

Supplementary Material

Table S1. Classification of the indicators by nation

Geographic area	Bibliographic reference	Article	Indicator	Scope
European Union	EEA (2019)	Waste recycling in Europe	Waste recycling	Shows Europe's rate of progress towards the objective of recycling more waste.
European Union	Eurostat (2020)	Contribution of recycled materials to raw materials demand - end-of-life recycling input rates (EOL-RIR)	Contribution of recycled materials to raw materials demand	Used to monitor progress towards a circular economy in the thematic area of secondary raw materials.
European Union	Eurostat (2020)	Trade of recyclable raw materials between the EU Member States and with the rest of the world.	Trade in recyclable raw materials	Shows the quantities (in units of mass) and the monetary value (in euros) of selected waste sent across internal borders and outside the EU.
Sweden	Linder et al. (2017)	A Metric for Quantifying Product-Level Circularity	New product-level circularity metric	The metric allows for different actors to calculate circularity that is reliable and robust when it comes to market dynamics and innovation.
Sweden	Linder et al. (2020)	Product-level inherent circularity and its relationship to environmental impact		
Netherlands	Di Maio & Rem (2015)	A Robust Indicator for Promoting Circular Economy through Recycling	Circular Economy Index (CEI)	Introduces the economic value of the materials incorporated into consumer products as a property to measure and account for.
Netherlands	Scheepens et al. (2016)	Two LCA-based methods to analyse and design complex (regional) circular economy systems. Case: making water tourism more sustainable	Eco-costs/Value Ratio (EVR)	Analyses the sustainability of products, services and their business models.
Netherlands	Di Maio et al. (2017)	Measuring resource efficiency and circular economy: A market value approach	Value-based Resource Efficiency Indicator (VRE)	Widely used in the decision-making process and also the key parameter for measuring the efficiency of resources.
Netherlands	Brown et al. (2018)	The Circularity Gap Report: An analysis of the circular state of the global economy	Global Circularity Metric	Measures the circularity of the global economy based on the share of recycled materials as part of the total inputs of material in the global economy.
Netherlands	Corona et al. (2019)	Towards sustainable development through the circular economy- A review and critical assessment on current circularity metrics	Circular Economic Value (CEV)	Illustrates the effects of the use of renewable energy resources on the improvement of the flow of energy and materials.

Hungary	Fogarassy et al. (2017)	A Circular Evaluation Tool for Sustainable Event Management – An Olympic Case Study	Circular Economic Value (CEV)	Illustrates the effects of the use of renewable energy resources on the improvement of the flow of energy and materials.
Germany	Pauliuk et al. (2017)	Regional distribution and losses of end-of-life steel throughout multiple product life cycles – Insights from the global multiregional MaTrace model	Cumulative Service Index (Circ(T))	Provides the relative measure of the cumulative mass of a material present in a system over a certain time interval in terms of an ideal reference case, where all the material remains in functional applications throughout the entire accounting period.
Portugal	Azevedo et al. (2017)	Proposal of a Sustainable Circular Index for Manufacturing Companies	Sustainable Circular Index (SCI)	Makes it possible to assess the sustainability and the circularity of manufacturing companies, with an educational orientation because it could be considered a guideline for managers to reach a defined level of sustainability or circularity.
France	Franklin-Johnson et al. (2016)	Resource duration as a managerial indicator for Circular Economy performance	Longevity indicator	Shows the length of time during which a material is retained in a product system.
France	Adibi et al. (2017)	Global Resource Indicator for life cycle impact assessment: Applied in wind turbine case study	Global Resource Indicator (GRI)	Integrates aspects of evaluation of resources to better characterise them. Combines scarcity, geopolitical availability and recyclability.
Italy	Sassanelli et al. (2019)	Addressing circular economy through design for X approaches: A systematic literature review	Life Cycle Assessment (LCA)	Evaluates the environmental impact and quantifies and evaluates the emissions, the resources consumed and the pressure on health and the environment of a product over its entire life cycle.
Italy	Tortorella et al. (2020)	A Methodological Integrated Approach to Analyse Climate Change Effects in Agri-Food Sector: The TIMES Water-Energy-Food Module	Nexus Thinking approach	Method for understanding and modelling the complex interactions between different resource systems (energy, water, food).
Italy	Razza et al. (2020)	Metrics for quantifying the circularity of bioplastics: The case of bio-based and biodegradable mulch films	Material Circularity Indicator (MCI) adapted to biological cycles	The modified MCI supports the eco-design of innovative bio-based products.

Italy	Amicarelli et al. (2021)	Material flow analysis and sustainability of the Italian meat industry	Material Flow Analysis (MFA) applied to the Italian meat industry	With the MFA it has been possible firstly to quantify and qualify the flows of food waste and, secondly, to calculate the relative cycles of materials and eco-efficiency indicators.
Italy	Rocchi et al. (2021)	Measuring circularity: an application of modified Material Circularity Indicator to agricultural systems	Material Circularity Indicator (MCI) adapted to biological cycles	Modification of the MCI to adapt it to biological cycles.
UK, Greece, Italy	Lokesh et al. (2020)	Hybridised sustainability metrics for use in Life Cycle Assessment of bio-based products: resource efficiency and circularity	Hybridised sustainability metrics	Evaluates the environmental performance of (bio-based) products, independently or compared to their commercial counterparts.
UK	Ellen MacArthur Foundation (2015)	An approach to measuring circularity—Methodology	Material Circularity Indicator (MCI)	The metric evaluates circularity at the product and business level.
UK	Cayzer et al. (2017)	Design of indicators for measuring product performance in the circular economy	Circular Economy Indicator Prototype (CEIP)	Measures the performance of a product in regards to circular economy (CE) principles.
UK	Nichols & Smith (2019); Sensoneo Global Waste Index, 2019	Waste Generation and Recycling Indices 2019: Overview and findings	Global waste index (Waste Generation Index)	Provides a quantitative evaluation of the rate of production of waste per country.
UK	Nichols & Smith (2019)	Waste Generation and Recycling Indices 2019: Overview and findings	Recycling index	Evaluates the willingness and capacity of a country to manage solid waste in such a way as to promote circular material flows.
UK	Nika et al. (2020)	Water Cycle and Circular Economy: Developing a Circularity Assessment Framework for Complex Water Systems	Multi-Sectoral Water Circularity Assessment (MSWCA) framework	Framework for assessment of the circularity of multi-sectoral water, following a multi-sectoral systemic approach.
Spain	Laso et al. (2018)	Combined application of Life Cycle Assessment and linear programming to evaluate food waste-to-food strategies: Seeking for answers in the nexus approach	WEFCNI	Method for understanding and modelling the complex interactions between different resource systems (energy, water, food).
China	Chang et al. (2016)	Quantifying the Water-Energy-Food Nexus: Current Status and Trends		
USA	ZWIA (2004)	Zero Waste Definition Adopted	Zero waste index	Assesses the performance of waste management and the replacement of materials with waste management systems in various cities.

USA	Park & Chertow (2014)	Establishing and testing the “reuse potential” indicator for managing wastes as resources	Reuse potential indicator	Measuring the extent of technological development, the reuse potential indicator expresses the usefulness of the material with an actual value on a scale from 0 to 1.
USA	Shukor et al. (2018)	Assessment of composting technologies for organic waste management	Multi-Criteria Decision Making (MCDM)	A support framework for decisions which can evaluate multiple conflicting criteria.
USA	Food and Agriculture Organization of the United Nations (FAO)	Food Waste Index Report	Food loss	Measures the losses for key raw materials in a country along the entire supply chain, up to and not including retailers.
USA	United Nations Environment Programme (UNEP)	Food Waste Index Report	Food waste	Measures food waste at the level of retail and consumption (families and food service); measures the total food waste (rather than loss or waste associated with specific products). The food waste index also allows countries to measure and report food waste generated during production processes.
Colombia	Mesa et al. (2020)	Developing an indicator for material selection based on durability and environmental footprint: A Circular Economy perspective	Material Durability Indicator (MDI)	Integrates chemical and mechanical durability in a single calculation, along with the environmental impacts associated with the material.
Australia	Zaman & Lehmann (2013)	The zero waste index: a performance measurement tool for waste management systems in a “zero waste city”	Zero Waste Index	Evaluates the performance of waste management and the replacement of materials with waste management systems in various cities.

Table S2. Classification of circularity indices

Indicator	Scope	Developer and bibliographic reference	Level (micro/meso/macro)	Critical factors	Functionalities
New Product-Level Circularity Metric	The metric makes it possible to calculate circularity that is reliable and robust in regards to market dynamics and innovation.	Linder et al. (2017) Linder et al. (2020)	Micro	1. Restricted and highly specific focus: does not contain information relating to toxicity, creation of jobs, environmental impacts and sales methods of products. 2. Measures only the degree of recirculated direct material in the product weighted by direct costs; the indirect resources used in the production process are not included. 3. Treats two products with different durations as equal.	1. Can be applied to different product categories and has a high degree of generality. 2. Can be used as a product label to inform consumer choices and as a criterion for procurement activities between companies or within the public sector.
Material Circularity Indicator (MCI)	Evaluates circularity at the product and business level.	Ellen MacArthur Foundation	Micro	Concentrating on the flow of mass, it is not able to distinguish between different types of component in the product. Focuses solely on technical cycles and in particular on non-renewable resources, excluding all biological production.	Already sufficiently general that it can be extended to be applied to numerous industrial sectors; clear, easy to use and rapidly understood.
Circular Economy Indicator Prototype (CEIP)	Measures the performance of a product in regards to circular economy (CE) principles.	Cayzer et al. (2017)	Micro	Hiding of complexity, potentially misleading results, superficial engagement with decision-making and reliance on context-specific assumptions.	Speed of application, simplicity and ease of diffusion.
Global Circularity Metric	Measures the circularity of the global economy based on the share of recycled materials as part of the total inputs of material.	Brown et al., 2018 Global Circularity Report (2018)	Macro	Does not consider asset sharing, lifetime extension or remanufacturing. Any quality loss and degradation in processing is not considered.	Can set a zero measurement for the globe and track progress over time.
Cumulative Service Index (Circ(T))	Provides the relative measure of the cumulative mass of a material present in a system over a certain time	Pauliuk et al. (2017)	Micro/meso/macro	Based on a one-dimensional concept of circularity, in other words considering only the recirculation of materials and covering only (and partially) the	

	interval in terms of an ideal reference case, where all the material remains in functional applications throughout the entire accounting period.			resource efficiency CE objective.	
Circular Economic Value (CEV)	Illustrates the effects of the use of renewable energy resources on the improvement of the flow of energy and materials.	Fogarassy et al. (2017)	Micro/meso	Not based on products but on organisations, materials and events and therefore does not specify how to tackle the problem of resource allocation.	Includes a renewable energy assessment in the calculation.
Circular Economy Index (CEI)	Introduces the economic value of materials incorporated into consumer products as a property to measure and account for.	Di Maio & Rem (2015)	Micro/meso		Easy to calculate, uses easily available data, does not require additional human resources in order to be calculated.

Table S3. Classification of circularity assessment tools

Indicator	Scope	Developer	Level (micro/meso/ macro)	Critical factors	Functionalities
Sustainable Circular Index (SCI)	Makes it possible to assess the sustainability and the circularity of manufacturing companies, with an educational orientation because it could be considered a guideline for managers to reach a defined level of sustainability or circularity.	Azevedo et al. (2017)	Micro/meso	Robustness has not been sufficiently tested through case studies from different manufacturing industries.	Very versatile and simple since it makes it possible to assess the sustainability and the circularity behaviour of manufacturing companies.
Eco-costs/Value Ratio (EVR)	Analyses the sustainability of products, services and their business models.	Delft University of Technology	Micro/meso		
Global Resource Indicator (GRI)	Integrates aspects of evaluation of resources to better characterise them. Combines scarcity, geopolitical availability and recyclability.	Adibi et al. (2017)	Micro/meso		
Longevity indicator	Shows the length of time for which a material is retained in a product system.	Franklin-Johnson et al. (2016)	Micro	Does not consider the entire consumption process and the hypothesised life cycle of the product does not take into account the complexities of restructuring and recycling. In the restructuring phase, additional material is not considered; the consumption of resources is not dealt with in any phase of the cycle.	Can be used by any stakeholder to determine the effect of their own activities, independently of the nature of their activities. Can be applied to a range of materials and/or products and industries, thus allowing application on a very large scale.
Reuse potential indicator	Measuring the extent of technological development, the reuse potential indicator expresses the usefulness of the material with an	Park & Chertow (2014)	Micro	Requires a large amount of technical data that can be hard to obtain, like the quality of a material to be used in a specific application and replacement rates.	Dynamic and not an intrinsic property of waste. The reuse potential increases with the increase in technological options that allow a greater recovery of material.

	actual value on a scale from 0 to 1.			The lack of available data increases the uncertainty in assuming replacement rates.	
Value-based Resource Efficiency indicator (VRE)	Key parameter for measuring the efficiency of resources.	Di Maio et al. (2017)	Micro/meso/macro		Simple, robust, convenient, adaptable and well-aligned with social, environmental and economic policies.
Material Durability Indicator (MDI)	Integrates in a single calculation the chemical and mechanical durability, along with the environmental impacts associated with the material.	Mesa et al. (2020)	Micro	Implementation of the indicator depends to a great extent on the type of material considered in the selection process. Reliable values are necessary for the parameters and the availability of databases could be a limitation. In the case of the combination of different types of materials (e.g. composites), attention must be paid to the determination of the reference values.	
Hybridised sustainability metrics	Evaluates the environmental performance of (bio-based) products, independently or compared to their commercial counterparts.	Lokesh et al. (2020)	Micro	Additional data needed, plus their application and performance in second-life products and other bio-based product groups needs to be undertaken.	

Table S4. Classification of indicators developed within the Sustainable Development Goal (SDG)

Indicator	Scope	Developer	Level (micro/meso/macro)	Critical factors	Functionalities
Food Loss Index	Measures the losses of key raw materials in a country along the entire supply chain, up to but not including retail.	Food and Agriculture Organization of the United Nations (FAO)	Macro		Sufficiently accurate data collection provides the base for tackling food waste,
Food Waste Index	Measures food waste at the level of retail and consumption (households and food service). Measures total food waste (rather than loss or waste associated with specific products). The Food Waste Index also allows countries to measure and report food waste generated during production processes.	United Nations Environment Programme (UNEP)	Macro	Variations in waste over time can have a significant impact on the estimated quantity of waste; heterogeneity among countries in collecting and analysing data.	providing an understanding of the nature of food waste in a country in order to implement a national food waste strategy and be able to monitor it over time.

Table S5. Classification of waste management indicators

Indicator	Scope	Developer	Level (micro/meso/macro)	Critical issues	Functionalities
Global waste index (Waste Generation Index)	Provides a quantitative evaluation of the rate of waste production per country.	Verisk Maplecroft	Micro/meso/macro		
Recycling Index	Evaluates the willingness and ability of countries to manage solid waste and promote circular material flows.	Verisk Maplecroft	Micro/meso/macro		
Zero Waste Index	Assesses the performance of waste management and the replacement of materials with waste management systems in various cities.	Zero Waste International Alliance	Micro/meso/macro	This indicator was limited to urban waste management systems for six broad categories of waste: paper, plastic, metal, glass and organic and mixed municipal solid waste. Further research is needed to develop a zero waste index system for other types of waste.	A useful tool for comparing different waste management systems in different cities and provides a broader picture of the potential demand for virgin materials, energy, carbon pollution and water in a city.
Waste recycling	Shows Europe's progress rate towards the objective of recycling more waste.	EEA	Micro/meso/macro	Currently does not include important waste streams such as organic waste and batteries and accumulators.	Shows and describes, in detail, the trends in recycling rates for two types of waste, municipal waste and packaging waste, at both a European and a national level, to support an early-warning mechanism.
Contribution of recycled materials to raw materials demand	Used to monitor progress towards a circular economy in the thematic area of secondary raw materials.	European Commission	Micro/meso/macro	Given the lack of data for certain phases of the value chain, the indicator is partially based on estimates.	Unlike the indicators for the monitoring framework on waste management, which focus on collection or recycling rates in various waste streams, this indicator measures the contribution of recycling to the demand for materials by type of material.
Trade in recyclable raw materials	Shows the quantities (in units of mass) and the monetary value (in euros) of selected waste sent across	European Commission	Micro/meso/macro		

internal borders
and outside the
EU.

Table S6. Classification of decision-making processes

Framework	Scope	Developer	Implementation level	Critical issues	Functionalities
Multi-Criteria Decision-Making (MCDM)	A support framework for decisions which can evaluate multiple conflicting criteria.	Triantaphyllou et al. (1998)	Meso/macro		Can be applied to any discipline in order to make effective and accurate decisions based on various assessment criteria.
Life Cycle Assessment (LCA)	Evaluates the environmental impact of a product over its entire life cycle (quantifies and evaluates the emissions, the resources consumed and health and environment pressures).	Midwest Research Institute; SETAC and SETAC-Europe	Meso/macro	Necessary to use databases. Complexity of the retrieval phase of the environmental data to be assessed.	Consolidated tool for analysing the eco-efficiency of processes and products.
NEXUS Thinking approach	Method for understanding and modelling the complex interactions between different resource systems (energy, water, food).	Food-Energy Nexus Programme of the United Nations University (UNU)	Meso/macro	Associated subjects (e.g. farmers, agronomists) must invest adequate capital to create the right circumstances to move towards a closed-cycle system. The water-energy-nutrient nexus requires significant correlations between them. Further steps are needed to create strong links from a CE perspective between the food industry and agriculture.	
WEFCNI					

Multi-Sectoral Water Circularity Assessment (MSWCA) framework	Framework for assessment of the circularity of multi-sectoral water, following a multi-sectoral systemic approach.	Nika et al. (2020)	Meso/macro	Increased data volume to favour the environment-sector integration and the complexities of the modelling create uncertainties.	The MSWCA framework for facilitating integration between the natural environment and various sectors provides large amounts of data from multiple sources.
Material Flow Analysis (MFA) applied to the Italian meat industry	With the MFA it has been possible to quantify and qualify the flows of food waste and to calculate the relative cycles of materials and indicators of eco-efficiency.	Amicarelli et al. (2021)	Meso/macro	Efforts are necessary to improve the robustness and reliability of the MFA; the level of uncertainty intrinsic in the MFA calculations is significant; difficult to distinguish between “consumed”, “used” and “by-products” which are not picked up in the current statistics.	Represents a snapshot of the whole supply chain, enhancing knowledge of inputs and outputs along the entire meat production process.
Material Circularity Indicator (MCI) adapted to biological cycles	Modification of the MCI to adapt it to biological cycles.	Ellen MacArthur Foundation and modifications by Rocchi et al. (2021)	Micro	Focus on the single product, meaning that crossed circularity along the supply chain or value generation have not been considered.	Attempt to create an index dedicated to biological cycles.
Material Circularity Indicator (MCI) adapted to biological cycles	The modified MCI supports the eco-design of innovative bio-based products.	Razza et al. (2020)	Micro	The proposed MCI must be seen as a complementary tool (quantitative) to further qualify the sustainability of BB products and not as a substitute tool. Additionally, the proposed MCI is only significant if the BB products meet the health and safety requirements of materials according to national and European laws and standards.	Allows a comparison of circularity, keeping in consideration the biological source and the expected end-of-life process, e.g. biodegradation.

Table S7. Classification of experiences and good practices

Experiences and good practices	Scope	Developed	Level (nano/micro/meso/macro)	Critical issues	Functionalities
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Product Circularity Data Sheet (PCDS)	Official standard for the communication of data on the circular economy properties of products, in consultation with other standards bodies.	Luxembourg Ministry of the Economy	Nano	Lack of efficient access to accurate data about the circular properties of a product.	The standard aims to facilitate the exchange of information along the entire supply chain.
Cradle to Cradle	Carries out assessments of the impact of products and services based on five key principles, including selection and reuse of materials, use of renewable energy in the production system, water management and social equity.	Cradle-to-Cradle Products Innovation Institute	Nano	A single variation in the method of a supplier of technical nutrients can disturb the C2C plan; lack of flexibility in the C2C design which could make it difficult for a producer to produce a more varied and diversified line of products.	If used correctly, C2C guarantees the lowest possible environmental impact; because production resources or technical nutrients are often reused, this can often lead to financial savings. The model can be repeated endlessly as long as the biological and technical nutrients are available and correctly sourced.
REPRO	Performs statistical analyses of different end-of-life (EoL) product scenarios based on a set of 82 criteria.		Micro	Weakly implemented, with low construct validity given that reuse and recycling are excluded. Moreover, the tool does not measure actual remanufacturing rates.	Allows designers to compare their products with others that have been successfully remanufactured with a view to improving remanufacturing rates.
Circle Assessment	Helps businesses to understand the different operational and organisational aspects of the circular economy.	Circle Economy	Micro		
Circular Transition Indicators	Helps companies prepare the assessment and interpret its results, understand its risks and opportunities, prioritise actions and establish SMART targets to monitor progress.	World Business Council for Sustainable Development (WBCSD)	Nano/micro	i) Lack of a classification of feasibility of implementation of circularity indicators; ii) exclusion of structured methodologies (e.g. LCA) as circularity indicators; iii) explanations can at times lack clarity when it comes to the methodologies of indicators that have hindered the analysis of the pillars of sustainability and life cycle phases.	Has valuable implications for companies, policy decision-makers, professionals in the sector and academic researchers. Subdividing the levels further into nano and micro contributes to i) avoiding confusion regarding an overly broad vision of the micro level; ii) separating the product-level circularity from the overall scores of the companies; iii) organising a large number of circularity indicators into a more rigorous division to help decision-makers.

Circulytics	Supports the transition of a company towards the circular economy, independently of its sector, complexity or size.	Ellen MacArthur Foundation	Micro		
Response-Inducing Sustainability Evaluation (RISE)	Model of assessment of the degree of sustainability allows an easy evaluation at farm level. Offers a holistic approach for advice, education and planning.	Bern University of Applied Sciences	Meso	Offers a holistic approach, covering the aspects of agricultural sustainability (ecological, economic and social); able to quantify the level of sustainability of agricultural systems; applicable at a global level.	Based only on 12 indicators and does not measure the interaction of the indicators.
UNI1608856 Measuring circularity – Methods and indicators for measuring circular processes in organisations	Wants to define a set of indicators applied at the macro, meso and micro level aimed at assessing the level of circularity of an organisation or group of organisations.	UNI Circular Economy Technical Commission	Micro/meso/macro		
UNI1608977 Analysis of good circular economy practices for the evaluation of their functioning and performance and to favour their replicability	Intends to collect an analysis of good circular economy practices from Italian organisations.	UNI Circular Economy Technical Commission	Micro/meso/macro	In in experimental stage by UNI Circular Economy Technical Commission	
UNI/TS 11820:2022 Circularity measurement - Methods and indicators for measuring circular processes in organizations	Defines a set of indicators designed to assess, through a rating system, the level of circularity of an organization or group of organizations. The rating system does not stipulate minimum levels of circularity, but provides an assessment of the level achieved.	UNI Circular Economy Technical Commission	Micro/meso	In in experimental stage by UNI Circular Economy Technical Commission	