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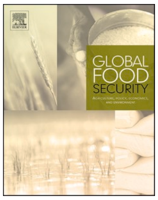

Perspective paper: Framework to assess the potential of circular food system technologies

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ABSTRACT

The circular bioeconomy has been identified as a paradigm useful in transforming food systems to a more sustainable state. However, there is no clear method to identify in which cases circular technologies are preferential over existing conventional practices and how to compare circular technologies against each other in a portfolio of technologies. In this Perspective, we present a framework to assess the potential of circular food system technologies, summarized in a matrix to assign clear policy and adoption priorities. We then use this framework to compare the net market and spillover benefits of three case studies of circular technologies: low-opportunity cost feeds in egg production systems in the Netherlands, biodigesters on dairy farms in Uruguay, and bonechar fertilizer production in Ethiopia. Our framework offers a starting point for future research and policy in adopting circular food system technologies in the food system.

1. Introduction

Global food systems have transitioned significantly over the past century. This transition has resulted in more affordable diets for a growing global population but has not achieved the UN Sustainable Development Goals related to food systems and the environment (Ambikapathi et al., 2022). This has spurred growing calls for transitions toward more sustainable food systems (Herrero et al., 2020). The circular bioeconomy is one proposed solution that could contribute to more sustainable food systems (Freeman et al., 2022; Moberg et al., 2021; Sandström et al., 2022; Springmann et al., 2018; van Hal et al., 2019; van Zanten et al., 2023).

As the economic contribution of environmental sustainability has been increasingly recognized in private and public decision-making related to food systems, the attention on reducing the impact of food production in a resource-constrained environment through circularity has likewise increased. The circular bioeconomy concept and paradigm have gained significant traction in policy, academia, and private industry in recent years (Kirchherr et al., 2017). While the definition of the circular (bio-)economy remains under debate (Loiseau et al., 2016), the essence of the various definitions centers on the sustainable management of various forms of side-stream and waste resources (for example, the usage of soy meal after soybeans are pressed for oil) (Ghisellini et al., 2016).

A circular bioeconomy has the potential to reduce numerous negative environmental and social externalities through the cycling of nutrients, biomass, and energy through the food system (Desing et al., 2020). For instance, van Zanten et al. showed that the land use and greenhouse gas emissions of the European food system could be reduced by 71% and 29%, respectively, under a transition towards a more circular system (2023). This type of result was achieved by widespread circularity in the form of avoiding the use of non-essential products and

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the waste of essential products, prioritizing biomass for basic human needs, utilizing and recycling by-products of agroecosystems, and consuming a healthy diet (Muscat et al., 2021). Adherence to these principles by both producers and consumers can make it possible to keep food systems largely within environmental limits (Springmann et al., 2018).

While modeling can demonstrate the systematic potential of circular food systems, much of the current investment and policy attention in circular food systems is dedicated to specific circular technologies that can improve the system's environmental and economic outcomes without requiring a whole system transformation. Circular bio-economy technologies can offer benefits at the food production, food consumption, and food waste (i.e., by-products, side-streams, and discarded materials) stages of the food system, with varying levels of technical-social buy-in. In these three entry points, numerous circular bio-economy technologies already exist at varying levels of technology development (Jurgilevich et al., 2016). As more policies and investments focus on food systems' role in achieving sustainability goals by reducing environmental and social externalities and boosting the reuse of resources, it will be increasingly crucial to assess and prioritize specific circular technologies that facilitate a transition to more sustainable food systems (Barrett et al., 2020; Herrero et al., 2020; Moberg et al., 2021). We, however, lack a general framework to systematically assess and compare the unique potential of circular technologies to generate benefits in today's food systems.

Circular technologies need to be evaluated not only for their ability to provide market (i.e., economic) benefits to private investors and users but also for their ability to reduce and minimize spillover (i.e., environmental and social) costs, such as nutrient pollution, to the general public. Both market benefits and spillover costs need to be assessed as an overall combination of benefits and costs for local and global users. As food systems technologies are rooted in the culture, diet, temporal setting, and agro-ecosystem in which they operate, the above abilities need to be compared to a baseline technology that currently fills the niche the circular technology bundle would occupy, such as using food waste to produce black soldier flies for chicken feed compared to growing maize for the same purpose (Parodi et al., 2018, 2021). This comparison has to be tied to the local valuation of market benefits and spillover costs, as certain externalities affected by the use of a circular technology will be valued differently according to their context. Finally, the circular practices need to be appraised in terms of their fit into pre-existing policy and governance frameworks. From these points, we aimed to fill this gap by creating a framework that would assess a circular food system technology and allow for its comparison to the baseline conventional technology and other potential circular technologies.

2. Framework and matrix for assessing a circular food system technology's potential

Based on the principles described in the paragraph above, we developed a framework to assess a circular food system's technology's potential (Appendix A). Previous frameworks and assessments of circular technologies were either highly specific to a certain type of technology or nutrient, missed the incorporation of economic or social dimensions, contained only qualitative assessment methods, or were meant to assess the degree of circularity for existing supply chains (Bocken et al., 2016; Silvius et al., 2023; Spiller et al., 2024; van Loon et al., 2023; WBCSD, 2023; WBCSD Circular IQ, 2023). To remedy this point, our framework can analyze any specific type of circular technology according to its economic, environmental, and social potential and compare different types of circular technologies for their specific context against each other.

Our framework is founded on the historical work done in the field of social cost-benefit analysis, where investments are valued for both their private economic returns and their social benefits compared to their respective costs. We then incorporated the field of life-cycle assessment for the social benefits, where the total environmental impact of a product along its lifespan is calculated. However, this life-cycle assessment data results in multiple relevant outputs, from land use to greenhouse gas emissions. To consolidate these outputs, we used true cost data, where a monetization factor for a certain impact in a specific location is used to homogenize the relevant environmental and social outputs into one metric, the true cost. By comparing economic costs and benefits (referred to as market benefits and costs in this work) and the monetization of environmental and social costs and benefits (referred to as spillover benefits and costs in this work), multiple circular and conventional (baseline) technologies can be analyzed and compared.

This work can inform research and policy to value and prioritize circular technologies. This framework relies on a set of equations that assess a technology's circular potential based on a comparison of its net market and spillover benefits relative to the baseline input it would replace. By comparing the technologies and their respective system's inputs and outputs using this framework, it is possible to determine the magnitude and ratio of change of these benefits. In our deployment of the framework in this article, we use private profit as the indicator for net market benefits and costs and net environmental true costs as the indicator for net spillover benefits and costs. For net environmental true costs, we focus on the major environmental true costs of agricultural production (which we calculated across a product's lifecycle from cradle to farmgate) (Galgani et al., 2023). The cost types included are scarce water use, pollution (freshwater and eutrophication, particulate matter formation, photochemical oxidant formation, and acidification), land use (adjusted for biodiversity loss), fossil fuel depletion, and greenhouse gas emissions. Other social costs that could be included in the frameworks are child and forced labor, education provision, and living income.

While the general framework we present (Fig. 1) could be applied to many technologies, the equations (see Appendix A) used to operationalize the framework are specific to circular food system technologies, which explicitly value waste streams. The accounting of their externalities subsequently shows the reduction of spillover costs while increasing market benefits that can occur with the circular flow of directly valorized inputs. This type of framework is particularly useful for any third-party group, such as governments, intergovernmental, or philanthropic organizations, interested in choosing technology grouping for investment in R&D, extension, or market promotion (or

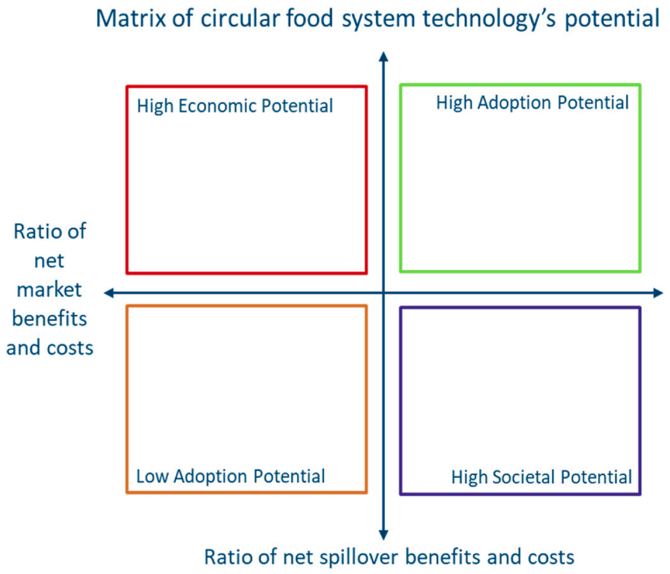

Fig. 1. Matrix of circular practices. Market benefits and costs are the private financial benefits and costs per adopter. Spillover benefits and costs are the reductions in the environmental and social true costs per adopter.

discouragement) to achieve reductions in spillover costs while accommodating market conditions.

This matrix (Fig. 1) provides conceptual groupings of the potential of circular practices. The scope for synergies and avoiding trade-offs between net market benefits and net spillover benefits is central to the adoption of circularity within the food system. Through the use of this framework, one can assess how the ratio and magnitude between the circular and baseline net market benefits and net spillover benefits sort the circular practice's placement on the matrix. This placement signals the current potential of a circular technology and can provide a starting point for the discussion on moving the technology across the matrix (Fig. 2).

The practices in the *upper right* grouping already have a high adoption potential from both net market benefits and net spillover benefits perspectives, as they have a higher direct economic return per adopter and a higher public benefit potential for reducing externalities compared to their respective baseline technology. The adoption rate of these technologies would depend on the technologies' readiness level (TRL), i.e., the progression of a technology from an initial concept through testing to being deployed as a complete solution, and the ability of the political landscape of the current food regime to absorb novel technologies, i.e. if a new technology is actively used and chosen instead of a current technology (European Commission, 2014). The technologies in the *lower right* grouping have a lower direct economic return per adopter and a higher diffused public benefit potential for reducing externalities compared to their respective baseline technology. The net spillover benefits derived from these technologies could be realized through a conducive policy regime that provides additional net market benefits for the adopter, either through economic subsidies or public research and development to drive down unit costs for the circular method, or regulatory requirements or taxes that increases costs of the incumbent technology. Governmental policy regimes have a clear preference for prioritizing both groupings on the right side of the matrix.

The technologies in the *upper left* grouping have a higher direct economic return per adopter and a lower diffused public benefit potential for reducing externalities compared to their respective baseline technology. While these technologies are highly attractive to private adopters, governments and policymakers need to carefully weigh the additional relative societal costs compared to the ability to produce a necessary service in the food system. These technologies could be either improved to reduce their spillover costs or disincentivized through increased adoption costs. The technologies in the *lower left* grouping have the lowest adoption potential of any circular practice. These technologies are not better than the current technologies in the market or spillover benefits. While analysts might monitor such technologies for changes that might reposition them within the matrix, they are commercially and socially unattractive.

3. Application of the framework and matrix through case studies

We applied this approach to three circular technology case studies that were chosen by the authors from peer-reviewed scientific literature to represent a range of technology levels as a proof-of-concept for this framework. We analyzed the case studies for their respective market benefits and costs and their environmental benefits and costs (using true cost monetization factors). By using true cost data specific to each

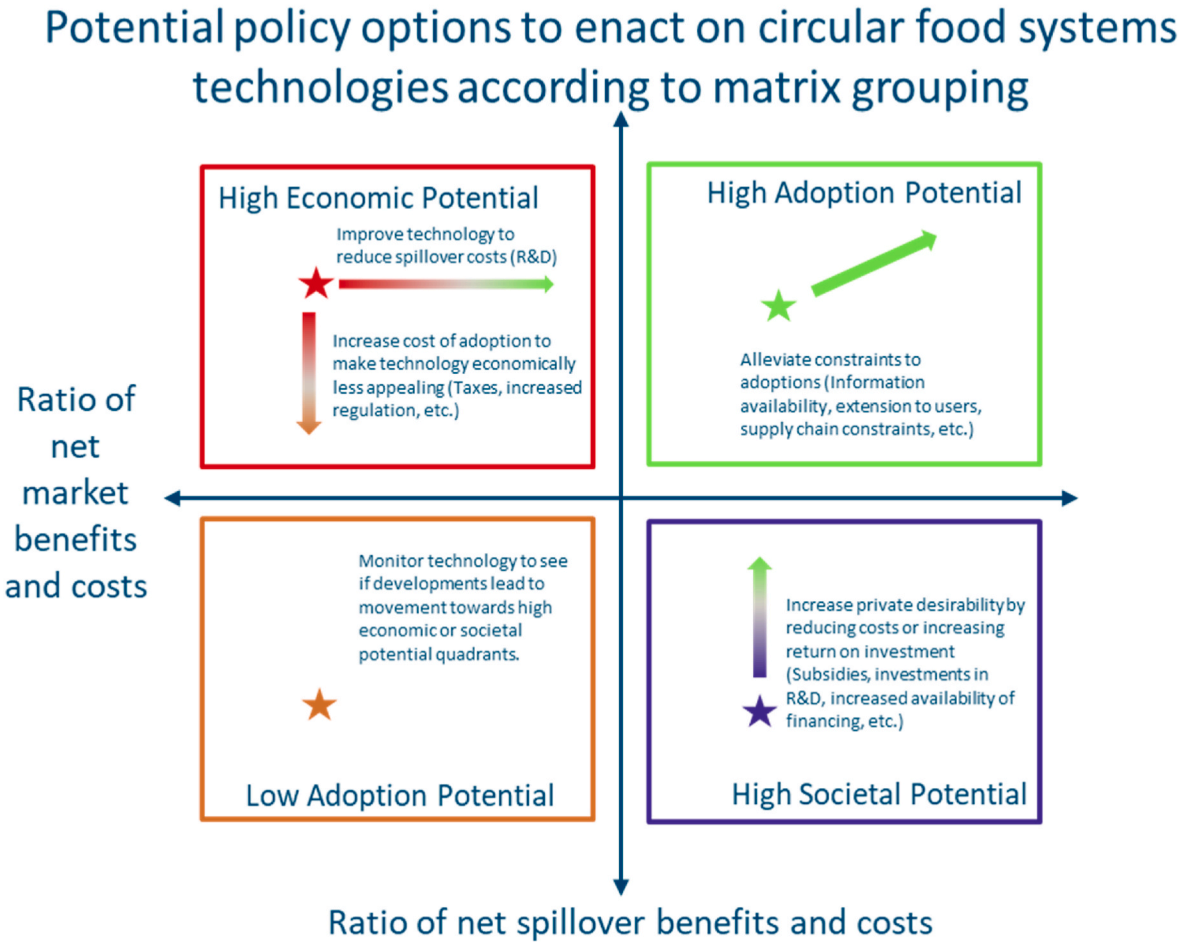

Fig. 2. Policy recommendations for each matrix grouping of circular food system technologies. The arrows designate the respective direction in which a technology (indicated by a star) would move (indicated by the directional arrow(s)) if the policies indicated in the text were applied.

country, local conditions and interests in environmental benefits and costs are reflected in a way that still enables systematic cross-country comparison. Data availability in the selected case studies prevented the use of social true costs (e.g., child and forced labor, education provision, living income), whose use could increase the insights generated from this framework and could be considered for future analysis. The technologies assessed ranged on the 1–10 scale of technology readiness levels (TRL) from a proof of concept (TRL 3), a technology demonstrated in a relevant environment (TRL 6), and actual technology proven in the environment it would typically be used (TRL 9) (European Commission, 2014). The case studies also represent a range of locations (Africa, South America, and Europe) and a range of national income levels (low, upper-middle, and high): the utilization of food waste as livestock feed in the Netherlands (TRL 6), the biodigestion of dairy farm effluent for fertilizer and energy in Uruguay (TRL 9), and the early stage niche technology of processing of discarded animal bones for locally produced phosphate fertilizer in Ethiopia (TRL 3). The analysis of these case studies utilizes information from published scientific studies. These studies, in turn, were the product of co-learning between local stakeholders, farmers, and interdisciplinary scientists (Blalock et al., 2022; Freeman et al., 2023; Simons et al., 2014, 2023; van Hal et al., 2019; Vassilev et al., 2013). We assessed each case study after one year and projected fifteen years to demonstrate the potential difference in framework and matrix results that can occur according to different time horizons, but this time horizon can be adjusted according to user needs (Fig. 3).

3.1. *Case study 1: Netherlands low-opportunity cost animal feedstuffs*

The livestock sector produces 15% of global anthropogenic greenhouse gas emissions and 57% of all GHG emissions related to food production (Gerber et al., 2013; Xu et al., 2021). The production of feed for livestock, of which poultry classically consume grains and soy, occupies approximately 40% of global arable land (Mottet et al., 2017). One circular opportunity to reduce the environmental impact of livestock is by feeding livestock ‘low-opportunity-cost feedstuffs’ (LCF). This LCF can entail food waste, food losses from farmgate and processing, grazing resources from non-arable lands, the by-products of food processing, and crop by-products (Van Zanten et al., 2018). Feeding livestock with LCF mitigates the related environmental and social burdens from food loss and waste, as well as growing livestock feed, contributing to a more efficient food system (Röös et al., 2017).

The LCF livestock system presented in this paper (Fig. 4) is a private egg production system called ‘Kipster’ (van Hal et al., 2019). The system utilizes LCF to feed its poultry, rears its male chicks for their meat, and uses a solar energy grid for its energy. The Kipster system was first piloted in the Netherlands and has now expanded to several locations in the Netherlands and the United States of America (Kipster, 2020). The LCF fed to the Kipster chickens is primarily food processing by-products and losses, such as eggshells, breadcrumbs, and sugar syrup, fortified with key nutrients and protein through sunflower meal, a by-product from sunflower oil processing (van Hal et al., 2019). We applied the framework described above to assess the net market and spillover benefits of the Kipster system compared to the baseline of free-range egg production in the Netherlands.

Using almost 1000 metric tons of LCF inputs, the Kipster system annually produces 335 metric tons of eggs and 17 metric tons of meat. This system produces 51% of the GHG emissions and uses 89% of the land use of a similar-sized free-range egg production system. The system’s reduction in GHG emissions (from 1,027,000 to 525,000 kg CO2eq) is primarily derived from the avoided emissions from feed production as well as the reduction of emissions from the decomposition of food by-products. The reduction in land use (1539 to 1297 ha) for feed production is related to the usage of LCF and the replacement of another system’s broiler chicken production through rearing male chicks in the Kipster system (Appendix B-C).

The Kipster case study shows that feeding LCF to layer chickens at an industrial scale in the Netherlands has significant potential over the baseline free-range production system, particularly due to its environmental benefits. While it is less profitable than the baseline system in the first year due to higher investment costs in buildings and equipment, the reduction in energy costs from solar energy production and the higher

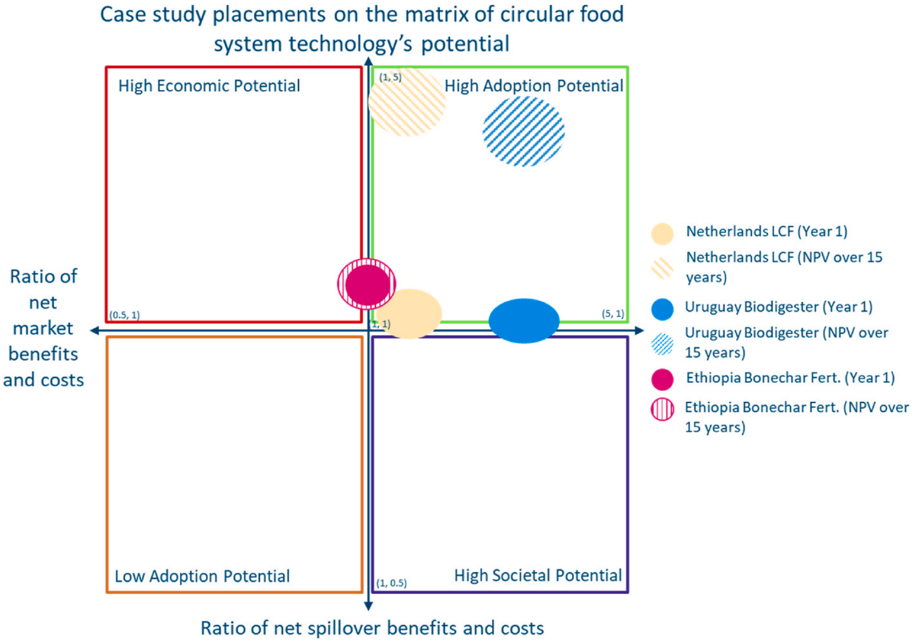

Fig. 3. Matrix of circular food system technology’s potential for selected case studies. The positions on the matrix for each case study were calculated in Appendix B using the framework of equations in Appendix A. The size of the points on the graph corresponds to 10% of the $\log_{10}$ scale difference between the baseline and circular technology. Oblong shapes reflect the relative differences in the $\log_{10}$ scale between the net market benefits and costs and net spillover benefits and costs. Netherlands LCF represents Case Study 1: Netherlands low-opportunity cost animal feedstuffs. Uruguay Biodigester represents Case Study 2: Uruguay Dairy Effluent Biodigester. Ethiopia Bonechar Fer. represents Case Study 3: Ethiopian bonechar phosphate fertilizer.

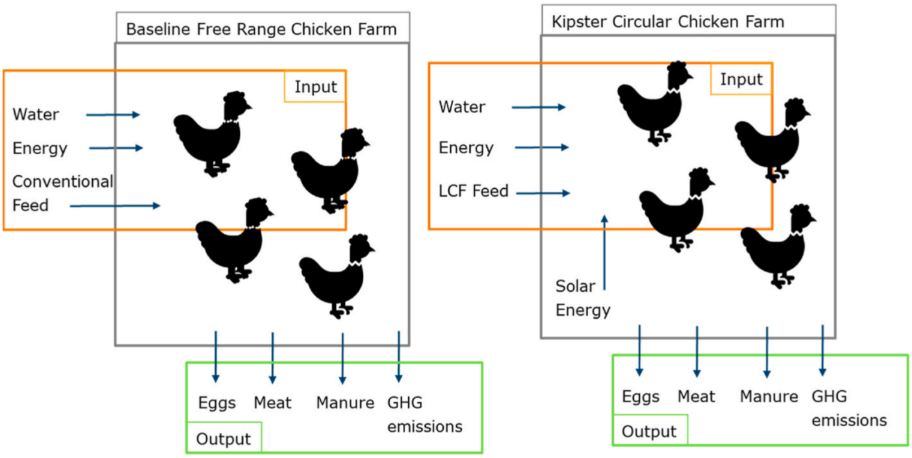

Fig. 4. Systems Diagram of the baseline free-range chicken farm and the Kipster circular chicken farm.

price of the premium eggs result in greater profits for the Kipster system by the 15th year. The real-world business case of Kipster solved this issue of their initial high costs by entering a multiple-year contract with Lidl (Kraaijenbrink, J., 2020). Due to the ratio of the net market and spillover benefits, this technology is placed in the high adoption potential grouping on the matrix for assessing circular technologies (Fig. 3).

Modeling results show that using LCF in animal production systems in Europe can provide substantial amounts of animal-based protein to meet our dietary needs (van Selm et al., 2022; van Zanten et al., 2023). LCF can play a substantial role in national protein strategies as the European Union is promoting the reduction of imports of plant proteins for animal feed (European Commission, 2018). However, LCF is a finite resource that can be diverted to other production systems, such as biodigesters, precision fermentation, and combustion for energy (Muscat et al., 2021). The appropriate and responsible prioritization of LCF usage for human-edible food production could be part of an enabling policy environment for this technology. In this, further exploration into the best usage of LCF in the context of the Netherlands could be conducted to determine how this usage compares to other cases. Our framework provides valuable contextualization and prioritization of the usage of LCF within the egg production industry in the Netherlands as a viable and high-potential technology.

3.2. Case study 2: Uruguay dairy effluent biodigester

Anaerobic digestors, also called biodigesters, are closed, airtight vessels in which organic material is deposited to support anaerobic digestion, a process that leads to the degradation of the material by bacteria in the absence of oxygen, converting it into methane and carbon dioxide mixture for use in energy and heat generation. On-farm biodigesters are used with agricultural waste streams or manure and are maximized when there is a concentrated source of feedstock. Effluent on dairy farms is a biodigester feedstock that is comprised of water, manure, urine, and waste milk. It contains high levels of nutrients, organic matter, and pathogens that, if not properly managed, can contribute to environmental issues, such as nutrient pollution in soil and waterways, health issues related to contaminated waterways, and GHG emissions (Sommer et al., 2013).

The biodigester case study presented in this paper was a pilot project financed in Uruguay by the Global Environment Fund as part of a program called Biovalor. The demonstration site called "Rincon de Albano" has 500 milking cows and is located in the country's most important watershed, Santa Lucia, which provides drinking water to the capital city of Montevideo (Uruguayan Ministry of IndustryE. and M, 2020). The farm is a pastoral-based system where the dairy cows graze freely. Cattle excrement (urine and manure) is produced when the cows are in the holding pen, the milking parlor, and the feeding area and are washed out, producing liquid effluent (Jesus et al., 2021; O'Connor et al., 2021; Yao et al., 2020). Before the Rincon de Albano biodigester was installed, this effluent was washed back into a wastewater lagoon with the potential of leaking N and P into the watershed.

Biodigesters could increase the circularity of organic waste streams, particularly on dairy farms. In the case of Rincon de Albano, urine, manure, and wasted milk are washed into a biodigester and, through the anaerobic digestion process, produce several outputs: a) clarified effluent that is used again as water for cleaning machines; b) digestate, a nutrient-concentrated solid containing primarily phosphate, nitrogen and potash, that is then reapplied to fields as fertilizer; c) biogas, comprised of carbon, methane, and nitrogen, that is passed through a motor generator to create electricity, which is used on the farm or sold to the grid; and d) heat, which is input into the motor generator for additional energy generation (Freeman et al., 2023). Biodigesters are also known to have other co-benefits like reducing farm odor, conserving ecosystem functioning through effective manure management, and generating local jobs, as well as increased risks for methane leakages, which are not included in this paper (Jesus et al., 2021; O'Connor et al., 2021; Yao et al., 2020).

We applied the framework to assess the wastewater lagoon of dairy farm effluent as the baseline system and the biodigester utilizing dairy farm effluent feedstock as the circular technology (Fig. 5). Through the use of 229,000 kg of effluent, the biodigester digestate is able to replace 10% of the inorganic fertilizer used by local arable crop production, and the motor generator produces 49,275 kWh per year, valued at 222,254 USD. The biodigester's energy production mitigated 512,219 kg CO_{2eq} of energy emissions. The clarified effluent replaced 20,000 m^3 of water used by the farm per year, and the biodigester system reduced yearly phosphorous eutrophication from 15,000 kg PO_4 in the lagoon system to 5,000 kg PO_4 in the biodigester system (Appendix B-C).

Biodigesters in Uruguay demonstrated relatively high economic, environmental, and social strengths over the baseline system (Fig. 5). There is a beneficial ratio of net market costs, as the initial capital cost of installing the biodigester system was fully recouped in three years due to monetary savings on energy and fertilizer. On the environmental side, the technology shows substantial benefits as well, with reductions in eutrophication and emissions reduction in the first year valued more than the cost of installation (Appendix B). As the high eutrophication rates from dairy production in the Santa Lucia watershed previously led to unpotable water in Montevideo (notably for drinking water in 2013), the reduction of phosphorous eutrophication has reduced the government's costs of purifying water and reduced harmful blooms (Delbene Lezama, 2020; Uruguayan Ministry of IndustryE. and M, 2020). This

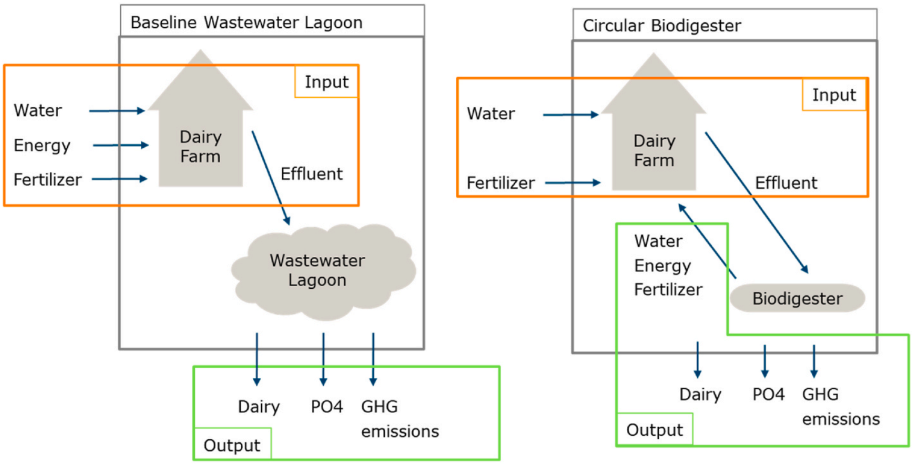

Fig. 5. Systems diagram of Biovalor pilot project, with the baseline wastewater lagoon and the circular biodigester systems.

technology, containing numerous economic, environmental, and social benefits, is placed within the high adoption potential grouping on the matrix for assessing circular technologies (Fig. 3).

Biodigesters have multiple benefits streams, and as a result, investment in the technology, both public and private, may have different primary purposes. In Uruguay, biodigester technologies are subsidized with the primary purpose of reducing dairy farm effluent entering the Santa Lucia watershed (Ministerio de Ganadería Agricultura y Pesca de Uruguay, 2020). Biodigesters deliver high on the intended environmental effect of reducing eutrophication but also provide higher net market and spillover benefits compared to the baseline wastewater lagoon system. As this circular technology falls within the high adoption potential grouping, it has the potential to achieve large-scale benefits across the dairy-producing region.

3.3. *Case study 3: Ethiopian bonechar phosphate fertilizer*

Phosphorous (P) is an essential plant nutrient typically provided by rock phosphate reserves mined mainly in China, Morocco, and the United States. A shortage of available phosphorous in arable crop farming results in stunted crop growth and limited yields. P fertilizer shortages challenge food security worldwide, especially in Africa, where the poorest farmers face the highest fertilizer prices and rates of food insecurity (Cordell and White, 2014). One early-stage niche circular technology that could partially replace the use of mined rock phosphate fertilizer is a procedure developed in Ethiopia to recycle the naturally occurring P in animal bones in a pelletized P fertilizer (Blalock et al., 2022; Simons et al., 2014, 2023; Vassilev et al., 2013). In this practice, animal bones are collected, ground down to pieces 1–5 cm in length, pyrolyzed at high temperatures, ground to fine dust, then sprayed with a binder and made into pellets via pan pelletization (Simons et al., 2023). Ethiopia was chosen to ground truth and explore the viability of this technology as it has the largest collective herd of livestock in Africa. The livestock bones used in this study were sourced from the municipal abattoir in Jimma, where the bones would have typically been sent to a local landfill after the livestock was processed (Blalock et al., 2022; Getahun et al., 2012). P fertilizer is a yield-limiting resource for arable crop production, wholly imported and thus expensive, and bone waste from livestock abattoirs is not utilized for another purpose (Central Statistical Agency (CSA), 2020; Simons et al., 2023).

The case study presented in this paper was an experimental demonstration of bonechar fertilizer viability in the region of Jimma, Ethiopia (Fig. 6). Cornell University and Jimma University researchers and students first conducted scalability studies that showed this circular practice's operational feasibility. They collected animal bones from across the Jimma region and produced a P fertilizer product that can viably replace mined P fertilizer, using a mixture of local and imported machinery. The local "triple-super phosphate" fertilizer was produced at an economic cost of 16–39% less than importing conventional P fertilizer. A willingness-to-pay auction was then conducted that showed that

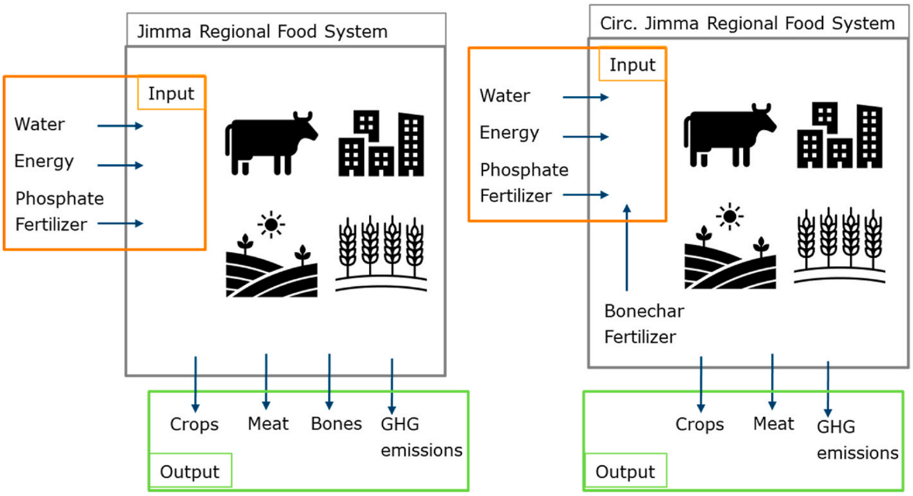

Fig. 6. Systems diagram of the current Jimma Regional Food System and a proposed circular system that utilizes bonechar fertilizers.

farmers had no cultural or economic hesitations to utilize the bonechar fertilizer (Simons et al., 2023). However, no further research was conducted on field tests assessing the relative yield compared to conventional fertilizer products.

In applying the framework described in this paper, we see that the production of bone char fertilizer generates a near equivalence of GHG emissions to the GHG emissions from the same quantity of P fertilizer produced in China. Bonechar fertilizers have the additional but unquantified benefits of removing the public health hazard of discarded animal bones in the environment and creating income-earning opportunities for workers in the lowest economic profile, who pick through refuse anyway and thus are the most likely harvesters of feedstock. As stated above, potential economic returns were discovered in the exploratory case study in creating local bonechar fertilizer; however, with any early-stage exploratory process, there is always a high degree of uncertainty. From these net market and spillover costs and benefits ratios, this case study is placed in the center of the two upper quadrants of the matrix (Fig. 3).

4. Discussion of the framework's future utilization

As circular technologies grow in popularity, so too will the need for a framework to assess their potential contribution to more sustainable food systems. The adaptability of this framework allows for organized analysis of circular technologies at different scales and technology readiness levels. The framework presents a snapshot in time of the current circular potential of the case study technology, and the model can be run as often as the economic and environmental landscape behind these technologies changes. Conducting repeated snapshots over time is beneficial as this framework helps to both assess innovation and document and monitor how its economic and environmental impacts might evolve over time.

There are different policy and practice implications for each stage of the circular technology market readiness (Figs. 2 and 3). Biodigesters for dairy effluent could benefit from the additional alignment of environmental public policy with on-farm technologies and further private-public partnerships in this sector. The market-viable technology of feeding low-cost feedstuffs to livestock could be expanded by creating a more favorable regulatory environment. The early-stage niche technology of bonechar fertilizer could have additional research to assess its feasibility in different cultural contexts and on-farm compatibility.

In the context of the United Nations 2030 Agenda for Sustainable Development and the Sustainable Development Goals (SDGs), and the UNFCCC Conference of Parties agreements and frameworks, the global discussion has increased related to how to finance technologies with GHG mitigation benefits in the context of supporting countries to reach their Nationally Determined Contributions (NDC) to combat climate change and meet the UN SDGs (UNFCCC, 2022a). Circular technologies, in particular, are touted as a potential tool to help countries reach their NDCs (Ministerio de Ganadería Agricultura y Pesca de Uruguay, 2020) and reimagine current food systems (Herrero et al., 2020; van Zanten et al., 2023). Commitments from countries and multilateral banks across the globe signal that there will be additional resources made available globally to help countries meet international NDC and sustainability targets (UNFCCC, 2022b). Investments in research and development and innovation systems have been shown to be highly positive of the estimated research benefits compared to the corresponding investment costs, with widespread benefits across countries (Alston et al., 2021; Hall et al., 2009). The approach presented in this paper has the potential to demonstrate the role of circular technologies within the scope of climate adaptation technologies. It also has the ability to guide public financing toward cost-efficient technologies that yield private and social benefits. Recognizing the importance of directing public resources and private capital towards suitable new technologies (Alston et al., 2023), this tool helps to identify high- and low-potential technologies ex-ante for prioritization.

We developed this framework to fill a gap in the current landscape of circular economy assessment and policy frameworks. These governmental, industry, and academic frameworks are largely aimed at assessing and improving the circularity of specific value or nutrient chains, primarily in industrial supply chains, in both agri-food and other sectors. Many of these frameworks rely on experimental, sensitive, or difficult-to-access private data. Other frameworks focus on the qualitative fit of circularity in agricultural systems. The frameworks that did integrate the circular bio-economy missed the location-specific complexity and, to some extent, the internalization of environmental and social benefits of implementing circularity technologies in food systems (Ahmed et al., 2022; Bocken et al., 2016; Bocken et al., 2019; Fassio and Chirilli, 2023; Hamam et al., 2021; Payne and Kwofie, 2024; Rodino et al., 2023; Silvius et al., 2023; WBCSD, 2023; WBCSD Circular IQ, 2023). Our framework is different from these methods as it provides a robust and quick method to assess multiple technology types. The system of equations developed for the framework (Appendix A) can be adapted to include the economic, social, and environmental indicators of direct interest to the implementing parties while using data that is reasonably expected while analyzing technologies. While developed for food systems, this framework can also be applied to other sectors (e.g., manufacturing, waste management) to assess their circularity potential.

The life-cycle assessment (LCA) data used within these case studies allow for the assessment of the status quo of the environmental impact of a technology. By utilizing true cost accounting for the net spillover benefits gained from adopting a technology, this framework can analyze the economics, environment, and social dimensions for an analysis of the technology in the food system to better avoid and reduce the spillover effects of our food system. However, as potential trade-offs with other resource chains are not accounted for in the LCA data used in implementing the circular framework, the framework results can potentially result in unforeseen systematic effects. Additionally, poor conceptualization of the base LCA data could result in the double counting of circular benefits, which would result in an overemphasis of the benefits of circularity. To remedy this issue, this framework could be complemented with consequential LCAs or a food systems model to map the indirect effects of a technology's widespread adoption and the valorization of previously unused side or waste streams.

On a similar point, the case studies analyzed in this article are technologies that have all been, to different degrees, co-developed by local stakeholders and interdisciplinary scientists. While this represents an inherent degree of ownership by the stakeholders that would be utilizing the technology, there is still a risk of top-down action that reduces the autonomy of smaller food system actors. This risk can be mitigated in future uses of the framework by ensuring the technologies studied are developed to ensure user agency and capacity in adopting the technology (Glover et al., 2019). However, there remains a risk that important social and environmental dimensions are left out of the framework analysis due to their hard-to-quantify impacts. Additionally, aggregating the impacts of a technology's adoption to higher spatial scales might obscure some important trade-offs between the market and spillover dimensions. Caution is required by those implementing this framework to ensure a holistic coverage of these important dimensions.

As circular systems are inherently less reliant on external markets than linear systems due to their usage of residual waste streams as inputs, they are more able to withstand the effects of shocks on external supply sources (Kennedy and Linnenluecke, 2022). Shocks, both internal and external to food supply chains, are expected to increase as the effects of climate change continue to disrupt the food system. As an example, the decision by China in 2021 to implement export tariffs on phosphate fertilizer caused the international market price for phosphate fertilizer to significantly increase (Barbieri et al., 2021). Had they used local circular technologies in the phosphate market, such as the bone phosphate fertilizer case study, this global shock on phosphate availability and price could have been mitigated locally. On-farm biodigesters recirculating nutrients, including phosphate, help make farms more fertilizer-independent and could have helped mitigate this decision at the farm level.

In order to achieve national and global goals of feeding a growing human population while meeting other UN SDGS for the protection of the environment and gaining social equity, the growth of the circular bio-economy and the implementation of technologies must occur with a general reduction of resource usage and over-consumption. While production-side circular technologies can have a profound impact on reducing food systems' environmental and social footprint, the consumption-side reductions of food waste and overconsumption are just as important. For example, this framework can be applied to assessing the relative potential of consumption-side technologies that valorize food waste, from compost to animal feed to microbial fermentation (Jurgilevich et al., 2016). Without public intervention to value the social benefits of circular technologies, the technologies with positive financial benefits will be preferentially absorbed by private food systems actors. Adopting a circular bio-based economy cannot be viewed as an end in itself but rather a tool to transition global food systems to more environmentally sound and future-proof systems (Urmetzer et al., 2022).

5. Building off of this framework for food systems transitions

The complexity of transitions in food systems requires a diverse set of technologies. It is necessary to understand the wide range of policies and conditions that are possible to increase the adoption of more sustainable circular technologies. By assessing the potential of circular food systems technologies through this circular economic framework and matrix of circular technologies, we aim to accelerate the adoption of these technologies and the adoption of the circular paradigm in the future. The matrix and framework described in this paper can be used to group technologies according to their potential to improve economic outcomes and reduce systems' spillover costs. While the general framework could be applied to virtually any technology, we operationalized it to circular food system technologies. The responsible assessment and choice of circular technologies are crucial as the circular biobased economy is increasingly considered a tool to transition current food systems to more sustainable states.

CRediT authorship contribution statement

C. Halpern: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **K. Kennedy Freeman:** Writing – review & editing, Writing – original draft, Validation, Investigation, Data curation. **C.B. Barrett:** Writing – review & editing, Methodology, Conceptualization. **M. van Dijk:** Writing – review & editing, Supervision, Resources, Methodology, Conceptualization. **D. Mason-D'Croz:** Writing – review & editing, Visualization, Validation, Resources, Methodology, Formal analysis, Conceptualization. **A. Simons:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Data curation. **B. van Veen:** Writing – review & editing, Resources, Methodology, Data curation. **M. Herrero:** Writing – review & editing, Supervision, Methodology, Conceptualization. **H.H.E. Van Zanten:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Methodology, Investigation, Funding acquisition, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gfs.2024.100814.

Data availability

The data and equations used in this research are included in Appendix A, B, and C.

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