Environmental Technology & Innovation 28 (2022) 102945

Contents lists available at ScienceDirect

Environmental Technology & Innovation

journal homepage: www.elsevier.com/locate/eti

A framework to assess indicators of the circular economy in biological systems

F. Kusumo [a,*], T.M.I. Mahlia [a], S. Pradhan [b], H.C. Ong [a,c], A.S. Silitonga [a,d], I.M. Rizwanul Fattah [a], L.D. Nghiem [a], M. Mofijur [a]

[a] Centre for Technology in Water and Wastewater, Faculty of Engineering and Information Technology, University of Technology Sydney, Ultimo 2007 NSW, Australia
[b] Faculty of Engineering and Information Technology, University of Technology Sydney, NSW 2007, Australia
[c] Future Technology Research Center, National Yunlin University of Science and Technology, 123 University Road, Section 3, Douliou, Yunlin 64002, Taiwan
[d] Centre of Renewable Energy, Department of Mechanical Engineering, Politeknik Negeri Medan, 20155 Medan, Indonesia

ARTICLE INFO

Article history:
Received 1 September 2022
Received in revised form 9 October 2022
Accepted 17 October 2022
Available online 22 October 2022

Keywords:
Circular economy
Business model
Sustainability
Circular economy indicator
Biological cycle

ABSTRACT

In regional and global contexts, the circular economy (CE) has gained significant traction to sustain the economy while maintaining environmental and social justice. However, the literature on CE lacks substantial information regarding the theory and methodology of putting CE into practice. The goal of this work is to create a framework for evaluating CE indicators and CE implementation in biological systems. The findings of this study suggest that CE may be more complicated than previously thought, involving a wide variety of interconnected mechanisms. The CE's guiding principles differentiate between biological and man-made (artificial) material and resource cycles. Biological cycles concern the safe and efficient movement of renewable biotic resources into and out of the biosphere. This study looks at the 13 different indicators of a circular economy, with a particular emphasis on the biological approaches that make up the biological cycle. The 13 papers were broken down as follows: four at the macro level, three at the meso level, and seven at the micro level. Furthermore, through the analysis of various literary sources, this paper proposed a framework for calculating and quantifying the CE. The framework's first steps are measurement criteria, the second are level monitoring procedures, and the third is the impact of CE. The proposed framework will aid in disseminating knowledge across regions, industries, and stakeholders, as well as accelerating CE implementation.

1. Introduction

Our current economic model is based on the linear approach, which states that all products start as raw materials, go through processing, are eventually consumed, and are discarded. However, this linear approach is coming under scrutiny because of its adverse effects on the environment and the economy. It also generates a significant amount of waste. The linear economy has the environmental disadvantage of placing commodities in the marketplace at the expense of ecosystem production. Excessive strain on ecosystems is caused by the implementation of vital ecosystem resources such as water, air, and soil cleaning (Elgarahy et al., 2022; Elwakeel et al., 2021; Michelini et al., 2017).

* Corresponding author.
E-mail address: Fitranto.Kusumo@student.uts.edu.au (F. Kusumo).

https://doi.org/10.1016/j.eti.2022.102945

Global resource extraction has increased tenfold over the last century, and the rate is expected to accelerate even further, with predictions estimating that global material usage by 2030 will be double that of 2010 (Arsova et al., 2022). Australia generated 54 megatons of solid waste, with landfills accounting for 40% (21.7 megatons) (Joe Pickin et al., 2018). Since the dawn of the industrial period, the average global temperature has risen by 1 °C. If current trends continue, temperatures will rise by 3 °C to 5 °C by 2100. Furthermore, over the last two decades, natural resource extraction and processing have increased significantly, accounting for roughly half of the impacts associated with deforestation, waterlogging, and global warming (Elgarahy et al., 2021; Pratt, 2022; UNEP, 2016).

A linear economy has economic consequences for providing ecosystem services, creating instability in the supply of resources in addition to ecological disadvantages. Instability is exacerbated by fluctuating raw material prices, scarcity of commodities, geopolitical reliance on certain supplies, and rising demand (Deutz, 2020; Mostert et al., 2021). The cost of raw materials has risen dramatically over the last two decades. Prospectors and raw material buyers were put to the test as a result, raising market risks. As a result, material extraction and processing investments are reduced, causing raw material costs to rise over time. Furthermore, price swings make it difficult for these businesses to develop pricing estimates, putting them at a disadvantage in comparison to less material-dependent businesses (Lucas and Wilting, 2018). Another disadvantage of this system is that it necessitates the use of numerous scarce resources for production. For example, many businesses rely heavily on essential elements such as indium and chromium in their manufacturing processes, despite the fact that these materials are only available in small quantities (Didenko et al., 2018). Because of increased trade, product geopolitical connectivity has become more robust. Countries with a scarcity of water but a surplus of oil, for example, will trade oil for grains. As a result, these raw materials have become inextricably linked. Furthermore, many items rely heavily on water and fuels for production. Because of this interdependence, the scarcity of one raw material has far-reaching consequences for the prices and availability of many other commodities (Gian Andrea Blengini et al., 2020).

The current economic paradigm of product creation and distribution is primarily linear; the goal of the circular economy is to transform this into a system that minimises the amount of waste that is discarded. A circular economy must find alternative applications for all of these potential material losses in order to prevent them. The term "circular economy" refers to the movement, or "cycling", of nutrients or energy transfer between various constituents of a natural ecosystem (Cecchin et al., 2021)." Circular economy aims to improve resource efficiency, with a focus on urban and industrial waste, capability methods, and renewable resources, in order to achieve greater balance and harmony among economy, environment, and society (Huang et al., 2018; Hueso-González et al., 2018). The CE literature distinguishes artificial cycles from biological cycles. In the artificial cycle, resources/materials are reused, repaired, and recycled, whereas, in the biological cycle, materials are returned to nature via processes (Sehnem et al., 2019).

Quantifying the circularity of products and services is critical in designing policies and business strategies and prioritising evidence-based sustainable solutions during the CE transition. In recognition of the need for a CE to decouple economic progress from resource depletion, circularity indicators have been established, albeit fragmented (Rigamonti and Mancini, 2021; Sassanelli et al., 2019; Shishkin et al., 2021). Because of this, it will be possible for economic progress to continue regardless of the consumption of resources. At the moment, new developments are being made in the field of research pertaining to CE. The form and content of the results that metrics and indicators produce can sometimes be at odds with one another (Corona et al., 2019). Additionally, because CE is a multidimensional idea, the measurement of it results in a variety of different interpretations. As a result of this, a number of different categories of circularity indicators have been offered (Corona et al., 2019; Elia et al., 2017). Circularity indicators can be used to evaluate the circularity of a product or system, which refers to the capacity to preserve both the quantity and quality of a material, as well as the efficiency with which a company can transition from linear to circular business models. Circularity indicators can also be used to evaluate the effectiveness of a company's transition from linear to circular business models. Indicators of circularity can also be used to assess how successfully a company is able to preserve both the quantity and the quality of a material. There are two types of circular system approaches: technical and biological. The biological cycle is shown to be representative of consumed goods (such as food, agricultural waste, and waste water), whereas the technical cycle is shown to be representative of materials used (e.g. washing machines, battery and solar panels) (MacArthur et al., 2015). For the reasons stated above, circularity indicators make a tangible contribution to the improvement of circular decision-making. However, the use of such measuring instruments is not without its limitations. For example, a large number of indicators and – in some cases – the ambiguity of their purpose make determining which one is more appropriate for use in a specific setting difficult.

The goal of this study is to provide a brief theoretical overview of the origins of the circular economy, circular business models, and a framework for accessing indicators and circular economy indicators in biological systems. In both research and policy settings, the framework can be used to address and conceptualise a circular economy indicator for agriculture. The CE's guiding principles differentiate between biological and man-made (artificial) material and resource cycles. Biological cycles allow for the recirculation of bio-based resources into new production methods and applications. As a result, this paper aims to characterise and develop the framework for implementing the CE indicator for the biological cycle at the macro, meso, and micro levels.

This article is broken up into seven sections, which are as follows: Following this introduction, the following section (Section 2) discusses the concepts and theory underlying the circular economy. The Model of Circular Economy is explained in Section 3, the Indicators of Circular Economy are presented in Section 4, an Overview of CE Indicators: Principles and Measures in Biological Cycles are provided in Section 5, Section 5.4 is devoted to Discussions, and Section 6 provides a conclusion to the paper.

Fig. 1. (a) Linear economy schematic diagram, (b) Circular economy schematic diagram.

2. Circular economy

In recent years, a fresh economic model that has been given the acronym CE and is intended to take the place of the linear economy model has been developed. The application of the first and second laws of thermodynamics, as outlined by Pearce and Turner (Pearce and Turner, 1990), is what is meant when people talk about the "circular economy" (Fig. 1). Products that conform to CE standards need to have a long functional life, be simple to repair, be able to be reconditioned, and be used multiple times before being discarded (Arsova et al., 2022; Bjørnbet et al., 2021). The CE model integrates three economic roles of the ecosystem to emphasise the link between the economy and the environment: resource supplier, waste assimilator, and source of utilitarian value (Didenko et al., 2018). The primary objective of a CE is to ensure that the natural resources that are mined have an infinite life cycle. This is accomplished by recycling production waste and obsolete goods (Kirchherr et al., 2017; Lonca et al., 2018; Pan et al., 2022).

The original recycling theory dates back to the early days of the industrial revolution. It was chosen because it has a low environmental impact, saves energy, and is inexpensive. On the other hand, the linear throughput flow paradigm has dominated industrial growth, resulting in significant environmental harm and massive consumption of finite natural resources (Joensuu et al., 2020; Michelini et al., 2017). The CE plan includes product, component, and material reuse, as well as reprocessing, reconditioning, repair, cascading, and upgrading. It also reduces energy consumption by encouraging the use of renewable energy sources (Ghisellini et al., 2016).

A "circular economy" would seek to close loops and reduce waste by repurposing materials that have outlived their usefulness as resources for others (Fig. 2). The economic rationale would be altered if sufficiency were replaced with production (reuse whatever you can, recycle whatever you cannot, repair whatever is broken, and remanufacture whatever cannot be repaired).

By making the most of available resources for the longest period of time, it may be possible to cut emissions by as much as 70%, increase the size of the labour force by 4%, and significantly cut down on waste (Stahel, 2016). The CE concept encourages the use of natural resources for long-term consumption and reuse. Its goal is to replace the current linear economic paradigm of low-cost, quick fabrication and discard with long-lasting commodities that can be easily repaired, deconstructed, or recycled. A CE production model would encourage repairing, refurbishing, and reusing products to extend their usefulness before they reach their natural end-of-life (Barros et al., 2020; Bjørnbet et al., 2021).

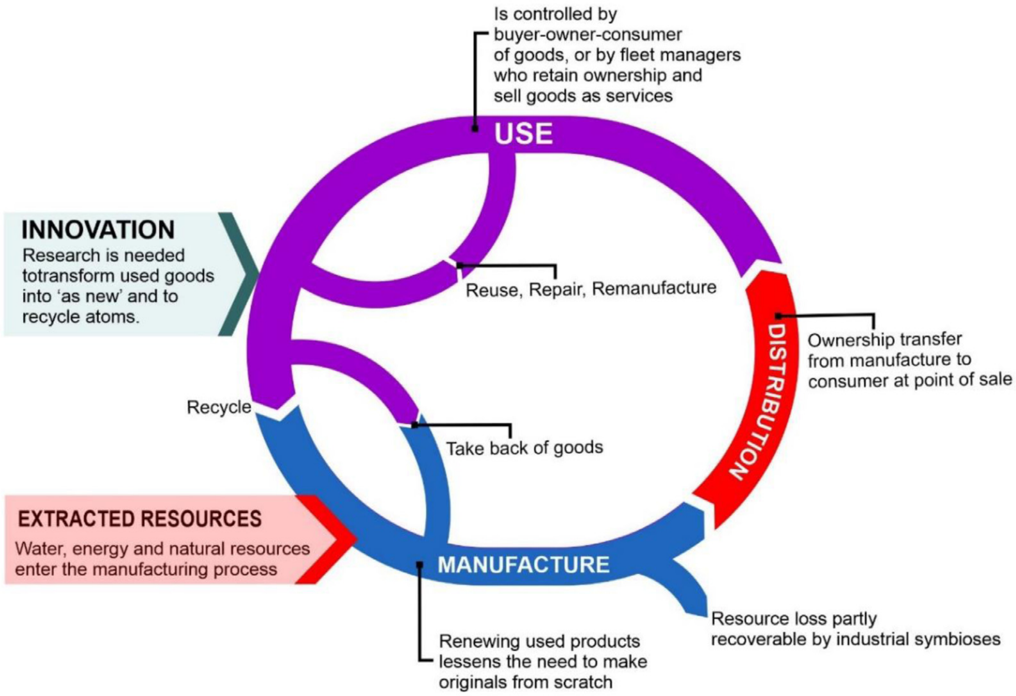

Fig. 2. Closing loops in industrial ecosystems and minimising waste.

2.1. Circular economy definition

The concept of a circular economy (CE) is a key concept that can help us revaluate our economy and society (Bell, 2021). As a result, the CE is a driving force behind this transformation, contributing to the UN 2030 Agenda's Sustainable Development Goals (SDGs). It proposes a holistic framework for system reform, a new model that would lead us to the "sweet spot" of "humanity's needs" within Kate Raworth's "doughnut" of social impacts and requirements (Kate, 2017).

2.2. Processes in the circular economy

CE entails far more than just recycling. Circularity can be supported by many processes throughout the value chain in a CE, from product design to manufacturing to consumer use (PwC, 2018). These processes differ in terms of who is accountable for them along the value chain: the supplier, the manufacturer, the consumer- or possibly all of them at the same time (Fig. 3).

2.2.1. Sustainable design

The first step towards being circular is to use sustainable design. This means that businesses examine the entire product life cycle, including the planning phase, when selecting the necessary raw materials and functionalities. Furthermore, they strive for the smallest possible economic footprint. There are three important approaches to accomplish this:

- *Design of durable products* — products that may be used for years or even decades due to the selection of high-quality, durable materials. For these items to be successful, they need an entirely different positioning and marketing plan.
- *Modular design* — the product should be constructed to allow for easy removal and replacement of components to extend the product's service lifetime.
- *Sustainable materials* — Use highly sustainable materials that can make the consumer only need to purchase a single item every ten years or environmentally friendly materials that are readily recyclable and biodegradable (PwC, 2018).

2.2.2. Sharing

The sharing economy enables people to share their excess capacity with others via digital channels (Mont et al., 2020). The growth of the sharing economy, aided by technological advancements, enables the benefits of usage without a long-term commitment. Solutions based on the sharing economy will reduce waste by creating a situation in which fewer goods are required if true sharing occurs. Consumers may use online platforms to share their free time with others thanks to the sharing economy and businesses such as Couchsurfing, Airbnb, and Uber (Geissdoerfer et al., 2017).

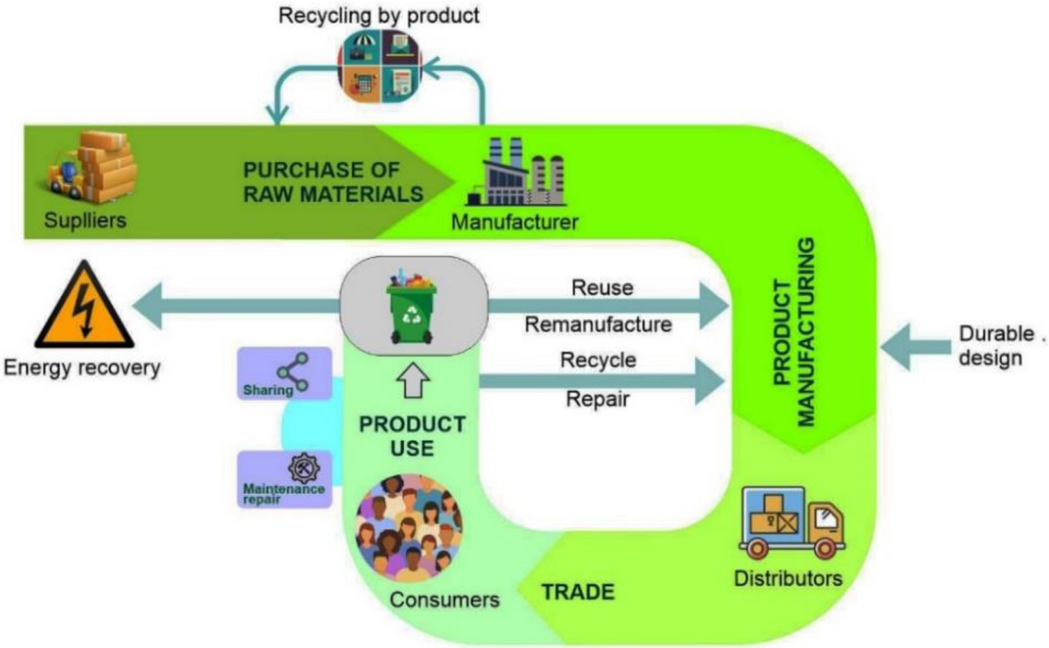

Fig. 3. Processes in the circular economy.

2.2.3. Maintenance and repair

Maintenance and repair can extend the usable life of produced objects that are currently in use. A product's usefulness can be retained through maintenance and restored through repair (Reike et al., 2018). Maintenance is a scheduled, continuing process in which critical sites are examined regularly to prevent malfunctions or accidents (Bakker et al., 2014). Maintenance services may also benefit manufacturers and present them with the opportunity to offer after-sales services. Additionally, creating replacement parts can result in up to three times more turnover than one-time sales (Sobral and Ferreira, 2018).

2.2.4. Renovation

The original function and fundamental features of worn or in-use products will be preserved through renovation, but the product may undergo aesthetic changes. However, the product's appearance can be altered. Similarly, the goal of restoration is to restore the original use value. Renovations can take the form of aesthetically pleasing improvements, such as house renovations. This example demonstrates the method's goal: The new facade evokes the original novel state while maintaining the original function (PwC, 2018).

2.2.5. Remanufacturing

Remanufacturing means returning a used product to at least its original state with a warranty that is equivalent to or better than that of a newly manufactured product. Performance after remanufacturing is expected to be at least to the original performance specifications (Fofou et al., 2021). The objective of remanufacturing is to make a product last longer while utilising the fewest resources possible (Hazen et al., 2017; Singhal et al., 2020).

2.2.6. Recycling

Recycling is the act of collecting and converting resources into new goods that would otherwise be thrown away as waste and will bring advantages to the community and the environment. In Australia, recycling systems allow households to sort paper and bottles separately to be sent to recycling stations (Mhatre et al., 2021b; Núñez-Cacho et al., 2018).

2.2.7. Recycling during the manufacturing process

In the production process, recycling can also contribute: if byproducts and waste are unavoidable during the production process, there are numerous options for repurposing or recycling them. It is possible to recycle the waste produced by one industrial process and use it as a raw material in another process. For instance, wood wastes can be compacted into composite boards after being made into sawdust. Plastics that cannot be recycled can be crushed and used in inexpensive construction materials (Fofou et al., 2021).

2.2.8. Reuse

It is possible to reuse an item after it has been discarded by the person who originally used the product. The realisation of reuse is dependent on the market, despite the fact that items are being given away with the intention of reusing them. Consider shopping at thrift stores or purchasing a pre-owned vehicle from a dealership (Ali and Yusof, 2018; Rigamonti et al., 2019).

2.3. Economic and environmental attributes of the circular economy

CE emphasises the use of limited virgin resources and the use of clean technologies. It is meant to help society in an industrial setting. The benefits will be gained primarily through exploiting the ecosystem as a reservoir for residual wastes, as well as as a garbage disposal site, and by reducing or eliminating the use of depleting materials in manufacturing operations (Kalmykova et al., 2018; Korhonen et al., 2018). Mastering the reverse material flow cycle can provide a business with a competitive advantage, whereas the CE creates job opportunities by developing knowledge in legal, mechanical, operational, and cross-sectoral difficulties (Kalmykova et al., 2018; Upadhayay and Alqassimi, 2019).

CE methods are highly scalable. Hence, a CE can fuel expansion and attract investment capital. Therefore, using CE methods at the research and development stage of an operation will speed up progress in the field of material sciences and can produce components that are of higher quality and last longer (Mhatre et al., 2021a). One of the advantages of eliminating waste from the value chain is that it reduces systemic and direct material costs, as well as resource dependence. As a result, the CE offers both strategic and operational advantages to businesses. The overall economy might save billions of dollars by reducing the quantity of raw material input required (Geng et al., 2012; Sariatli, 2017).

2.4. Five business models driving the circular economy

On a conceptual level, the CE model benefits both businesses and society as a whole. Businesses are able to lessen their dependency on increasingly limited and expensive natural resources while growing income and value and improving consumer understanding and value proposition. However, most businesses today are not designed to take advantage of the CE's prospects (Lacy et al., 2014). Current business growth methods, structures, and operations are all based on a linear approach to growth. As a result, companies seeking the circular edge must develop business models that are not constrained by linear These strategies aim to have a good impact "through growth" rather than just doing "less evil". That is a philosophy that both businesses and economies can support. There are five underlying business models for the CE (Fig. 4).

2.4.1. Circular supplies

The circular supplies business model refers to selling resources that are renewable, recyclable, or biodegradable and support circular systems of production and consumption. By doing so, businesses may phase out the usage of finite resources, replace linear resource methods, and reduce waste and inefficiency (Kurt et al., 2019; MacArthur, 2015).

2.4.2. Resource recovery

The resource recovery concept converts trash into value through innovative recycling and upcycling services. By deferring final disposal as long as possible, the goal is to create more uses and capture more value from materials. This strategy reduces the need for new resources by repurposing waste and converting it into a resource.

This business strategy, which has its roots in traditional recycling markets, employs cutting-edge technology and capabilities to recover practically any type of resource output at a cost that is equivalent to or more than the initial investment. Desso is an example of a company that is recovering residual value potential in post-consumer product trash. The business created the separation process, which allows for the separation of yarn and other fibres from carpet backing. After a purification stage, the yarn can be reused to make new yarn. Solutions include industrial symbiosis, incorporated closed-loop recycling, and Cradle-to-Cradle designs, which allow abandoned items to be recycled into new ones. This strategy is a suitable fit for enterprises that create large amounts of by-products or waste material from items that may be reclaimed and reprocessed cost efficiently (Velenturf and Purnell, 2017).

2.4.3. Product life extension

Product Life Extension allows businesses to expand the lives of their commodities and assets. Repairing, improving, remanufacturing, or remarketing commodities helps to preserve or even increase the value of items that might otherwise be thrown away. Furthermore, improved utilisation leads to increased revenue. This model can be used by companies to ensure that products are kept as economically useful as long as possible, and that product upgrades are concentrated (Despeisse et al., 2015).

2.4.4. Sharing platforms

Sharing Platforms allow users to collaborate on a platform, whether they are individuals or businesses. This model helps maximise utilisation and may benefit a company whose commodities and assets have a low use or return rate. Currently, businesses that focus on boosting product consumption without manufacturing anything are the most likely to employ it, placing a lot of pressure on traditional producers (Schwanholz and Leipold, 2020).

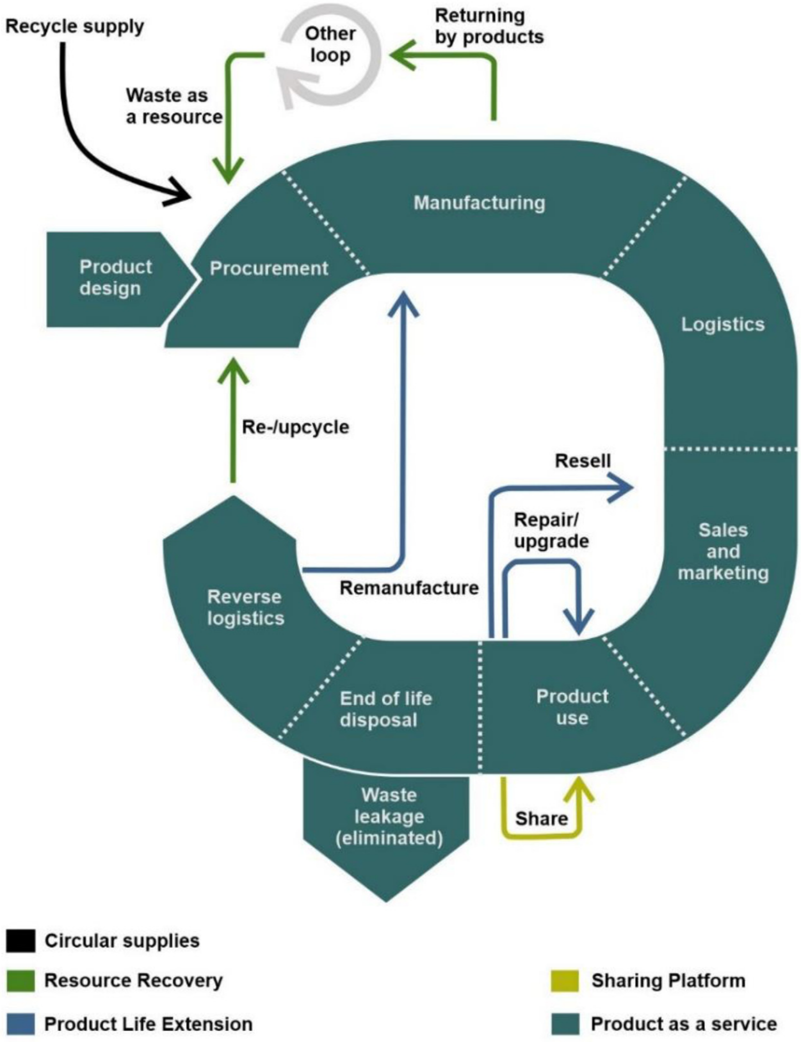

Fig. 4. Business models driving the circular economy.

2.4.5. Product as a service

The "purchase and own" paradigm is being challenged by the "product as a service" concept. One or more consumers can use things through a lease or pay-for-use arrangement. With this business strategy, performance-based rewards replace volume-based ones for product life and upgradeability. Life cycle, reusability, and sharing are no longer considered cannibalisation threats in a Product as Service business model but rather revenue and cost drivers. This strategy would be beneficial to businesses with a high product price of operations share and a skill advantage in managing product service over their competitors (Kwon et al., 2019).

Circular business models are upending industries all over the world. The adoption rate of various marketing methods has increased dramatically over the last decade (Lacy et al., 2014). Airbnb, for example, is a C2C digital platform for lodging accommodations. Through an internet platform, customers can rent rooms or entire homes from other members. The company, launched in 2008, has eclipsed InterContinental Hotels and Hilton Worldwide as the largest hotel in the world (with over 650,000 rooms) and has been increasing reservations and revenues at a rate of several hundred percent every year (PwC, 2018).

3. Model of circular economy

By replacing the traditional, one-way life cycle concept, the circular economic model defined in the action plan is essentially an industrial service system that aims to reorganise material flows while encouraging the use of renewable energy. The fundamental goal of this approach is to eliminate waste by incorporating efficient business models into the

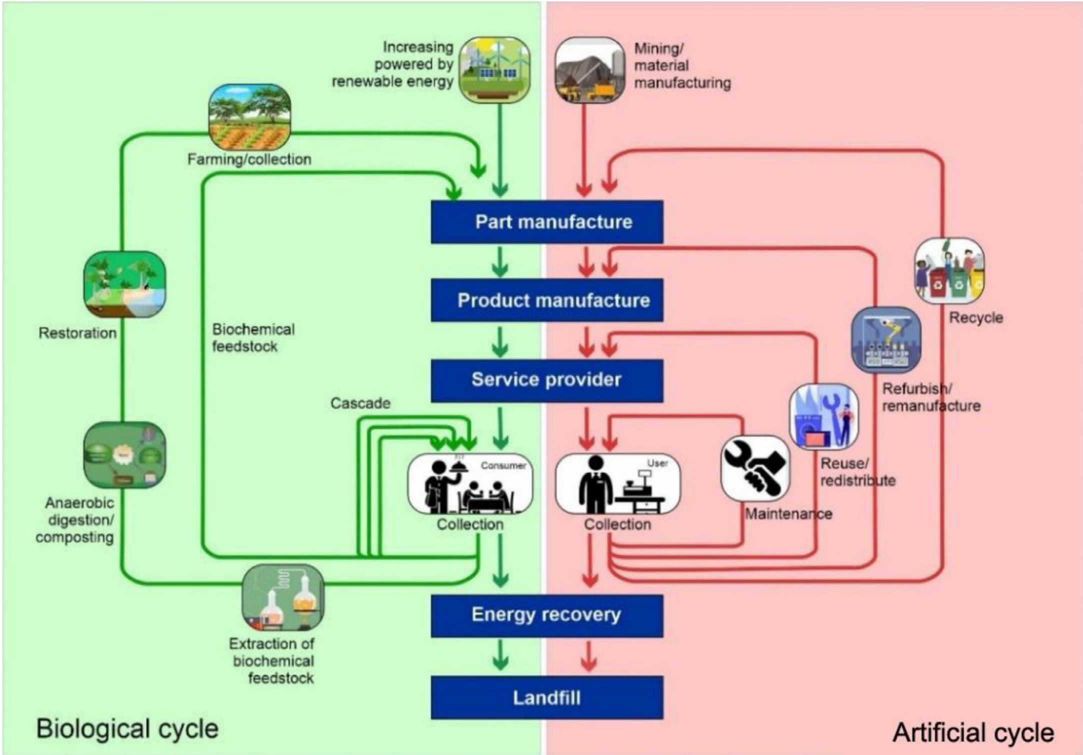

Fig. 5. Biological and artificial cycles.

circular design of material consumption, product use, and system applications (Rizos et al., 2017). The CE is segmented into biological and artificial loops in its own paradigm. In the biological loop, naturally occurring, biologically based, biodegradable raw materials cycle through the system (Sehnem et al., 2019). Artificial cycles cover man-made materials, environmentally risky compounds, and rare metals employed in many applications, as depicted in Fig. 5

3.1. Artificial cycle

The raw materials used in artificial cycles originated in nature, but due to the addition of chemicals during the manufacturing process, they can no longer be returned to nature. These substances should circulate as quickly as possible to limit or reduce the amount of new raw materials harvested. The raw materials may either be reused directly or processed further to become new materials. As long as mixed-material commodities are repairable or reusable, they can circulate within the production processes. When the product can no longer be used, the materials can be recycled or reused rather than discarded and sent to a landfill. The materials utilised in the product must be properly sorted into several categories, which may be applied to produce a variety of products (Jawahir and Bradley, 2016; Murray et al., 2017). To retain the maximum potential value of materials throughout their life cycle, abiotic materials must be kept in the technical cycle for as long as possible, not only through recycling but also through the use of inner rings (maintenance, reuse, remanufacturing, and refurbishing).

Almeida et al. (2017), in their study, suggested a method based on Design Science Research Methodology (DSRM) that can discover the best opportunities for designers early in the product development process. The method's scope is based on the measurement of material and energy flows in terms of exergy, which eventually represents energy efficiency, environmental effect, cost, and technical efficiency (Almeida et al., 2017). Bakker et al. (2014) compare the environmental implications of refrigerators and laptops to their improving energy efficiency over time and concludes that extending product life is the best solution. The report examines a variety of product life extension options and concludes that customised solutions are required. One of the most difficult aspects of product development research is determining which product life extension technique to use (Bakker et al., 2014).

Moraga et al. (2019) created resource efficiency indicators that reflect the advantages and disadvantages of the material used. They demonstrated the signs using a case study of four materials integrated into laptops (aluminium, copper, iron, and plastics). The research includes scenarios using several CE techniques, such as energy recovery, recycling, refurbishment, and reuse. The scenarios depict the materials' utilisation in many laptop cycles across a 25-year time period. When compared to recycling scenarios, simulations with refurbishment and reuse cycles demonstrated improved resource efficiency. Furthermore, hybrid products also contain a combination of technological and biological elements, necessitating proper design for disassembly operations in order to reintroduce both technical and biological nutrition fluxes.

3.2. Biological cycle

Biologically based products can be reused in production processes and new applications. Biological cycles allow bio-based products to be reused and recycled in current manufacturing processes and applications. Bio-based materials are developed with the intention of being returned to natural ecosystems and then regenerated to create renewable resources. The biological cycle produces products that are designed to be consumed by the economy, generating new resources.

Materials are recycled in a biological cycle by natural life processes, both through human touch and on their own. Human intervention gathers materials and reproduces this arrangement within a specified timescale in a technical cycle if there is enough energy. In biological cycles, there are three fundamental ideas:

Principle 1: Manage finite supply resources while balancing the flow of renewable ones. When resources are needed, the circular system carefully chooses them and, where possible, uses technologies and processes that use renewable resources to provide the best performance.

Principle 2: Products, elements, and materials need to circulate at maximum utilisation in both technical and biological cycles, to maximise resource output

Principle 3: Identify and eliminate external costs to improve system efficiency. This includes reducing harm to essential commodities and services, including food, transportation, housing, education, health, and entertainment, as well as externalities like land, air, and water usage, noise, toxic material release, and climate change (Ghisellini et al., 2016; Velasco-Muñoz et al., 2021).

The biological cycle aims to extract them biochemically and in a cascade to maximise their utilisation, by composting or anaerobic digestion, returning their nutrients to the biosphere, and recovering biogas if possible (Fan et al., 2020; Jin et al., 2022). In practice, the distinction between technical and biological cycles is not always clear. Many items, for example, are composed of biomaterials such as wood and abiotic materials such as metals. Furthermore, biomaterials can be converted into non-biodegradable polymers, increasing their technological potential. Separating biological and technical materials would theoretically allow biological resources to maximise their circular potential (Rizos et al., 2017). Fabio and Ruso (Sgarbossa and Russo, 2017) present a foundation for constructing Closed-Loop Supply Chain (CLSC) models to recover resources from generic outputs (e.g., unavoidable trash) with no product value. This study is to create a new, long-term paradigm for utilising CLSCs in meat processing and waste recovery. A profitability metric, an energy self-sufficiency indicator, and a qualitative assessment of social implications are presented to assess global sustainability potential or activate new loops. Xue et al. (Secco et al., 2020) provided a model for evaluating the CE in the pig farming cycle in terms of environmental and social factors, as well as property costs. Ktori et al. (2018) investigated the use of pyrolysis to recover valuable materials and energy from discarded coffee grounds waste for the creation of fuels and carbon compounds such as biochar, which may then be utilised as fertiliser in parched regions, thereby closing the loop in agriculture.

4. Circular economy indicators

The complexity of defining efficiency metrics in the CE is substantial (Potting et al., 2017). It is challenging for researchers to establish metrics that measure the performance of the CE in businesses (EASAC, 2016; Calzolari et al., 2022).

4.1. Circular economy indicators

As discussed earlier, the definition of efficiency metrics in the CE is quite complicated, making it difficult for academics to create indicators that measure the performance of the economy in businesses, such as measures for waste reduction, reuse, and recycling. Due to the lack of indicators and unclear targets to be achieved, there is a lack of understanding of the options offered by the CE and its financial advantage for business and society. According to Haas et al. (2015), a set of credible indicators must be established as tools to measure and quantify the benefits of the CE.

This is supported by the European Commission, which highlighted the need for circularity indicators in its European Union action plan (European Commission, 2015; MacArthur et al., 2015; Preisner et al., 2022), adding that "*it is necessary to have a set of trustworthy indicators to assess progress towards a more CE and the efficacy of action at national and EU levels*". In the CE, indicators must be aimed towards CE practices to precisely quantify the desired efficiency impact of new CE practices (Kalmykova et al., 2018). As a result, Key performance factors, including their numerous applications, level of performance, and effect of laws on this kind of activity, should all be taken into account (Linder et al., 2017; Thomas and Birat, 2013).

In a CE, defining appropriate indicators allows the quantification of their impact on the organisation's efficiency and serves as a source of important knowledge to help managers and entrepreneurs make better decisions (Walker et al., 2018). Given the volume and variety of sustainability indicators produced, managers are finding it increasingly difficult to grasp the meaning and significance of each indicator, thereby quantifying how the metric affects their productivity

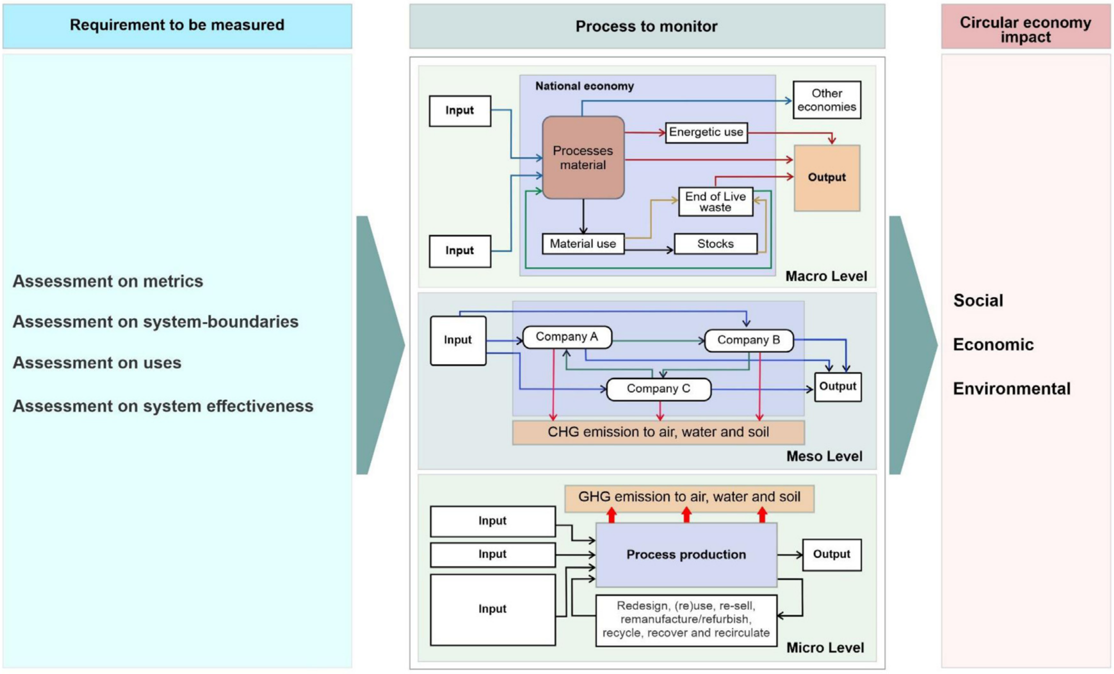

Fig. 6. Frame work of CE indicator implementation.

levels. Environmental impact, recycling quotas, and environmental impact in waste management are extremely difficult for researchers and industry managers to assess.

Despite the hazy concept of CE, there is a need for precise methods to track the development of the CE (Moraga et al., 2019). Indicators can be used to determine the remaining distance to a completely CE, compute and quantify the degree of circularity in present systems at various implementation sizes as well as the degree of circularity in current systems, processes, and products (Ghisellini et al., 2016; Sánchez-Ortiz et al., 2020).

A framework for calculating and quantifying the CE has been established through the analysis of various literary sources. The first steps of the framework are criteria for measurement, the second step is the level monitoring procedures, and the third step is the impact of CE, as depicted in Fig. 6. The previously reviewed studies clustered and aggregated resources through thorough analyses, starting with the first steps. In the first step, we define what kind of requirements we want to measure (Van Bueren et al., 2021). In the next framework, these subsequent stages stand in for the processes whose effectiveness must be assessed to determine how circular the entire system is under consideration. The third framework is CE Impacts, related to CE's ultimate goal, which is to improve society and nature's quality of life sustainably and equitably. Three main categories may be used to summarise these cyclical impacts: assure a socially just and market-relevant economic contribution, enhance environmental performance, and contribute to social development (Garcia-Saravia Ortiz-de-Montellano and van der Meer, 2022).

4.1.1. Macro-level

The CE, which can be developed in cities, or regions, entails the integration and redesign of four systems (the industrial system, the infrastructure system that provides services, the cultural framework, and the social system) (Naustdalslid, 2014). The CE indicator will pay particular attention to (material) interactions between the environment and the economy, international commerce, and material accumulations in national economies at the macro level, instead of flows within the economy (Stahel and Clift, 2016).

4.1.2. Meso-level

The CE at this level is limited to the production side. This also involves developing industrial symbiosis networks, eco-industrial parks, and other areas (Su et al., 2013). In these industrial systems, businesses that formerly operated as independent entities become involved in intricate resource exchanges (materials, water, energy, and byproducts), referred to as "industrial symbiosis", in order to gain economic and environmental benefits (Zhu et al., 2007). Industrial symbiosis focuses on the inter-firm level since it involves physical transactions among several institutions that do not require to be taken place within the "strict boundaries of a "park" (Chertow, 2000). Eco-industrial Parks are built when an appropriate mix of manufacturing units can reduce the waste and emissions of the entire facility as the distance between participating companies increases energy demand.

Meso-level indicators provide more specialised knowledge tracking and a more in-depth examination of the flow of material within the economy, defining material types and sectors or divisions of consumption and production (Smol et al., 2017).

4.1.3. Micro-level

Adopting a CE strategy comprises a company implementing various techniques to increase the circularity of its manufacturing systems and collaborating with other companies throughout the supply chain to produce a more efficient circular pattern. Within a company's production processes, eco-design or green design and cleaner production (CP), are the major methods to be regarded as a precursor to CE within a company's manufacturing processes (Winkler, 2011). Environmentally friendly design and cleaner manufacturing are inextricably linked. Cleaner production encompasses three interconnected practices: pollution avoidance, reduction of hazard material usage, and environmental design. The design stage is important since the product's relative sustainability is largely determined by decisions made early in the design process (Ramani et al., 2010). This assists in minimising the possibility that reducing some effects could result in an increase in others (Kristensen and Mosgaard, 2020). Also pertinent to CE are problems such as "disassembly, disposability without negative environmental implications, ease of distribution and return durability, dependability, and customer success".

Micro-level indicators offer quantitative information on a company's or a region's decision-making process, as well as specific chemicals or commodities. Micro-level assessments support the application of rules and decisions in areas like waste management systems, energy efficiency, and packaging rules (Kirchherr et al., 2017).

Currently, no indicators or methodologies could monitor all of the characteristics in the single CE indicator model. According to Bocken et al. (2016), companies are unable to give solutions to problems arising from a CE due to a lack of indicators and targets. The European Commission supported this statement, stating, "It is vital to have a credible indicator to assess progress towards a more CE and the efficacy of national and EU-level actions". The most accessible indicators for CE strategies are at the macro and meso levels rather than at the product level scale. Linder et al. (2017) argue that a product-level circularity indicator should focus only on quantifying circularity as a single feature of product quality.

Until date, CE indicators are primarily focused on the macro or meso level, with micro indicators being less established. The majority of indicators come from academic papers, indicating that researchers are becoming more inclined to quantify micro-level circular economies, with fewer contributions from practice (Kristensen and Mosgaard, 2020). Most micro level indicators are designed to evaluate individual items and materials. This means that indicators used to measure product circularity should be practical to businesses, additionally being pertinent and significant for practitioners (De Pascale et al., 2021).

5. Principles and measures of circular economy in biological cycles.

Unrecyclable biomass materials, such as food leftovers, can be recirculated and converted to chemical inputs to the industry by biological means (Vu et al., 2020). When biological material-based products approach the end of their lifetimes, materials are cycled through flows without waste, with end-of-life materials becoming nutrients for future products, in a manner similar to how biological systems handle materials in nature. For example, cotton clothing and hardwood furniture can be rotated through both technological and biological cycles. They can be repaired, reused, and recycled, but they must finally be returned to the biological cycle from where they originated. When composted or anaerobically digested, they can nourish the soil to grow new cotton or wood.

The CE indicators in this study was chosen based on the ability to analyse the progress of circularity of the biological cycle, such as renewability, the potential for cascading use of material, closing the biological nutrient cycle and environmental impact.

- Renewability, the basic premise of CE, "to limit the input of virgin resources", to replace fossil-based resources with biotic resources. The renewability of these resources, on the other hand, can only be ensured by generating and harvesting them in a way that does not deplete their regeneration capacity (Sikkema et al., 2017).
- Cascading use materials. Materials originating from biomass, which have the potential for cascading use, are biodegradable, and it is more difficult to protect the value of biodegradable materials. It is difficult to return these materials to their former state. With each succeeding application, their quality deteriorates, resulting in reduced structural qualities and utility. The application of the main CE concepts – recycling and maximisation of utility – to biological cycles is thus limited. By employing biotic resources in cascades, the usage of biotic resources is maximised. Cascading is the process of repeatedly using resources for composite materials for as long, as many times, and as efficiently as feasible, and then recovering energy when no further material applications are available. Cascading encourages the utilisation of waste streams for creative goods, such as post-consumer trash and industrial residual streams (Jarre et al., 2020; Kapinya et al., 2008).
- Closing the biological nutrient cycle, *bio*-based materials are generally biodegradable and contribute to ecosystem regeneration following decomposition. As a result, guaranteeing the "closure of the biological nutrition cycle" is critical. Validation of whether biotic resources feed the regeneration of ecological systems following decomposition is critical (Mayer et al., 2019).

- Environmental impact — Agriculture, forestry, and fisheries, which provide biotic resources, have significant environmental implications. Biotic resource usage has an impact on ecosystem quantity and quality, environment (soil, water, and air), bio-diversity, and landscape amenity value. As a result, biological cycles should never be expected to be ecologically favourable by default.

A list of indicators for CE levels have been compiled based on the literature study. The following information is collected using a summary table of CE indicators (Tables 1, 2 and 3): name of CE indicator, description, and level

5.1. Macro level

At macro level, the analysis of the progress of CE includes regulatory instruments that could be deployed to encourage economic actors to adopt CE models. This allows for the monitoring of transition strategies and the assurance of a transition that is not just circular but also environmentally, economically and socially sustainable. The following is a quick summary of the CE indicators at the macro level in the biological cycle (Table 1).

5.1.1. Material flow analysis

This article presents an MFA of the Swiss MSW management system with detailed subsystem MFAs for materially recycled fractions of MSW (paper, cardboard, glass, polyethylene terephthalate [PET] bottles, tinplate, and aluminium). The material flow analysis (MFA) of the 2012 Swiss waste management system is based on statistics on total waste generation reported by Dettli and colleagues (Dettli et al., 2014). The rates of both closed-loop and open-loop recycling method are measured. Closed-loop recycling uses secondary resources to create the same product, whereas open-loop recycling refers to creating something new. In this study, Haupt et al. (2017) used multiple studies with varying levels of material recovery to evaluate recycling rates in closed and open loops. This study examines municipal solid waste in Switzerland in depth by categorising recycling rates as closed- and open-loop collection rates and RRs. For the vast majority of the individually obtained items studied, the rates determined are far lower than those publicly stated.

5.1.2. Eco-innovation

This CE indicator studies the environmental impact of resource depletion on ecosystem services and time-dependent carbon flow. Eco-innovations are addressed by three groups of indicators: inputs, activities, and outputs. The adoption of eco-innovation has resulted in two groups of indicators: resource efficiency and socio-economic outcomes. The indicator value is derived from the average of 16 sub-indicators. The use of five group indicators for gauging regional CE–eco-innovation is proposed in this study, which is based on eco-innovation elements. Three of the proposed indicator groups are directly related to inventions, based on the Eco-Innovation Scoreboard, which specifies innovation measurement and takes into account CE principles. The other indicators include effects of CE–eco-innovation introduction: resource efficiency results and socio-economic outcomes (Smol et al., 2017).

5.1.3. Evaluation index system for evaluating the circular economy development

Chemical industries, the backbone of the Chinese industry, face significant challenges from resource and environmental issues. Therefore, the growth of the CE must ensure sustainability throughout the whole chemical sector. Several organisations (Li and Su, 2012) have used the Evaluation Index Model to investigate the situation of CE growth in China. The assessment methodology was based on economic development, utilising resources, lowering effluents, increasing biological effectiveness, and the possibility for development. These organisations calculate ecological efficiency as a function of land area, water usage, energy consumption, and emissions per unit output.

5.1.4. Green growth indicators

The Green Growth Indicators framework relates several elements of green growth to accounting standards and the pressure-state-response (PSR) model being used for environmental evaluations. By concentrating on the production and consumption processes in the economy, this Green Growth monitoring emphasises the relationship between environmental policy, natural resources, and the economy (OECD, 2014).

5.2. Meso level

The meso level is defined as a group of enterprises based in a particular region that aim to increase economic, environmental, and social efficiency through reciprocal collaboration in order to provide a large overall benefit. Below is a quick overview of the CE indicators at the meso level in the biological cycle, as tabulated in Table 2.

5.2.1. R esource productivity indicators

The Resource Productivity Indicator (RP), developed by Wen and Meng (2015), is a metric that measures GDP production per unit of consumed resources and so defines resource efficiency. As a result, RP is seen to be a good indicator for assessing CE development quantitatively. The authors combine the Substance Flow Analysis (SFA) approach with the Resource Productivity (RP) indicator. Key enterprises in Suzhou New District (SND) have received field surveys and questionnaires. The SFA and RP for core materials in the fabrication of printed circuit boards (PCB) were built on these foundations, ignoring waste utilisation scenarios. The findings of the RP estimation show that a greater RP corresponds to less resource utilisation. As a result, RP can be considered a key indicator for determining the efficiency of resource consumption in the industrial system.

Table 1
Circular economy indicator in the biological cycle for macro level.

Circular economy indicator	Description	Ref
Material flow analysis	The CE indicator calculated the rate of closed- and open-loop collection. In this study, recyclable materials from municipal solid trash in Switzerland were examined, including paper, cardboard, aluminium, tinplate, glass, and polythene terephthalate (PET).	Haupt et al. (2017)
Eco-innovation	The proposed indicators that based the eco innovation scoreboard, can be used to assess regional policy execution throughout the present transition period and as a foundation for generating final CE indicators.	Smol et al. (2017)
Evaluation index system for evaluating the CE development.	Measure the growth of the CE in Shaanxi province by looking at five elements such as social economic, resource efficiency, resource recycling and reuse, environmental protection, and pollution reduction.	Qing et al. (2011)
Green growth indicators	The economy's roles of production and consumption, as well as the connection between the economy, natural resources, and environmental policy, are stressed.	OECD (2014)

Table 2
Circular economy indicator in the biological cycle for meso level.

Circular economy indicator	Description	Ref
Resource productivity indicator (RP)	The substance flow analysis method and the resource productivity indicator were merged in the approach to evaluate the impact of industrial symbiosis on the growth of the CE.	Wen and Meng (2015)
Quantitative assessment of economic and environmental aspects	Throughout quantitative study to gain a better understanding of the economic and environmental outcomes of industrial ecology	Jacobsen (2006)
Wastewater circonomics Index	The index captures the reuse and recycling efficiency of a waste water treatment process, which reflects the specific nature of wastewater, and the indicator employs scientifically generated weights that indicate the environmental benefits of the treatment method.	Kayal et al. (2019)

Table 3
Circular economy indicator in the biological cycle for micro level.

Circular economy indicator	Description	Ref
Recyclability benefit rate	The cumulative exergy extraction from the natural environment approach is used to calculate the environmental effect in terms of resource use.	Huysman et al. (2015)
Eco-cost value ratio	To evaluate potential adverse environmental effects of business operations on a system level, the LCA-based eco-costs value ratio was applied., as well as present a conceptual approach to designing sustainable business models based on a three-dimensional approach of costs, eco-costs, and market value (EVR).	Scheepens et al. (2016)
Longevity indicator	This method uses initial lifetime, gained refurbished lifetime, and earned recycled lifetime to evaluate a resource's contribution to material durability through time. Management of these factors can be used to make decisions and assess performance in the CE.	Franklin-Johnson et al. (2016)
Recycling index	This method uses the newly developed recycling index (RI), which includes a new Material-RI (similar to EU Energy Labels).	Reuter and Schaik (2016)
Global resource indicator	The purpose of this article is to go beyond current life cycle impact assessment methodologies by including critical aspects (such as recycling) that are not currently addressed by resource impact assessment indicators used in life cycle impact assessment.	Adibi et al. (2017)
Product-level circularity metric	The method estimates value chain costs and employs a circularity measure of the ratio of recirculated economic value to total product value.	Linder et al. (2017)
Product-level circularity metric	To adapt it to biological cycles, the material circularity indicator (MCI) was modified. The modified MCI's results were combined with the life cycle assessment technique and applied to the poultry industry.	Kankanamge et al. (2019)

5.2.2. Quantitative assessment of economic and environmental aspects

According to the notions of ecological sustainability and Industrial Symbiosis, transforming trash into resources for another institution will result in environmental benefits such as reduced virgin resource extraction and/or lowered emissions. Many environmental benefits emerge from industrial symbiosis exchanges. According to Jacobsen (2006) economic motivation is frequently linked to greater or lower levels of operational efficiency rather than the frequency of the substituted waste or byproduct.

Industrial symbiosis exchanges have been shown to point to a variety of direct and indirect economic advantages that make the practice a practical method for inter-industry cooperation with a consistent environmental result. To illustrate how these connections impact the environment and the economy, the author concentrates on industrial symbiotic relationships involving water and steam. The evaluation is based on numerical data records (Jacobsen, 2006).

5.2.3. Wastewater circonomics index

The Composite Reuse Indicator now has an objective measurement system based on hidden expenses for emissions brought on by wastewater treatment. The product of three (sub)indicators in the Wastewater Circonomics Index are Wastewater Production Efficiency Indicator, Composite Wastewater Reuse Indicator, and Wastewater Recycling Indicator (Kayal et al., 2019).

5.3. Micro level

The micro-level is characterised by analysing at the firm, product, or consumer level. Some indicators appear to have specific definitions, whereas others estimate CE using mixed-method approach criteria. Furthermore, some existing indicators focus on a single aspect of CE, whilst others consider many dimensions. A brief review of several micro-level CE indicators, as well as their ratings, is provided in Table 3.

5.3.1. Recyclability benefit rate

It may be defined as the proportion of significant ecological savings through recovery and reuse product to ecological exploitation from the use of virgin resources during manufacturing and disposal. The indicator takes into account potential values for environmental effects from the life cycle assessment (LCA) technique. It employs the Cumulative Exergy Extraction technique, which was developed from the Natural Environment methodology to quantify the environmental implications of resource exploitation. It gives quantitative data insights that policymakers may find useful (Huysman et al., 2015).

The case study presented evidence of the advancements made in CE in the province of Shaanxi. The system of indicators proposed by Qing et al. (2011), is intended to analyse a province's CE development. The level of growth in terms of CE that a province has achieved is proposed to be evaluated based on the following five categories: social and economic development, resource efficiency, resource recycling and reuse, environmental protection, and pollution reduction. The findings suggest that the development of continuing education (CE) in Shaanxi province is on the rise.

5.3.2. Eco-cost value ratio

This indicator is a tool that combines environmental and market aspects of production to evaluate potential environmental flaws in business models and to offer a replacement model based on costs, eco-costs, and market value that provides useful information. Eco-efficient Value (EVR) benchmarking and the Circular Transition Framework is used in the analysis and design. It delivers numerical outcomes (Scheepens et al., 2016).

5.3.3. Longevity indicator

The Longevity Indicator evaluates the product's average life and material utilisation. It shows how long a material is held during the production process. Product and material reuse/recycling ensure maximum resource exploitation within the same product system through this retention. The initial lifespan earned restored lifetime and earned recycled lifetime are compared in this indicator's calculation (Franklin-Johnson et al., 2016).

5.3.4. Recycling index

Reuter and Schaik (2016) developed the Recycling Index using simulation models with a foundation in processing minerals and metals. It is similar to the authors' prior work, which conceptualises and communicates a product's recycling result and individual materials in a clear, basic, and easy manner. It assists consumers in making informed purchasing decisions and communicating a more environmentally friendly design. It is similar to the European Union's Energy Labels. It will assist consumers in making educated purchasing decisions. Furthermore, RI are critical for communicating greener design and producers' efforts to improve resource efficiency, as well as industry's cutting-edge recycling and processing technologies.

5.3.5. Product-level circularity metric

The Product-level Circularity Metric was created as a result of the relationship between the recirculated economic value and the total worth of the product. In terms of raw resources and recycled materials, it converges on a circular product structure and the essential recycling procedures. This indicator permits genuine and effective circularity to be determined by avoiding environmental damage and using a cost-based technique. It gives quantitative findings with a metric that runs from 0 to 1, or 0% to 100% recycled parts (Linder et al., 2017).

5.3.6. Global resource indicator

To enhance resource qualities, the Global Resource Indicator combines several areas of resource evaluation. A multi-criteria indicator is made up of multiple characteristics related to accessibility, such as geographical availability and resource recyclability, to complement resource deficiency.

The following variables influence GRI:

- Deficiency, which is based on CML (an LCIA approach) and characterises renewable resource-corrected attributes (features).
- Dispersion and recycling rates are used to determine recyclability.
- The World Governance Indicators (WGI), the number of nations, and the standard deviation determine geopolitical accessibility (the inverse of criticality). It generates numerical data (Adibi et al., 2017).

5.3.7. Modified MCI

The Material Circularity Indicator (MCI), proposed by the Ellen MacArthur Foundation, is one of the most recent initiatives in this scenario. MCI's methodology is exclusively intended for non-renewable-source technical cycles and materials that focused on material flow (Trollman et al., 2021).

The modified MCI proposed by Rocchi et al. (2021) for livestock production may be a useful tool for assessing the degree of circularity in rearing systems and contrasting various species' methods of animal husbandry. Circularity is only examined inside the single rearing system in the approach described here. Hence crossing circularity is not considered. This decision was based on the types of indicators that were available at the time (micro-level indicators).

5.4. Discussion

There has been some promising progress on CE indicators in recent years. However, the current dearth of organised and standardised approaches to evaluate CE at each level, as indicated by a growth in the number of published articles, has resulted in a large number of distinct CE indicators. Furthermore, the emphasised case studies show how CE patterns are being applied in various industries and geographical locations, as well as how they are growing, demonstrating an increasing trend towards the implementation of CE assessment despite differing development stages and settings. CE indicators continue to demonstrate an insufficient uniformity of definitions, measurement standards, and methods, jeopardising any quantitative approach aimed at ensuring the economic system's long-term viability. Circularity metrics, as stated in a number of the articles reviewed, would be used to assess how the CE principles are being implemented. Furthermore, the analysis reveals a significant number of fragmented indicators and evaluation methodologies that occasionally overlap, resulting in metrics redundancy that leads to mismatches and poor comparability of results, necessitating academic discussions (Arbolino et al., 2019).

Despite the fact that CE indicators can help promote circularity, there are no standardised criteria for assessing CE. This could be a barrier to deeper learning and development, making tracking progress towards CE objectives impossible. In terms of the study's limitations, we emphasise that due to the small number of researchers who examined this topic, the decisions should be approached with caution. The valuable literature shows that biological cycle research is scarce and dispersed. Several practices have yet to be investigated throughout the biological cycle. The studies only looked at a few biological cycle approaches in which materials are reclaimed and repaired, and nutrients are replenished (Kankanamge et al., 2019). Many indicators are specialised and only useful in certain applications. Due to a lack of data and an international standard for the application of specific indicators, it is not easy to maintain objectivity in measurement (Arbolino and De Simone, 2019).

6. Conclusions

A circular economy (CE) is an alternative to the traditional linear economy that maximises value during resource consumption and produces fully usable items and materials. Despite the CE paradigm's positive claims, research on indicators and measures for monitoring CE applications is still in development. This review tries to address this shortcoming by presenting a framework of CE indicators, so readers understand what they measure and by highlighting the existing indicators and methodology used to monitor CE performance and advancement. The key findings are: (i) the selected indicators each have their own distinct characteristics, and as a result, the degree to which they satisfy the evaluation criteria may vary quite a bit from case to case; (ii) the vast majority of frameworks place a greater amount of importance on indicators that may track progress towards decreased resource input, decreased material losses and waste, and increased resource input from renewable and recycled sources; and (iii) in certain frameworks, a sizeable number of the indicators are contextual indicators, which do not reflect the qualities of the circular economy. It may be necessary to develop an authentic and distinct standard measurement model in order to handle and manage the complexity of the CE transformation. Starting with data availability and quality, as well as offering free access validated data bank, may be important for a successful measuring procedure. To obtain representative conclusions based on this common knowledge, quantitative data may be used in various sets of indicators selected under a specific operating system. Finally, the practical implications of this paper can be divided into two categories. For starters, it provides a deeper understanding of the structure and content of existing indicator-based frameworks for assessing the performance of circularity in biological systems, as well as a better understanding of their benefits and drawbacks. It is possible that this will aid the industry and stakeholders in hastening CE adoption. Second, it provides a comprehensive database of indicators that are part of the frameworks identified. This database could be used to revise previously established frameworks or to develop new frameworks that are more comprehensive and balanced.

CRediT authorship contribution statement

F. Kusumo: Writing – original draft, Conceptualization, Methodology. **T.M.I. Mahlia:** Writing – review & editing, Conceptualization, Supervision. **S. Pradhan:** Writing – review & editing, Conceptualization, Supervision. **H.C. Ong:** Writing – review & editing, Investigation. **A.S. Silitonga:** Writing – review & editing, Formal analysis. **I.M. Rizwanul Fattah:** Writing – original draft, Validation. **L.D. Nghiem:** Writing – review & editing, Project administration, Supervision. **M. Mofijur:** Writing – original draft, Validation.

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.

Acknowledgements

The authors wish to acknowledgement the research is supported by the University of Technology Sydney, Australia under International Research Scholarship

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