure, and labeling requirements, and reducing regulatory barriers to developing new bio-based technologies.

Markets for circular products

Demand for circular products and processes can emerge voluntarily to some extent from socially responsible firms, investors, and environmentally conscious consumers. Voluntary markets for circular products can align private with social well-being. Credible certification of products and processes, branding and labeling of commodities as circular and bio-based will be needed to enable differentiated pricing of products. To measure and certify the level and impact of circular bioeconomy practices, a comprehensive framework which includes measurable indicators and certification standards is necessary. These indicators help track the effectiveness of circular practices in increasing resource use efficiency, reducing waste, enhancing biodiversity, regenerating natural systems and increasing profits. Verifying the adoption of circular practices in agriculture is essential for enhancing credibility and trust among consumers, investors, and regulators and for inducing environmentally conscious consumers to pay a premium for sustainably produced goods. This financial incentive encourages businesses to adopt and maintain circular practices. Emerging digital twin and blockchain technologies would allow practices to be benchmarked against best case scenarios and evaluate potential improvements to be implemented as well as offer a state-of-the-art method to verify and demonstrate compliance with sustainability standards effectively[57] This digital approach is crucial for meeting regulatory requirements, enhancing market access, improving operational efficiencies, and promoting sustainability. By leveraging advanced technologies, we can ensure more transparent, traceable practices which are aligned with the principles of the circular bioeconomy.

Public education and awareness

The environmental impacts of linear economic systems are often not immediate (as in the case of climate change) or felt by those contributing to those impacts (as in the case of water quality impacts on downstream waterbodies) through their production and consumption decisions. Educating consumers about the ecosystem services provided by circular bioeconomy products can lead to a change in their preferences and a higher willingness to pay, create a market for circular products, and generate political support, making circularity more sustainable in the long run.

Equity considerations

The regulatory, market and institutional transformations that accompany the transition to a sustainable circular bioeconomy are expected to have political economy implications since they are likely to create winners and losers. Higher production costs across the supply chain are likely to be borne partly by producers, consumers, and the government. Prices of circular agri-food products may also be higher due to market power induced by differentiation of products by CPGs. Anti-trust standards and efforts at increasing free entry by firms can play a critical role in preserving competition in differentiated product markets and prevent prices rising above competitive levels. Incorporating equity considerations into processes that support a sustainable and circular bioeconomy is crucial for ensuring that the benefits of such an economy are distributed fairly among all stakeholders, including marginalized and vulnerable communities. Aggregated measures of well-being such as social welfare, GDP, and the social cost of pollution hide the distributional impacts of the transition to a circular economy and who benefits and who would bear the transition costs. An equitable circular bioeconomy requires the governance and decision-making processes guiding the transition to be inclusive, involve diverse stakeholders, and consider ways to mitigate adverse consequences for vulnerable sections of society[58]. To compensate those that may lose from the transition to a circular bioeconomy, governments should establish compensation mechanisms including safety nets, income redistribution programs and workforce reskilling and upskilling programs.

Conclusion

The notion of a circular bioeconomy is appealing because it embodies eliminating waste, reducing environmental contamination, and converting waste into bioproducts that displace fossil fuels. However, the concept needs to provide a framework for transforming a linear economy into a circular bioeconomy that can be sustainable in a market-based system and design mechanisms to achieve that. The transition to a circular bioeconomy is expected to inevitably involve trade-offs between profits for producers, low-cost goods for consumers, and lower environmental impacts. Investment in research, improvement in scientific knowledge, and introduction and adoption of solutions that take advantage of this new knowledge and are enabled by sound regulation and policies will allow improvement of the set of trade-offs that society must make in the long run. The transition toward a circular bioeconomy will require political will to provide the needed policy changes (incentives or taxations) and investments to expand the research agenda to develop novel technological solutions to address major economic, market, and current policy challenges. It also requires private-sector partnerships to induce the adoption of new technologies and consumer acceptance of them. These significant changes in public and private sector choices can only be done with policy changes, that price waste and fossil fuel emissions and create incentives for industry and consumers to adopt these new technologies. We must formulate comprehensive strategies to smoothly transition between sunrise and sunset technologies, products, and practices and favor an overall reduction in societal consumption. The design of the mechanisms to enable a circular bioeconomy should be based on interdisciplinary science. Economics offers a social cost-benefit framework that together with life-cycle environmental impact accounting, engineering solutions for recycling and reusing waste, and agronomic and soil science knowledge of the causes of pollution on the farm can provide a systems approach to developing a circular bioeconomy. Sound economic thinking may result in more circular outcomes but not necessarily fully circular. Furthermore, the transition to a circular bioeconomy will likely be gradual and must adjust to political economic considerations. It is a diffusion process that occurs gradually due to heterogeneity among producers and regions. It benefits from learning and innovation, making circular approaches more attractive to larger fractions of the population over time. Depending on their social preferences, different societies may pursue policies varying in their tradeoffs between economic welfare and the extent of circularity.

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Author contributions

M.K. and D.Z. conceived of the paper; All authors contributed ideas and text; B.B. and G.H. contributed the figures; M.K. was the lead writer.

Competing interests

The authors declare no competing interests.

Additional information

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