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A scalable index for quantifying circularity of bioeconomy systems

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ABSTRACT

Increasing resource demands and efforts to mitigate anthropogenic impacts have thrust circular bioeconomy into the spotlight. However, there currently lacks a metric to provide singular quantification of circularity. This study showed development of a Circularity Index (CI) with value between 0 (completely linear) and 1 (completely circular) to quantify circularity of resource flows at different system scales, identify weak links in value-chains, and determine tradeoffs in the system. This study describes 1) CI for systems containing consumable, renewable, and recovered resources; 2) CI application for two examples: nitrogen in a corn-soybean farm and energy in the U.S. food and agricultural system. CI showed that nitrogen circularity increased from 0.687 to 0.860 through implementation of renewable fertilizer from manure compared to synthetic fertilizer. CI also demonstrated improved energy circularity in the U.S. food and agricultural system, increasing from 0.179 to 0.843 when integrating food-energy-water systems via hydrothermal liquefaction and nutrient recycling.

1. Introduction

Population growth and rising resource demands have resulted in increasing efforts to adopt circular economies (CE). The conventional economic system is linear, in which product flow has a clear beginning and a clear end, with resources consumed and then discarded (Moraga et al., 2019). Meanwhile, a CE utilizes products and services that can be reused in biological or technical cycles (Geissdoerfer et al., 2017). It is regenerative by design and aims to maximize efficient use of products, resources, and materials (Homrich et al., 2018). Transforming to a CE could achieve not only sustainability, but also economic efficiency (Avila-Gutierrez et al., 2019; Hamam et al., 2021). Significant increase in scientific interest for CE is evident, with 75 % of CE papers published between 2018-2020, and 81.3 % between 2020-2023 according to Scopus database (Nobre and Tavares, 2021). Although CE systems have been studied, especially with respect to biocircularity, there still lacks a single, comprehensive quantifier of circularity. Moreso, current approaches for CE indicators are restricted by system boundaries, lack of quantitative data, and use of qualitative categories.

Bioeconomies are of special interest due to their inherent circularity, in which biogenic material and other renewable resources replace use of non-renewable, fossil-based products. Biowaste valorization technologies are a promising solution to achieve a circular bioeconomy system (CBS). Biochemical (anaerobic digestion, enzymatic hydrolysis), thermochemical (pyrolysis, torrefaction, gasification, liquefaction), and other biowaste technologies for bioenergy and biochar are pathways to renewable value-added products (Cheng et al., 2020). For example, biological treatment of acid mine drainage with sulfate reducing bacteria promoted the removal of harmful environmental pollutions and recovery of valuable metals (Rambabu et al., 2020).

Agricultural, food wastes, and algae have potential to be significant biomass feedstocks in the CE (Koytsoumpa et al., 2021; Muscat et al., 2021; Ubando et al., 2020). These carbon-rich biowastes can be used in a biorefinery for production of biofuels and other high-value bioproducts (Awasthi et al., 2020; Chandrasekhar et al., 2020; Chew et al., 2017; Khoo et al., 2020; Maina et al., 2017; Rosenboom et al., 2022; Ubando et al., 2020). Specifically, the 2014 European Commission Action Plan identified food waste as a significant contributor to the lack of circularity in the current economy (Carus and Dammer, 2018). Basso et al. proposed circularity design for corn-soybean farm production systems (Ferasso et al., 2020).

Indices for CE have been developed to define circularity at the process, company, industry, and regional level. Several are listed in Table 1 with their parameters and boundary levels. Despite ability to address environmental, economic, and/or social concerns, many relationships are just descriptive, only serve a specific scope, and lack standardization. Furthermore, current CE indicators have different attributes and wide variation in application. Thus, the methods are case-specific and

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Table 1
Summary of CE indicators in literature, their associated parameters, and boundary levels.

Systems	Parameters	Boundary Level	Reference
Life Cycle Assessment (LCA)	Material flows, environmental impacts	Process, industry, region	(Mak et al., 2020)
Material Flow Analysis (MFA)	Material flows	Process, industry, region	(Pomponi and Moncaster, 2017)
Standardization Framework for Sustainability	Life cycle indicators	Company	(Avila-Gutierrez et al., 2019)
Water footprint	Material flows	Process, industry, region	(Avila-Gutierrez et al., 2019)
Trophic chain	Mass and energy flows	Industry	(Liwarska-Bizukojc et al., 2009)
Industrial symbiosis	Economic and environmental flows	Industry	(Olesen, 2008)
Material Circularity Indicator (MCI)	Material flows from non-renewable sources	Company	(The Ellen MacArthur Foundation and Granta Design, 2015)
Circularity and Maturity Firm-Level Assessment Tool (CM-FLAT)	Porter's Value Chain Categories	Company	(Sacco et al., 2021)
Multiple Criteria Decision Making (MCDM)	European Commission circular economy indicators	Region	(Garcia-Bernabeu et al., 2020)
Decoupling assessment	Material flows	Process, industry, region	(Lonca et al., 2019)
Zero Waste Index	Virgin materials, energy, water, GHG emissions, recovered waste streams	Waste management system	(Zaman and Lehmann, 2013)
Circular Economy Index (CEI)	End of life products, recycled raw materials	Recycling facility	(Di Maio and Rem, 2015)
Maturity Model for Sustainability	Company dimensions (strategy, design, etc.)	Company	(Hynds et al., 2014)
Circular Economy Indicator	Output, consumption utilization, disposal	Company, industry, region	(Geng et al., 2012)
BS 8001:2017	Material flows	Company	(Pauliuk, 2018)

difficult to apply in different sectors or scenarios (Papageorgiou et al., 2021).

A comprehensive review of the literature showed that existing CE metrics utilize varying elements but lack flexibility in scope (Kristensen and Mosgaard, 2020; Linder et al., 2017). The metrics are particularly inflexible for CBS, which includes 94 % of the total CE publications between 2020-2023. Merli et al. reviewed over 500 articles on CE, highlighting inconsistencies in definition for CE and its principles (Merli et al., 2018). Elia et al. proposed a four-level framework to assess circular economy (Elia et al., 2017), but their analysis confirmed a lack of standard methods, especially at the micro level. Linder et al. reviewed five circularity metrics for products but found none met criteria for construct validity, reliability, transparency, generality, and aggregation (Linder et al., 2017). Kristensen and Mosgaard identified 30 circularity indicators, but they mainly addressed economic and business management aspects and lacked scalability (Kristensen and Mosgaard, 2020; Linder et al., 2017). In contrast, Vinante et al. reviewed 365 firm-level circularity metrics and found that a majority were environmentally focused (Vinante et al., 2021).

On a global scale, approaches for achieving CE were presented as a top-down approach in China and a bottom-up approach in the European Union, U.S., and Japan (Ghisellini et al., 2016). In China's 2008 Circular Economy Promotion Law, CE indicators were established but adoption was hindered by lack of quantitative criteria (Geng et al., 2012). In 2021, the European Commission concluded that there is no indicator that can be a single measurement for the circular economy (European Commission, 2022). Spain Circular 2030 was the first attempt to regulate consolidation of sustainable development goals (SDGs) (European Commission, 2022; Pauliuk, 2018). In 2018, ISO standard ISO/TC 323 was developed in France and joined by 26 countries (Pauliuk, 2018). It covered development for requirements, frameworks, guides, support tools, and implementation of circular economy. Another standard (BS 8001:2017) was developed by the UK for principles and implementation of circular economy (Pauliuk, 2018). The framework consisted mostly of CE indicators based on material flow analysis, cost, and LCA. Schroeder et al. found that circular economy practices are relevant for the implementation of the United Nation's Sustainable Development Goals through a scoring system (Schroeder et al., 2019). Although this system is quantitative with "the higher the better" mantra, it does not provide a benchmark and thus is difficult to use for comparison of different systems.

Holden *et al.* identified major challenges in defining and developing a CBS: sustainable production and consumption; quantifying externalities; decoupling economic growth and depletion; scalability; valuation of natural resources; renewable energy needs; transition pathway from the current economy; and integration with food systems (Holden et al., 2023). A recent study explored correlation between LCA, circularity, and sustainability indicator-based approaches design of products that are not only circular, but also sustainable (Saidani et al., 2021). These indicators were able to relate both social and economic goals to environmental goals. However, they may not be suitable for more generic systems involving complex processes such as carbon, energy, nutrient, water, and other resource flows. Currently, CE indices are mostly descriptive with some quantitative efforts for individual systems. Moreover, there is no benchmark to compare among different systems when desirable. In this work, we propose a new Circularity Index (CI) to provide a single, standardized evaluation of circularity that is easy to implement and capable of quantifying weak-links and tradeoffs associated with the identified value-chain categories in a system.

Specifically, this CI addresses the gap for a scalable and quantitative index to benchmark the degree of circularity in a system. The CI can be applied to various resources, including energy, mass (carbon, water, nutrients), economic, or combinations of these. Further, the circularity can be quantified at different scales, ranging from a single process to an industry sector, from a farm to a state or a country. Specific objectives of this paper are: 1) develop a CI with a single value between 0 and 1 for different systems or for a system of systems containing consumable, renewable, and recovered resources; and 2) demonstrate CI application. The latter will be achieved using two examples: nitrogen circularity of a corn-soy farm production system and energy use of the U.S. food and agricultural system (FAS).

2. Method

2.1. Concept of Circularity Index (CI)

The phylogeny of circularity will likely advance through four major phases: random, descriptive, quantitative and control (Johnson and Phillips, 1995). It is the quantitative phase that provides measurements propelling technologies by improving identified weak value-chain categories. For that reason, it is important to establish a scalable and measurable index to quantify circularity of interest.

Matter and energy are conservative. The "total inputs" of matter or energy into a system (such as energy or nitrogen into a farm) is equal to

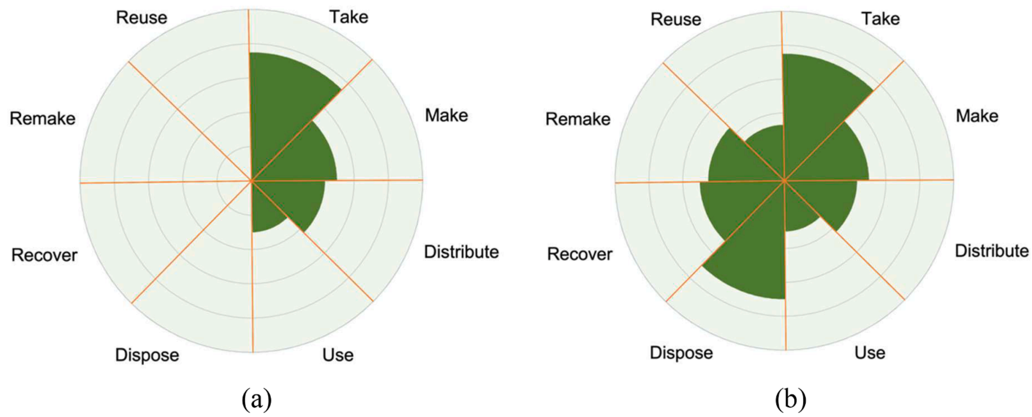

Fig. 1. Radar-pie diagrams of circularity defined by value-chain categories, where the outer circle is a perfect circular system (CI=1), and the green-region represents a partial circularity (0<CI<1). The pie dimension shows a category's fraction of the system, and the radar dimension shows the fraction of renewable and recovered resources for each category: a) A linear value-chain system including some renewable resources but no recovery; and b) A circularity system including recovery, remake, and reuse of resources as shown in the dark green region.

the "total outputs" minus matter or energy that remains in the system over a specified time span. Without anthropogenic activities, a natural system can be considered in an equilibrium state (or as a de facto circular system) through its carbon and nitrogen cycles, with energy from solar and carbon from the atmosphere. This natural circular system has evolved over millions of years and relatively stable over a time scale of millennium. Natural disturbances, such as volcano eruption and Ice-Age cycle are not considered in this circularity context. When anthropogenic activities occur, more natural resources are extracted for use and disposal outside a defined system, resulting in a skewed cycling system as shown in Fig. 1a. Human activities including take, make, distribute, use and discarded resources comprise an open-loop "linear value-chain system" (The Ellen MacArthur Foundation, Granta Design 2015).

This traditional open-loop "linear value-chain system" can be analyzed to determine how to transition it to be more circular by adding three resource categories: recover, remake and reuse (Fig. 1b). The circularity in Fig. 1b consists of eight generic key value-chain categories derived from anthropogenic activities: take, make, distribute, use, dispose, recover, remake and reuse. In such a circularity system (Fig. 1b), the first four anthropogenic categories (take, make, distribute, use and dispose) represent the traditional linear system. The last three categories (recover, remake, and reuse) are included to close the loop of material and energy flows for forming a more circular system. Note that the category "Dispose" can represent resources (or feedstocks) that could be used in the "recover, remake and reuse" processes. The anthropogenic value-chain categories are classified as follows (Zhang, 2022):

1) Take – Natural resources (conservative and dissipative) being exploited including land, water, air, and raw materials.
2) Make – Production and manufacturing to obtain consumer goods and services.
3) Distribute – Transportation and logistics to link 'Make' and end 'Use' of the value chain categories.
4) Use – Consumer and service utilization of consumer products.
5) Dispose – Discard losses, unwanted materials, and residuals of "used" resources (e.g., solids in landfills, aqueous discharge in waterways, and gaseous emission into the atmosphere).
6) Recover – Reclaim resources (energy and materials) from the "Disposed" or waste streams not typically used instead of discarding them.
7) Remake – Manufacturing or processing to develop consumer products from recovered resources.
8) Reuse – Utilization of resources or products from recovered resources.

Table 2
Description and examples of resources for value-chain categories.

Resources	Description	Examples
Natural	Embedded naturally, non-anthropogenic	Solar, wind, ocean waves, carbon dioxide in atmosphere, nitrogen in biosphere, water
Consumable/ nonrenewable	Extracted from natural resources but not able to be recycled naturally	Fossil fuel, minerals via mining, synthetic fertilizers made from fossil fuel, chemicals could not decompose
Renewable	Derived or recovered from natural resources	Usable energy from solar panels or wind turbines, hydro power, biofuel
Recovered	Recovered from residual or disposed waste streams	Methane from waste digestion, biocrude converted from waste, utilization of exhausted CO_2 and heat, and N, P, K recovered from disposed waste for crop production, recycled materials, etc.

For computing CI, it is assumed that only categories derived from anthropogenic activities affect the circularity of a resource, whilst natural disturbances including volcano and extreme climate are excluded. Therefore, the CI in this paper is a relative measure to the non-anthropogenic disturbed natural systems. In addition, the natural balance varies over time (in scale of decades or centuries) with specific circularity of concern (such as carbon), thus the CI is also a relative measure over a given period of time. Hence, the CI determination should be considered as a function of state rather than a dynamic process. Further, the number of value-chain categories can vary. For example, in a water system, the "Recovered" water may be directly "Reused" without "Remake", thus use less than eight categories as described above. When all categories utilize 100 % renewable and recovered resources, the radar-pie graph forms a perfect circle with a circularity index value of 1.0. As an illustration, the dark green region in Fig.1b shows a system with anthropogenic activities having a Circularity Index less than 1.0.

With the value-chain categories defined, it is important to define "Resource" types involved in each value-chain category. Each category is composed of four types of resources: natural, consumable (i.e., nonrenewable), renewable, and recovered. Natural resources include those that are dissipative (e.g., solar energy) and conservative (e.g., carbon and nitrogen). Consumable resources such as fossil fuel and minerals via mining are not renewable. Renewable resources are derived from natural resources such as solar energy and bio-based energy;

Recovered resources are derived from the "disposed" category such as carbon and nitrogen recovered from food waste and biofuels converted from biowaste. Though the "renewable resources" and "recovered resources" are both renewable and positively contribute to circularity, the difference is their origin – "renewable" is from natural resources and "recovered" is from the disposed (or waste streams) from anthropogenic activities. Table 2 describes the definition and examples of the four types of resources, thus establishes the basis of value-chain categories for circularity analysis.

2.2. Development of Circularity Index (CI)

Here we consider a system comprised of n value-chain categories. Based on the assumption that only anthropogenic activities affect the circularity of concern, natural activities are not included in this circularity analysis. In a linear open-loop value-chain system without recycling of resources, each category, X_i, has two fractions, a consumable fraction C_i, and a renewable fraction, R_i., noting that $C_i + R_i = 1$. The total output of the system, Y, containing n categories is

$$Y = \sum_{i=1}^{n} (C_i + R_i)\, X_i \ (i = 1,\ 2,\ 3 \ldots \ldots n) \tag{1}$$

where

X_i is the content of the i^{th} category and has the same unit as Y; each X_i is independent to each other.

C_i is the fraction of the content (X_i) from consumable (nonrenewable) source.

R_i is the fraction of the content (X_i) from the renewable source.

A circularity index (CI) for this linear system can be defined as the ratio of the total renewable resources fraction to the total content including renewable and nonrenewable resources in the system.

$$CI = \frac{\sum_{i=1}^{n} R_i X_i}{\sum_{i=1}^{n} (C_i + R_i) X_i} (0 \le CI \le 1) \tag{2}$$

processing and consumption. In addition, derivative categories could be added to the whole system; for example, energy recovered from a disposed resource can be reused in the categories of production and transportation; carbon dioxide produced by different food processes could be captured and fed back for crop production. Consequently, such interactions or derivatives could be synergistic, reductive, or amplifying in terms of resources in the system. Considering all possible interactive or derivative scenarios, a circularity system should include an additional term Y_a, representing recycled resources, which is expressed as

$$Y_a = \sum_{j}^{n} \sum_{i=1}^{n} a_{ij} (X_i \subset X_j) \tag{3}$$

Where the term $X_i \subset X_j$ indicates the category of X_j is a subset or a derivative of X_i, or it can be described as the recycled resources generated by the interaction of the two categories. For example, harvest loss of grain in category "make" and food waste in category "use" are both subsets of "disposed"; and methane produced from anaerobic digestion is a derivative of "disposed" waste. The coefficient a_{ij} could be negative when the interaction is reductive; it could be positive when the interaction is additive; and it could be amplifying ($a_{ij} > 1$) when the interaction is synergistic. Considering a category could have interactions with all other categories, the total number of possible interactions is

$$\sum_{i=1}^{n} (i - 1)) \tag{4}$$

There is no interaction when i=j, i.e., $a_{ii} = a_{jj} = 0$. The matrix is also symmetric, i.e., $a_{ij} = a_{ji}$ and the interaction between two categories can only be counted once. Thus, the recovered resource, Y_a for a system with n categories can be rewritten as

$$Y_a = [\mathbf{a_{ij}}][\mathbf{X_i}] \tag{5}$$

where

$$[\mathbf{a_{ij}}] = \begin{bmatrix} 0 & 0 & & 0 & 0 \\ a_{21} & 0 & \cdots & 0 & 0 \\ a_{31} & a_{32} & & 0 & 0 \\ & \vdots & \ddots & & \vdots \\ a_{i1} & a_{i2} & & 0 & 0 \\ a_{n1} & a_{n2} & \cdots & a_{n(n-1)} & 0 \end{bmatrix} \quad \text{and} \quad [\mathbf{X_i}] = \begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ \vdots \\ X_i \\ X_n \end{bmatrix} \tag{6}$$

When CI = 0, the system is completely linear with no renewable resources. When CI =1, the system is completely circular with 100 % renewable resources.

Obviously, Equation 2 only considers the additive effect of X_i, ending at the "Disposed" phase in a value-chain. Thus, it is still a mostly linear system even with some renewable resources utilization (Fig. 1a). To achieve circularity, it is necessary to add categories of recovery, remake, and reuse (Fig. 1b) after "disposed". Recovered resources can be dissipative such as energy from biowaste or exhausted heat from buildings for greenhouse production; and it can also be conservative such as CO_2 utilization in exhausted building air and fertilizer (N&P) recovered from disposed biowaste.

A circular system must include "Recovery, remake and reuse" categories. A system with n value-chain categories is complex because interactions may occur among different categories.; for example, food waste could result from several value-chain categories: harvesting, food

From a circularity point of view, the total renewable resource in a system includes existing renewable resources and recovered resources. Thus, the total renewable and recovered resources in a circular system, Y_R, can be written as

$$Y_R = \sum_{i=1}^{n} R_i\, X_i + [\mathrm{a_{ij}}][\mathbf{X}_i] \tag{7}$$

where the first term on the right side of Eq.7 is the existing renewable resources in the system, and the second term is the recovered resources as the results of derivative, interactive or synergistic effects among all the categories in the system as shown in Eq.5. Recovered resources in the second term of Eq.7 is illustrated in the examples in the Results and Discussion section.

From Eqs. 2 and 7, the circularity index for a closed-loop system becomes

$$CI = \frac{Y_R}{Y} = \frac{\sum_{i=1}^{n} R_i X_i + [a_{ij}][X_i]}{\sum_{i=1}^{n}(C_i + R_i)X_i} (CI > 0) \quad (8)$$

Unlike Eq. 2, Eq.8 could have a value of greater than one in a particular system because the recovery term (Y_a) could be greater than the nonrenewable term ($\sum C_i X_i$). When CI>1, it indicates that the system is capable of producing additional renewable resources than it consumes. For example, for a carbon flow in crop production, CI>1 indicates that it has a carbon capture/sink effect compared to the fossil fuel carbon consumption. For an energy system, CI>1 indicates it could recover more energy than it consumes and provide surplus renewable energy to other categories in the system, or to other systems.

The circularity index concept can be applied to different categories of circularity of concern such as total mass of production, individual elements in the product (such as carbon and nitrogen), energy consumption and economic output. It can be scaled for different systems such as a single process, an industry sector, a state, or a country. Some examples of resource categories of circularity of concern at different system scales could be:

- Carbon system – Y is the total anthropogenic carbon output of the system; and Y_R is the fraction of the carbon outputs from renewable and recovered input resources.
- Nitrogen system – Y is the total anthropogenic nitrogen outputs of the system including reactive fertilizers, food and animal feed; and Y_R is the fraction of the nitrogen outputs from renewable and recovered input resources.
- Water systems – Y is the total water outputs by anthropogenic activities; and Y_R is the fraction of the water recovered such as reuse of treated wastewater.
- Energy system – Y is the total energy consumption; and Y_R is the fraction of the renewable and recovered energy.
- Monetary – Y is the total gross output of a system such as a farm, or the U.S. FAS, and Y_R is the fraction of the gross output generated from renewable and recovered resources.

3. Results and Discussion

Application of circularity indices for circularity at different system scales can be described in the following step-by-step fashion:

1) *Define the system scale and boundary:* In this step, system boundaries are established, such as a selected process, an industry sector, a watershed, a state, or a country.
2) *Define the circularity element of concern, such as carbon, energy, water, nitrogen, or economy:* In this step, circularity of concern is identified so that the categories of the system can be standardized in the next step.
3) *Define the element flow categories in a system such as take, make, distribute, use, dispose, recover, remake and reuse, etc.*: In this step, the number and type of value-chain categories vary with different systems and different circular elements. For a given system and element, the categories are standardized (dimensionless or consistent dimension).
4) *Identify the resource type for each category including consumable, renewable and recovered:* Differentiate the resources type based on their origins: consumable is nonrenewable; renewable is from natural sources; and recovered is from disposed waste streams.
5) *Collect data:* In this step, data of different resources attributed to each value-chain category are determined including X_i, c_i, R_i, a_{ij}.
6) *Compute the circularity index using Eq. 8 and the data collected in Step 5.*

Following these steps, CI application are demonstrated below using two examples: System A is a corn-soy farm production system in Midwest of U.S. with the circularity concern being nitrogen; and System B is the Food and Agricultural Systems (FAS) of the United States with circularity of concern being energy use.

3.1. System A: Nitrogen cycling in a corn-soy farm in Midwest of U.S

Step 1: Define the system scale and boundary. In this example, published data from nitrogen balance at farm level was used to determine nitrogen circularity in a Midwest farm. The system scale is a farm located in Midwest with a corn-soy rotation, alternating crops each year. The boundary of the system is the crop production on the same 360-hectare farm, starting from cultivation and ending after harvesting and nitrogen contained in the transport or loss of nitrogen from the farm boundaries.

Step 2: Determine the circularity element of concern. In this example, the element of concern is nitrogen (N) for this farm over a period of eight years. The N inputs and outputs in forms of nitrous compounds lost to water, ecosystem, and air are considered resource losses (negative effects on circularity). Natural N inputs via symbiotic N fixation and manure fertilizers are considered positive in the circularity (Fig. 2). All N inputs and outputs of this production system were considered (Table 3). The time range for the system is eight years (2008-2015) with four years of corn and four years of soybean cultivation. For comparison, two parallel fertilizer strategies were included: one with summer application of urea-ammonium nitrate (coded as treatment SU168), and the other with fall-manure application (coded as FM168), both at the same nitrogen application rate of 168 kg per hectare per year.

Step 3: Determine the value-chain categories: In this production system, value-chain categories were described for nitrogen flow in the system: fertilizer (X_1), assimilation (X_2), losses via drainage (X_3), losses to air (X_4) and recovered N (X_5). Fertilizer includes synthetic nitrogen fertilizer applied, manure N, recovered crop residue back to soil, and nitrogen fixation. Assimilation was nitrogen taken up by the crop, some of which is in the grain product. Losses of nitrogen included nitrous compounds lost by drainage and air emission. Recovered N was from the disposed streams (including manure and crop residue). The recovered N from disposed streams in this system was also considered as N inputs to the system. The nitrogen system network and its value-chain categories (X_i) are shown in Fig. 2. The categories of nitrogen fertilizer application and nitrogen in the products are beyond this farm system boundary. For instance, while fertilizer was the input for this farm system, it was an output from the chemical fertilizer industry and livestock outside the boundary of this farm. Similarly, nitrogen in the crop product (grain) is the output of this system but is an input for food processing industry. Therefore, it is again important to determine the system scale and boundary prior to CI analysis.

Step 4: Identify resource type for each value-chain category. For each fertilizer category, reactive nitrogen fertilizer was considered as consumable. Nitrogen fixation (both by plants and microorganisms in soil) was considered renewable. Nitrogen in manure and crop residue were considered as recovered as they are from waste streams. Alternatively, manure and crop residue can also be considered as renewable, which will not alter the results of the CI calculation using Eq.8. For the N assimilation, all N uptake by grain including fixation N is considered as renewable. The nitrogen fractions lost to water and air are considered consumable. Part of the nitrogen lost to water could be recovered for reuse, but it was not exercised in this corn-soy rotation system. For recovery category, nitrogen in crop residue remained in field is considered as recovered. Nitrogen in manure nitrogen has already been included in the “fertilizer category” thus is not counted as recovered resources in this example.

In this case study, we assume the synthetic N input is negative because the synthetic fertilizer is made of fossil fuel (CH_4 for Fischer-Tropsch reaction) although the nitrogen is from atmosphere.

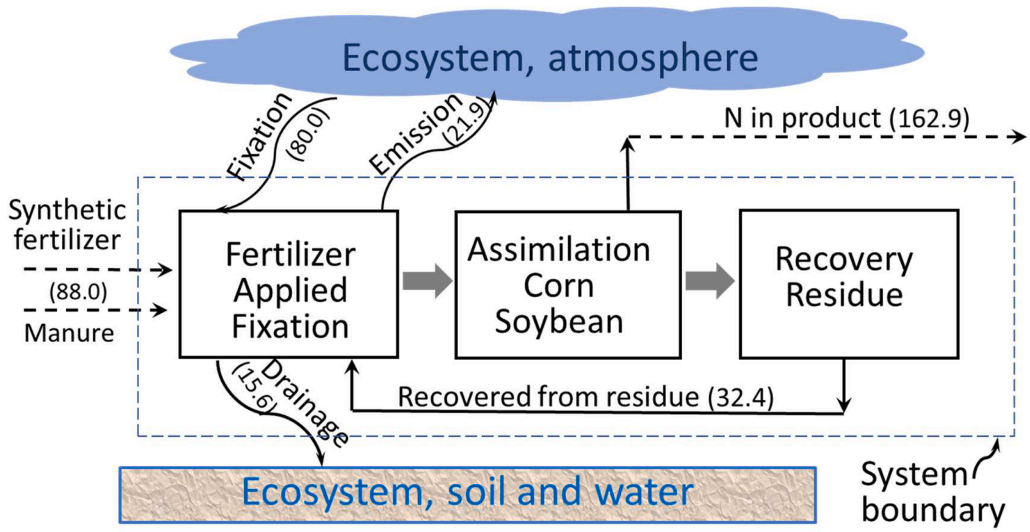

Fig. 2. A diagram of nitrogen flow network for a corn-soy production system. Denoted numbers associated with nitrogen flow are in kg/ha per year for treatment SU168 (Dougherty et al., 2020). Dashed lines (Fertilizer and Product) indicate the nitrogen categories are beyond the system boundary.

Table 3
Identification of nitrogen resource input and output types for each value-chain category for the farm of concern.

Value-chain category	Nitrogen Resource Type		
	Consumable	Renewable	Recovered
Fertilizer	Urea	Manure	-
Assimilation		Urea uptake by corn & Fixation by soy	-
Drainage	Loss to drainage	-	-
Air emission	Loss to air	-	-
Recovery	-	-	Crop residue
Transported in product		Grain product	-

"-" = Not applied.

Alternatively, synthetic fertilizer (e.g., NH_3) could be considered renewable if its hydrogen comes from a renewable source such as biogas and manufactured using renewable energy such as solar.

Step 5: Collect the data. Data for each category and the fractions of consumable, renewable and recovered resources were determined based on the original data (Dougherty et al., 2020). Missing data of nitrogen lost to atmosphere were calculated based on the total nitrogen mass balance of the system. Detailed data assignment (X_i, c_i, R_i, a_{ij}) to value-chain categories is explained in Supplementary Section, Table S1a.

Step 6: Calculation of Circularity Index. The results of CI calculation are shown in Fig. 3. The circularity indices are 0.687 for the SU168 system and 0.860 for the FM168 system. Obviously, with all other conditions the same, using manure resulted in a much better circularity than using reactive nitrogen fertilizer. The pie-dimension shows the weighted fraction of the total nitrogen in the system (X_i/Y). The radar-dimension shows the fraction of renewable and recovered (R_i+a_{ij}), and the green area representing the circularity. For example, in Fig. 3a, the fertilizer category has a 36.2 % share (in pie-dimension) of total nitrogen in the system and has a 47.6 % renewable and recovered fraction (in radar-dimension) of renewable nitrogen (Table S1a).

As seen in Fig. 3, it is apparent that the weak links for circularity of this system are the 'drainage loss' and 'air emission' categories for both SU168 and FM168. Therefore, reduction of nitrogen drainage loss and air emission will improve circularity. For example, nitrogen recovery can be increased by culturing algae using drainage water and implementing a biofilter. Further, it was seen that 'fertilizer' was the weak link in SU168. 52.4 % fertilizer came from reactive nitrogen synthesized from nonrenewable energy sources, whilst FM168 had all fertilizer nitrogen from manure. The CI for SU168 could be improved by using reactive fertilizer made of renewable energy and hydrogen sources. For example, if the reactive fertilizer had used 50 % of renewable biogas (CH_4 as both a hydrogen and energy source) for making urea, the CI of SU168 would have been improved to 0.797.

The tradeoff analysis can be performed at two levels:

1) Identify and quantify weak links in a value chain system. For example, in Fig. 3a, the system has no renewable or recoverable fractions, indicating weak links in the nitrogen value-chain. However, there are options for increasing circularity (CI) of this system. The fraction of nitrogen lost through drainage could be recovered and reused as fertilizer for algae culture. The algal biomass could be reused as fertilizer for crop production or other bioproducts. Such weak links could also be improved by applying fertilizer below the soil surface to reduce ammonium loss to the atmosphere.
2) Identify and quantify tradeoffs by comparing a similar system with different goals. In Fig. 3b, FM168 shows a much-improved circularity index than the SU168 by replacing reactive nitrogen fertilizer with manure at the same N-fertilizer application rate (168 kg per hectare per year). On the other hand, FM168 had a nitrogen loss via drainage 28.1 kg compared with 15.6 kg for SU168 case (Dougherty et al., 2020). This 12.5 % higher nitrogen drainage loss in FM168 relative to SU168 could cause more severe water pollution and eutrophication. Such tradeoff analysis could elucidate potential solutions such as recovery of nitrogen in drainage and improve fertilizer application method.

3.2. System B: Energy use of Food and Agricultural Systems (FAS) in U.S

This example demonstrates that CI can be applied to large scale systems.

Step 1: System scale. In this example, the system scale is the food and agriculture system (FAS) of the United States including all sectors such as production, processing, consumers, and food waste disposal. The system boundary is the FAS system within the territory of U.S. as

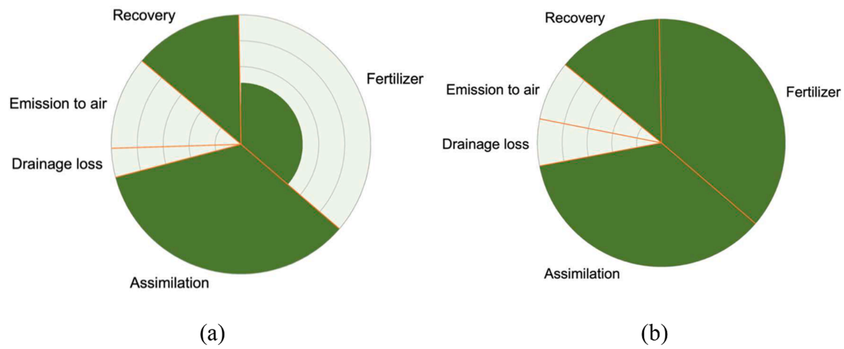

Fig. 3. Radar-pie diagrams for a corn-soy production system with two different fertilizer managements: a) SU168 – summer urea-ammonium nitrate, CI = 0.687; and b) FM168 – fall manure application, CI = 0.86; both at a nitrogen application rate of 168 kg per hectare per year.

defined by the national statistics such as USDA, EPA, or DOE. For example, energy used in producing the imported food, and energy used in processing exported grain are out of the boundary. Each sector in this FAS system is a system itself.

***Step 2*: *Circularity element of concern*.** The circularity concern is energy use in the FAS. Unlike nitrogen which is conservative thus the input and output must be balanced, energy is dissipative thus may not be best described in terms of 'input-output balance' for FAS. Since CI is a function of state rather than a process, energy efficiency is not appropriate as a category in the CI because efficiency is not a 'resource'. Overall, the circularity of concern is primarily based on climate change and environmental reasons, for which energy circularity concern is translated into a circularity concern of carbon emission from 'consumable resources'.

Step 3: Value-chain categories. The value-chain categories can be defined in the following corresponding to a FAS energy circularity network as shown in Fig. 4:

- Agriculture production (X_1)
- Food processing and packaging (X_2)
- Transportation and wholesale (X_3)
- Food storage, service, and household (X_4)
- Food system derived waste disposal (X_5)
- Resources recovery fraction of the total food waste (X_6)
- Remake of the resources from the recovered (X_7)
- Reuse of the recovered resources in the system (X_8)

Step 4: Identification of resource type for each value-chain category. The energy resource type is defined as following:

- Consumable/nonrenewable – energy from fossil fuel (gasoline, diesel, natural gas).
- Renewable – energy from solar, wind, hydropower, biofuel produced from renewable resources such as soybean and corn.
- Recovered – energy recovered from disposed streams such as food and agricultural waste.

Step 5: Data collection. Values for each category in terms of energy consumption per capita per year are determined based on national statistics and literature (Table S2). Food and agriculture system (FAS) contributed $1.11 trillion to the U.S. gross domestic product (GDP) in 2019, a 5.2-percent share of national GDP (USDA Economic Research Service, 2020). The annual national energy use totaled 93 Q-Btu (EIA, 2020), of which 14.4 percent flows into food and agricultural sector (Canning et al., 2010). It is estimated that the agriculture production takes about 8 %, while the food processing, food service and cooking take about 60 % of the total energy for the food sector (Schnepf, 2004). The total annual energy flow in the food system was 44,467 MJ per capita according to USDA's report (Canning et al., 2010). Of the total energy used, renewable energy was

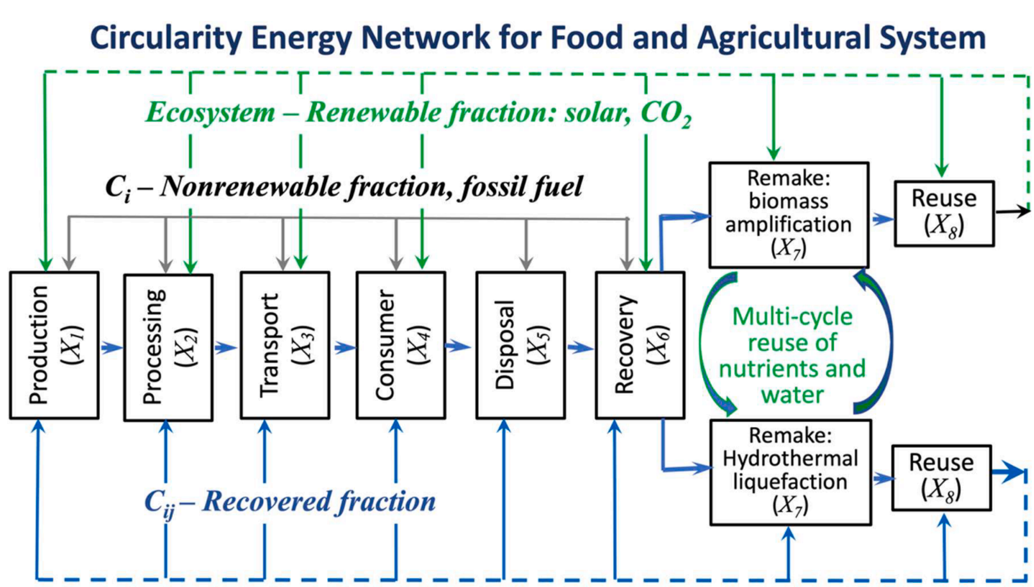

Fig. 4. A circularity network for food and agriculture system (FAS) in terms of energy flows, including value-chain categories of the system.

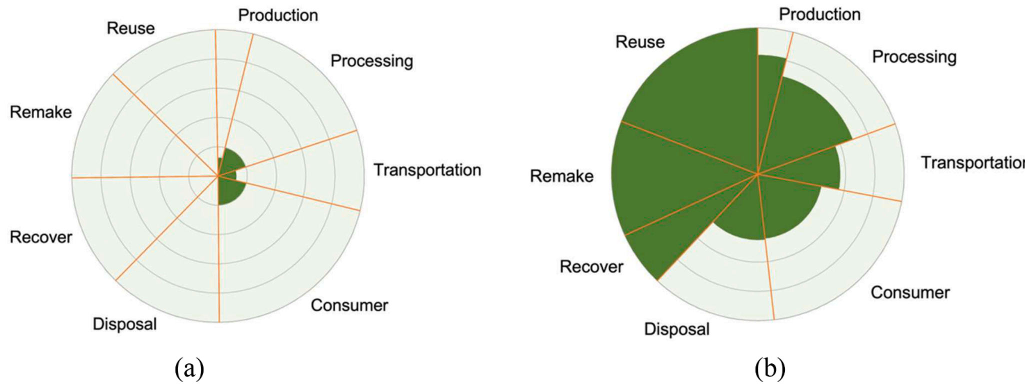

Fig. 5. Circularity of the energy flow in the U.S. food and agricultural systems: a) existing approach without resources recovery but with some renewable energy use, CI=0.179; and b) with energy recovery using an EE-FEWS approach, CI=0.843.

12.6 % for year 2020 (DOE BETO, 2017; EIA, 2020) with electrical sector 19.8 % (Canning et al., 2010). Food system derived waste (FSDW) energy content ranges from 23.5-24.5 MJ/kg (Aierzhati et al., 2021; Ouadi et al., 2019). The middle value of 24 MJ/kg and elemental carbon content 50.5 wt% of the biowaste were used in this study. The annual food system derived waste (DOE BETO, 2017) can be translated into 240 kg food waste containing 6,760 MJ of energy per capita per year. With the EE-FEWS paradigm, 70 % of the energy in the biowaste can be recovered with 10 % processing energy used for recovery. Algae culture uses the nutrients in the original biowaste and the post-HTL aqueous three times, thus amplifying the biomass by three times ($a_{5\text{-}6}$ and $a_{5\text{-}7}$ are both equal 3 in Eq.5). In Fig. 4, carbon is recovered from the biowaste at 70 % using 10 % of the total energy recovered as the process energy for reactors and pump (DOE BETO, 2017; EIA, 2020).

For the categories of "recovery, remake and reuse" (X_6, X_7, X_8), data are derived from the national statistics and experimental data. The United States produces 77 million dry tons of biowaste annually from food system alone, and as much of algal biomass resulted in from of eutrophication (DOE BETO, 2017), which has been treated as a burden bearing negative value. On the other hand, this fraction of biowaste could be a valuable resource if recovered and reused to the existing FAS.

A promising paradigm for biowaste valorization referred to as Environment-Enhancing Food, Energy and Water Systems (EE-FEWS) was tested to strengthen weak links in the food and agriculture system. This paradigm draws inspiration from nature – All fossil fuels come from biomass underneath the earth via high-temperature and high-pressure with geological times. In particular, crude oil from algae, coal from wood and peats, according to biogenic theory and geological evidence (Hunt, 1997). This integrated systems approach can recover and reuse waste materials (energy, nutrients, and water) multiple times thus amplifying recoverable biomass and HTL biocrude oil yield, a synergistic scenario among the value-chain categories in the system (DOE BETO, 2017; EIA, 2020).

Step 6: Calculation of Circularity Index. Applying Eq. 8 in an existing FAS energy system, the circularity index is only 0.179 (Fig. 5a). This is because the renewable energy used in existing FAS is only 12.6 % in production and 19.8 % in food processing, packaging, food service and cooking sectors, where electricity is the primary energy source (Canning et al., 2010). In the EE-FEWS paradigm, the circularity index for energy improved to 0.843 (Fig. 5b) with energy recovered from the biowaste stream and redistributed to energy sectors of the FAS for reuse. Previous work shows that the nutrients can be reused three times in the EE-FEWS system (Zhou et al., 2013). This biomass amplification resulted in the same factor in the biocrude oil production because the algal biomass produced from the post-HTL aqueous has the similar biochemical composition, thus the similar oil yield (DOE BETO, 2017; EIA, 2020).

The circular index calculated in Fig. 5b was based on the existing experimental data[49,51]. As the renewable fraction increases, the nonrenewable term ($\sum c_i X_i$) decreases. Moreover, when resource recovery among the categories [$a_{ij}(X_i \subset X_j]$ redistributed to the value-chain categories, the numerator in Eq. 8 increases, further increasing the CI value. For food and agriculture system, it is possible that the CI can be greater than 1 with proper renewable and recovered fractions, i.e., a food and agricultural system could provide additional renewable energy for other industry sectors and serve as a carbon sink.

In each case study, CI analysis produced a standard value that confirmed the improved circularity of the system through implementation of renewable and recoverable resources. Significantly, this CI can quickly pinpoint weaknesses in the system, as well as identify tradeoffs between different cases. In this CI example we assumes recovered material has the same quality as original material and there are no material losses during use or reuse. Changes in value-chain categories may also occur with time, location, and technology, leading to variability in CI value. Number of reuses for an element must be defined based on available data (i.e. 3 times in System B). Lastly, aggregation of systems into whole sector or a larger system of systems can be limited by data availability. Although scalable, assumptions may need to be made which can cause uncertainty.

Compared to other approaches, this CI provides a relatively simple method to calculate a single value for circularity of a system. For instance, application of LCA to System A or B could give values of impact indicators, such as global warming potential (kg CO_2 eq), eutrophication (kg N eq), and depletion of fossil fuels (MJ). Although this is valuable information, it does not convey circularity of a specific element. Use of LCA in industry is also hindered by its complexity in performing and communicating results, availability of accurate data, and inability to directly identify trade-offs (Nizami et al., 2017; Saidani et al., 2021). Therefore, while LCA may be a good addition to evaluate effects of a circular economy, it is not effective in evaluating circularity. Furthermore, different circularity indicators such as the MCI also provide a single circularity value for a company, but they don't account for weighted values and disaggregation down to the component level can cause unrealistic deviations (Lonca et al., 2018). Additionally, other approaches like MCDM rely on the quantification of qualitative categories, causing the circularity index to change in value with use of different sustainability perspectives (Garcia-Bernabeu et al., 2020).

While the examples for CI analysis in this work are two single systems, future work can include CI for a system of systems and different circularity of concerns such as water, carbon or economic output. For example, FAS is comprised of many subsystems including energy, carbon, nitrogen, phosphorous, water, or even other non-material systems such as finance and labor. If the purpose of circularity analysis is to understand the entire FAS sustainability, then the energy and carbon systems become subsystems of the FAS system. As such, the value chain categories would include energy, carbon, nitrogen, phosphorous, water, etc. Since these categories are measured in different units, they must be standardized prior to using Eq. 8 for CI calculation. The value for each category could be standardized using the CI values ($0 \leq CI \leq 1$) of the corresponding subsystems. Furthermore, a "system of systems" can be treated as a multi-layer circularity system. For a single layer circularity analysis, all categories are measured in the same units thus the weight of each category (pie-dimension) in the CI calculation has already been included. However, in a multi-layer analysis, the weight of each sub-layer's categories (standardized using the CI of that category) needs to be determined. For example, what is the weight (in percentage of pie-dimension) of carbon circularity (CI for carbon balance) versus water circularity (CI for water balance) in a corn production system? The weight factor analysis for multi-layer circularity analysis is not within the scope of this paper.

4. Conclusion

Quantifying circularity can provide a measurement to identify weak links in the value-chain and to expedite the development of technology or management to improve circularity. In this study, a single value, scalable, and quantitative CI unit was developed based on value-chain categories of a system and resource type: natural, consumable (nonrenewable), renewable and recovered. The CI calculation only takes anthropogenic activities into account, and can be computed for systems at different scales, such as a process, a farm, a watershed, an industry sector, a state, or a country. The resource analyzed with CI can be mass, energy, or economic elements. A step-by-step approach to determine CI was demonstrated using two system examples at different scales and resources. Results showed that at a farm-level, nitrogen circularity increased by 17.3 % through application of manure-based fertilizer compared to synthetic fertilizer, directly quantifying improvements in fertilizer application, and addressing weaknesses in resource recovery. For the U.S. food and agricultural system (FAS), CI for energy use increased by 66.4 % when implementing waste recovery and conversion technology, resulting in improved circularity across all value-chains in the FAS. The CI results clearly showed the weak links in value-chains, provided an approach to identify options to improve circularity, and identified tradeoffs when different strategies are employed. Future studies can further improve upon this CI by evaluating systems that consist of multiple subsystems with weighted value-chains in the system, as well as identifying uncertainty of propagation.

CRediT authorship contribution statement

Yuanhui Zhang: Writing – original draft, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sabrina Summers:** Writing – review & editing, Visualization. **James W. Jones:** Writing – review & editing, Investigation. **John F. Reid:** Writing – review & editing, Investigation.

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.

Data availability

No data was used for the research described in the article.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2024.107821.

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