Journal of Environmental Chemical Engineering 11 (2023) 111023

Contents lists available at ScienceDirect

Journal of Environmental Chemical Engineering

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

Measuring the symbiotic performance of single entities within networks using an LCA approach

Fernando Arce Bastias [a], Paula Daniela Rodríguez [a], Alejandro Pablo Arena [a], Laura Talens Peiró [b,*]

[a] Grupo CLIOPE, Facultad Regional Mendoza, Universidad Tecnológica Nacional, Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Mendoza 5500, Argentina
[b] SosteniPrA Research Group (2021SGR00073), Institut de Ciència i Tecnologia Ambientals (ICTA-UAB), Unitat Excelencia Maria de Maeztu (MdM 2015–0552; CEX2019–000940-M), Universitat Autònoma de Barcelona, Cerdanyola del Vallès, Barcelona 08193, Spain

ARTICLE INFO

Editor: Teik Thye Lim

Keywords:
Environmental performance
By-product exchange
Entity level
Life cycle assessment
Indicator

ABSTRACT

This paper introduces the Symbiotic Performance Indicator, a novel indicator aiming to quantify the environmental benefits generated by by-product exchanges in an industrial symbiosis network. Despite the significant advancements in assessing industrial symbiosis, the lack of indicators for individual entities involved in by-product exchanges hinders a comprehensive understanding of its environmental benefits. This indicator accounts for resource use and greenhouse gas emissions using a life cycle perspective. The resource use is measured using the Cumulative Exergy Extraction from the Natural Environment method, while greenhouse gas emissions are evaluated using the IPCC 2013 Global Warming Potential (100a) method. The use of this indicator is illustrated in a real case study where plastic waste is exchanged among three entities in Mendoza (Argentina). The overall results show that resource use and greenhouse gas emissions can be reduced by 19% and 15%, respectively. Full and partial allocation methods are proposed within the formulation of the Symbiotic Performance Indicator. The indicator results show that the exchange of materials may seem less attractive when using full allocation methods, as one entity gets 100% of the benefits from the by-product exchange compared to the other. Partial allocations make the by-product exchange convenient for both entities which may encourage collaboration. In conclusion, the proposed indicator helps account more precisely for individual environmental benefits behind by-product exchanges, and thus enables better decision-making to set up an industrial symbiosis network.

1. Introduction

In contrast to the current linear economic activity ("take-make-dispose"), the Circular Economy (CE) proposes a broader and more comprehensive approach to understanding systems, products and services and their interaction with the environment, over the entire life cycle of any process [1]. Although the basic principles for CE have been developed for nearly 30 years, there is no commonly accepted definition [2]. However, the main objective of CE is to analyze systems using a systemic approach with the intention to optimize the use of resources and reduce waste from a life cycle perspective. This is done to achieve sustainable development by deploying a regenerative system [3].

Industrial Symbiosis (IS) presents a systems approach to promoting a CE through the collaboration of various entities to exchange their by-products and reduce the use of primary resources overall [4]. The generally accepted definition of IS states that wastes or by-products of one industry become inputs to other industry. Based on such cooperation, these industries create an IS network that additionally generates economic, environmental and social benefits [5,6]. The most referenced and clear-cut case is the Kalundborg Symbiosis Park located in Denmark. In this park, water, energy and materials are exchanged in closed loops between private and public entities. The Kalundborg Symbiosis began

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Abbreviation: CE, Circular Economy; CEENE, Cumulative Exergy Extraction from the Natural Environment; GHG, Greenhouse Gas; IS, Industrial Symbiosis; IPCC, Intergovernmental Panel on Climate Change; LCA, Life Cycle Assessment; MFA, Material Flow Analysis; MPM, Madera Plástica Mendoza; PE, polyethylene; PP, polypropylene; RBR, Recyclability Benefit Rate; RBR_{OL}, RBR for open-loop recycling; S-LCA, Social Life Cycle Assessment; SPI, Symbiotic Performance Indicator; UP, Urquiza Plásticos.

* Corresponding author.
E-mail address: laura.talens@uab.cat (L. Talens Peiró).

https://doi.org/10.1016/j.jece.2023.111023
Received 29 May 2023; Received in revised form 16 August 2023; Accepted 12 September 2023

with a couple of collaborative initiatives between a few firms 40 years ago. The exchanges in the network were not originally intended to demonstrate the benefits of industrial symbiosis but were negotiated and established to pursue an economic benefit [7,8]. Since new firms have joined this network, the exchanges of waste flows and resources have expanded gradually to result in an annual savings of 635,000 tonnes of CO_2 and 87,000 tonnes of primary materials, including ethanol, fly ash, gypsum, sulfur and sand [9]. To date, few examples of IS developed in emerging countries of America have been found. Brazil stands out as the most advanced in the exchange of solid waste through IS [10]. For instance, Sellitto et al. [11] highlighted that a Brazilian network of manufacturing companies facilitates the exchange of nearly 300,000 tonnes of by-products per year. In Argentina, a study proposed a green urban planning system that integrates agro-urban symbiosis with circular flows of energy and water [12].

Even though CE has acted as the main driver to set material and energy exchanges, accounting for the potential environmental benefits of such exchanges is becoming gradually more relevant. When a life cycle perspective is applied, the environmental assessments show that not all by-product exchanges yield an environmental benefit. For instance, Mohammed et al. [13] found that converting phosphogypsum –an industrial waste generated by phosphoric acid production– to sodium sulphate and ammonium sulphate leads to negative environmental impacts (global warming potential, eutrophication potential and water use). Moreover, Rodríguez et al. [14] evaluated a symbiotic system linking a fishmeal facility with a microalgae plant, where flue gas replaces pure CO_2. The results showed that a net reduction of greenhouse gas (GHG) emissions was achievable only when low-carbon electricity was consumed (less than 9% of fossil fuels). Otherwise, the symbiotic system entailed a rise in GHG emissions compared to the conventional scenario without exchange.

To support the progress toward a CE, indicators have been the focus of numerous studies [15–17]. Most authors broadly agree that indicators can be essential tools for assessing CE at different levels. In the context of IS, Dong et al. [18] and Chen et al. [19] have highlighted that methods and indicators are expected to monitor, reflect and quantify the benefits of IS practices. Some of those indicators are referred to as eco-efficiency indicators, resource efficiency indicators and indicators that reflect the resilience of the IS network. Nevertheless, one existing limitation of most of them is the lack of a systemic perspective for measuring IS at the entity level [20]. Thus, the aim of this work is to develop an LCA-based indicator to quantify the individual environmental benefits of by-product exchanges. This indicator can be used as guidance for entities operating within the IS network. By performing an individual assessment of each by-product exchange, the indicator would aid entities in deciding whether to establish and further encourage synergies.

Firstly, the paper examines the assessment of IS through methods and indicators. An overview of the methodological considerations of the allocation method of environmental burdens in Life Cycle Assessment (LCA) is done to in a later stage support the description of the possible allocation method for the SPI. Secondly, the related credits in an IS network are described, and then the proposed indicator is formulated. The indicator is later used in a case study to illustrate the potential environmental benefits of a real industrial network set to exchange plastic by-products. The potential environmental benefits of such exchange are calculated through LCA and quantified in terms of environmental impacts. For simplification purposes, two single life cycle impact assessment methods are used. The resource use is evaluated through the CEENE (Cumulative Exergy Extraction from the Natural Environment) method, proposed by Dewulf et al. [21] and Alvarenga et al. [22]. The potential GHG emission savings are calculated through the IPCC 2013 GWP 100a method. The paper concludes with a discussion on the potential use of the indicator to enhance further IS networks, including some aspects regarding the allocation method in IS exchanges.

2. Literature review

2.1. Assessment of the environmental benefits of IS practices

Wadström et al. [23] examined the methods used to study IS and found that interviews followed by LCA are the most frequently used method to collect data for quantitative studies. Similarly, Harris et al. [24] showed that Material Flow Analysis (MFA) and LCA are the most common methods to evaluate resource savings and environmental performance of IS networks. MFA is a systematic method to map the changes in flows and stocks of any material-based system [25]. However, it does not provide information about the potential environmental impacts related to the system. LCA, on the other hand, is suitable to understand better the environmental performance and resource savings of the system under analysis. As a result, most authors propose using LCA to assess the environmental benefits of IS [26]. Besides, Corona et al. [27] stated that the advantage of LCA compared to MFA is that the assessment framework could be expanded to an economic LCA –referred to as Life Cycle Costing– and to a social LCA –referred to as S-LCA– to cover all three dimensions of sustainable development. The authors concluded that, although LCA has a high potential to assess the environmental benefits of CE strategies, many essential issues remain unresolved, e.g., allocating environmental costs/benefits in open-loop recycling. Many authors have performed an environmental evaluation of IS networks with a life cycle perspective [28–32]. For instance, Kerdlap et al. [33] developed a multi-level analysis where LCA results could be disaggregated into three levels: network, individual companies and specific flows. The authors stated that this disaggregation allowed each stakeholder to decide whether they participate in the IS network based on their environmental performance.

Many scholars have used different metrics to evaluate the performance of CE strategies with a particular focus on material efficiency [34–36]. Niero and Kalbar [37] highlighted the need to couple those metrics with life cycle-based indicators to address CE trade-offs and rebound effects. For instance, Ardente and Mathieux [38] proposed the Recyclability Benefit Rate (RBR), which uses LCA results. The RBR is defined as the ratio of the environmental savings obtained from recycling a product over the environmental burdens regarding production from virgin material followed by disposal (landfill or incineration). Huysman et al. [39] further developed the RBR for open-loop recycling (RBR_{OL}). This indicator is applicable when the recycled materials are only usable for other product applications, as in the case of IS exchanges. Subsequently, Huysveld et al. [40] introduced several improvements to the RBR_{OL} indicator. One of the main modifications was the adjustment of the denominator to consider the two new terms: environmental impact of the disposal of the by-product and the environmental impacts of the product made from virgin material (including virgin material production, manufacturing, use and disposal). This variation allows a more accurate comparison between the primary raw materials-based and recycled materials-based products. Another notable example is the Industrial Symbiosis Indicator proposed by Felicio et al. [41] which combines two methodologies: MFA and Environmental Impact Assessment. The derived IS indicator was created using the “Environmental Impact Momentum”, an index that considers the qualitative impact criteria and the quantity of by-products. Table 1 summarizes a list of the diverse environmental assessments and their related indicators (if available) used to evaluate IS practices retrieved from the literature.

Although the indicators included in Table 1 use a systemic approach to assess the environmental benefits, they are not capable of quantifying the individual benefits for each entity involved in the by-product exchange. Fraccascia and Giannoccaro [20] already highlighted the need to develop indicators assessing the environmental performance at the company or entity level. Such information is essential to motivate companies to engage in an IS practice and identify processes in the IS network to improve their environmental performance [33].

Table 1
Description of environmental performance methods and indicators used to assess Industrial Symbiosis practices in existing literature. NA means not available.

Method	Indicator	Description	Author
Life Cycle Assessment (LCA)	NA	The environmental impacts of the current implementation of IS in an Italian tannery cluster are assessed using LCA by comparing them with a non-symbiotic hypothetical scenario.	Daddi et al. [28]
LCA	NA	This study evaluated the life cycle CO_2 emissions of using wood-derived fuel in the co-combustion process of a cement plant in Hong Kong.	Hossain et al. [29]
LCA	NA	The article evaluates the environmental performance of an IS network comprising firms in waste management, soil, surfaces, paper, lumber, and energy sectors. Using LCA, the study compares the current IS network with a reference scenario and a potential future development. It emphasizes the importance of recognizing the benefits of IS at both the network level and its potential advantages for individual firms and products within the network.	Martin [30]
LCA + socio-economic assessment	NA	This study presents an LCA and socio-economic assessment of an emerging IS network in Sweden, which comprises existing firms engaged in fish processing industries, algae production, a system for recycling plastic wastes, and a land-based salmon farm. The research sheds light on the broader implications and benefits of the IS network for the involved firms and the overall regional sustainability	Martin and Harris [31]
LCA	The ratio between investment cost and reduced global warming potential	This study evaluates the environmental impact reduction potential of two strategies for an existing chemical industry cluster in Sweden using LCA. The assessment is performed for on-site processes and for the whole cycle, i.e., if upstream and downstream processes are also included.	Røyne et al. [32]
Multi-level matrix-based modeling and analysis of the life cycle environmental impacts of IS networks (M^3-IS-LCA)	NA	This study introduces M3-IS-LCA, which is constructed so that LCA results can be provided at the levels of the network, individual company, and specific resource flows. The case study focuses on a potential food waste valorization IS network in Singapore.	Kerdlap et al. [33]
LCA	Recyclability Benefit Rate for open-loop recycling (RBR_{OL})	The proposed indicator uses LCA results to calculate the environmental savings achieved through recycling a product compared to producing it from virgin material and disposing of it. Moreover, improvements have been made to account for open-loop recycling, specifically suited for IS exchanges involving the use of recycling materials in other product applications.	Ardente and Mathieux [38], Huysman et al. [39], Huysveld et al. [40]
Material Flow Analysis (MFA) and Environmental Impact Assessment	Industrial Symbiosis Indicator	The authors proposed an indicator that accounts for qualitative impact criteria and the quantity of by-products. A Brazilian eco-industrial park was evaluated, and three scenarios were created: an industrial park without symbiosis, with symbiosis, and with perfect symbiosis.	Felicio et al. [41]

2.2. Allocation of environmental burdens in LCA

In an IS network, a waste (hereinafter also referred to as by-product) generated from one entity enters another entity to be reused or recycled, and thus replaces virgin material input. As a result, the environmental burdens from the common process shared among the different entities must be partitioned. From a methodological standpoint, this partitioning, also known as allocation in LCA, needs to be applied to IS exchanges. Although Mattila et al. [42] addressed the linkages between LCA and IS networks in detail, only guidance to provide the environmental performance of the system's total output is given. The ISO 14044:2006 standard for LCA provides a conceptual framework and distinguishes between closed-loop recycling (material substitutes the virgin material and is used in the identical type of products as before) and open-loop recycling (material is recycled from one product into another) [43,44]. This conceptual framework is intended to guide practitioners in modelling end-of-life processes; however, it is general and open to various interpretations [45]. Martin et al. [46] have developed methodological considerations focusing on allocation procedures. The authors provided an approach to identify benefit-sharing between firms and distribute impacts and credits in the IS network. Likewise, Kim et al. [47] applied three by-product impact allocation methods (cut-off, avoidance and the 50:50 method) to distribute the GHG impacts between two companies involved in a real IS exchange developed in Ulsan (Korea). Furthermore, Ekvall et al. [48] highlighted an allocation problem in LCA when recycling systems are assessed since two or more products use the same material stemming from another product's life cycle.

3. Materials and methods

In IS networks, companies are particularly interested in determining their individual environmental savings while also considering a holistic approach. When assessing the potential environmental benefits of by-product exchanges at the entity level, the allocation procedure for accounting for them needs to be well-defined. First, the possible methods for allocating the environmental impacts and the allocation factor are explained (Section 3.1). Once the allocation factor is defined, the proposed indicator is detailed (Section 3.2). The indicator is then tested in a real case study, where the entities involved in the IS network and the possible scenarios are described (Section 3.3). An environmental assessment using LCA follows (Section 3.4), including the definition of the goal and scope, the inventory analysis and the impact assessment.

3.1. Allocation factor

As Martin et al. [46] stated, there is an unfair distribution of impacts and benefits from using by-products as raw materials when applying the system expansion method. Therefore, the authors recommended the 50:50 allocation method, which is used to equally distribute credits between the entities directly involved in the exchange. This approach for crediting entities involves deducting the environmental impact of the virgin raw material production avoided through by-product exchange. In the 50:50 allocation method, credits are equally shared between both entities involved in the exchange. As seen in Fig. 1, By-product A substitutes Raw B; therefore, 50% of the impacts of Raw B are removed from Entity B and 50% from Entity A. Entity B must receive the impact for the virgin Raw B to avoid double-counting of credits created by the avoidance. Given this, Entity B receives only 50% of the impact for the production of Raw B. Furthermore, if an intermediate process may be needed to enable the exchange, the impacts from this process should be equally shared between Entity A and Entity B. The partial allocation was compared with two full allocation methods (100:0, 0:100) considered as limit cases. In the 100:0 allocation, the impact credits produced when Entity B avoids using raw materials by using a by-product of Entity A are assigned to Entity A. In the 0:100 allocation method, the impact credits are assigned to Entity B if it avoids using raw materials by using a by-product of Entity A.

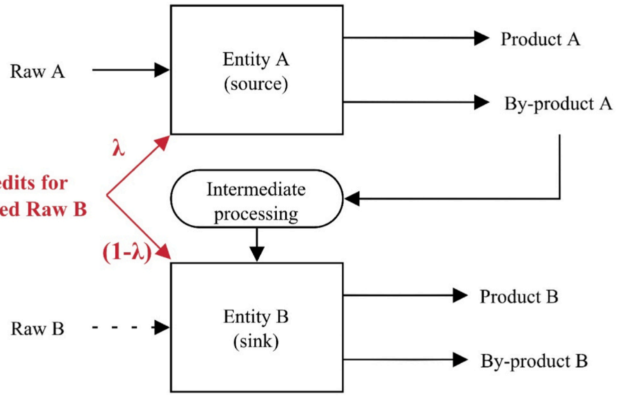

Fig. 1. Definition of λ factor for defining possible allocation methods of the potential environmental impacts and burdens (*Modified* from Martin et al. [46]).

In this paper, the λ factor is introduced, which will be used to refer to the credits for avoiding Raw B. The value of λ factor is 0.5, 1, or 0 according to the different allocation methods: 50:50, 100:0, or 0:100, respectively. Fig. 1 shows the meaning of each of these allocation methods conceptually. In certain situations, alternative λ factors, such as 0.25 or 0.33, might be appropriate to accommodate varying degrees of involvement by the relevant entities. However, any deviation from the standard values (0.5, 1, or 0) must always be well-justified with clear motivations.

3.2. Definition of the symbiotic performance indicator

For each entity involved in the by-product exchange, it is possible to calculate the Symbiotic Performance Indicator (SPI). The SPI is defined as the individual environmental benefits that an entity gains by participating in a by-product exchange over the environmental impact of a reference scenario with no exchange of materials and energy. Then the SPI of each entity is calculated for any impact category, as shown in Eq. (1).

$$SPI = \frac{\text{benefits from by} - \text{product exchange}}{\text{impact of the entity in the reference scenario}} \tag{1}$$

Eq. (2) shows how to calculate the SPI is calculated for the source, which is any process or plant that makes a resource available to the general system [49]. Calculating the benefits from the by-product exchange must consider the recycling rate (r), defined as the amount of recycled material produced over the amount of input waste material. Then, the benefit of the source for participating in the by-product exchange is the impact from the disposal of by-product α_0 (D_{α_0}) minus the impact from intermediate processing (I_{α_0}), and the latter is multiplied by the allocation factor (λ). The source is credited with the avoided impact of the production of virgin material α (V_α), multiplied by the allocation factor and the substitution percentage (m). The substitution percentage is defined as the amount of virgin material substituted by the amount of recycled material ($m = m_v/m_r$).

$$SPI_{source} = \frac{r \bullet \left[\left(D_{\alpha_0} - \lambda \bullet I_{\alpha_0} \right) + m \bullet \lambda \bullet V_\alpha \right]}{\left| r \bullet D_{\alpha_0} + I_{ENTITY \quad A} \right|} \tag{2}$$

Eq. (3) illustrates how to calculate the SPI for the sink, which is any process or plant that consumes a resource [49]. The environmental benefit of the by-product exchange for the sink involves summing the avoided impact of virgin material production with the impact from manufacturing (M_α), multiplied by the substitution percentage. Then, the impact of the recycling (R_{α_0}) and intermediate processing, multiplied by one minus the allocation factor ($1 - \lambda$), is subtracted from the previous result. The sink is also credited for avoiding the production of virgin material. However, the impacts from the production of virgin material are still summed to the sink to avoid double counting of credits created by the avoidance. Therefore, the avoided impact for the virgin production, multiplied by the allocation factor and the substitution percentage, is subtracted.

$$SPI_{sink} = \frac{\left[\left(m \bullet \left(M_\alpha + V_\alpha \right) \right) - \left((1 - \lambda) \bullet I_{\alpha_0} + R_{\alpha_0} \right) - \lambda \bullet m \bullet V_\alpha \right]}{\left| r \bullet m \bullet \left(M_\alpha + V_\alpha \right) + I_{ENTITY \quad B} \right|} \tag{3}$$

The definition and design of the reference scenario are essential issues for the best quantification of the studied scenario's environmental benefits. In this work, the definition of “reference scenario” proposed by Aissani et al. [50] was adopted. The reference scenario is a hypothetical non-symbiotic scenario built with no exchanges between the entities within the IS network. Therefore, the total environmental impacts of each entity are evaluated assuming it is in isolation. The environmental impact of the source in the reference scenario is the impact from the disposal of by-product α$_0$ (D_{α_0}) multiplied by the recycling rate (r). The impacts from processing and other inputs ($I_{ENTITY\quad A}$) are summed with the disposal impact. The environmental impact of the sink is the impact of virgin material production, which is summed with the environmental impact from manufacturing ($M_\alpha + V_\alpha$). This result has to be multiplied by the recycling rate (r) and the substitution percentage (m). The impacts from processing and other inputs ($I_{ENTITY\quad B}$) are summed with the latter.

As the SPI accounts for net impacts, i.e., burdens minus avoided burdens or benefits, the indicator can have a positive or negative value. If the SPI results in a positive value, the larger the value, the more beneficial is the by-product exchange for the entity. If the SPI results in a negative value, the by-product exchange is inconvenient for the entity from an environmental perspective. The denominator is accounted for as an absolute value to limit the change in the sign and, consequently, the meaning of the indicator.

3.3. Case study

The applicability of the SPI was evaluated using a real case study on plastic by-products (see Fig. 2). These plastic by-products are generated during the processing phase and exchanged between three companies located in Mendoza (Argentina). The dashed line in Fig. 2 represents the system boundary of the study, i.e., establishes the processes considered in the assessment, and the red arrows depict the by-product exchanges.

Company 1, called BARESI, produces two types of recycled plastic pellets from plastic scraps and industrial packaging waste: polyethylene (PE) and polypropylene (PP). Table S1 of the Supporting Information 1 shows the inputs and outputs for BARESI in the IS network. The recycled plastic pellets are used to produce new products such as industrial packaging, strapping, pipes, hoses and crates. BARESI primarily deals with post-industrial plastic waste, which is generated during the manufacturing stage, as the impurities of this waste stream can be controlled and minimized. BARESI processes 1200 tonnes of industrial plastic scraps per year and generates 72 tonnes of mixed plastic waste per year, consisting of PP (50%) and PE (50%).

Company 2, named *Madera Plástica Mendoza* (MPM), specializes in producing recycled plastic posts used in vineyards. Table S2 of the Supporting Information 1 shows the inputs and outputs for MPM in the IS network. MPM can use post-consumer plastic waste, which material consumers generate after its use (e.g., household waste), because their end-products have low technical requirements. At MPM, the recycling process consists of three main steps: shredding, further mixing of plastics and extruding the resulting mix of plastics into posts. This waste treatment system was described in an earlier study [51]. The amount of waste generated is negligible; therefore, the recycling rate is 100% ($r = 1$). This indicates that one kg of recycled plastic is produced per kg of waste input. Also, MPM uses an antioxidant* to improve the quality of recycled plastics. The proportion to products of the additive intake is 0.1 wt%.

Company 3, *Urquiza Plásticos* (UP), is a producer of plastic crates primarily supplied to the agricultural market, covering the needs for crates for harvest, export and transport trays. Table S3 of the Supporting Information 1 shows the inputs and outputs for UP in the IS network. UP specializes in the production of crates made of mainly three materials: recycled PP (rPP), recycled PE (rPE) and virgin PP (vPP). The recycled plastic crates are obtained by processing mixed plastic waste in situ (30% of the total input) –supplied by different informal sorting plants– and buying recycled plastic pellets (54% of the total input) –half of them supplied by BARESI. A company producing virgin PP supplies the remaining fraction (16%). The processing of the mixed plastic waste consists of the following steps: shredding, separation in water and drying, and then extrusion. When processing mixed plastic waste, part of the materials is lost during recycling. The recycling rate is assumed to be 90%, indicating that 0.9 kg of recycled plastic is produced per kg of waste input. The recycled pellets and the mixed plastic waste processed in situ are blended in equal proportions to produce a recycled crate. The plastic crates have an average weight between 0.4 kg and 2.1 kg, which was estimated based on the data reported by the company. Plastic scrap is generated during the extrusion process and transported to BARESI. UP cannot reprocess it because its volume exceeds their shredding machine’s capacity. Based on Tua et al. [52], it was assumed that the plastic scrap generation is 100 g per crate.

The symbiotic scenario implies that plastic by-products are supplied to MPM and BARESI. Additionally, intermediate processing is required to upgrade or change the properties of the by-products, such as the shredding processes done at MPM and BARESI and the transportation of plastic by-products. It was assumed that the same amount of virgin material is substituted by recyclable materials ($m=1$). In this scenario, there are two material sources (UP and BARESI) and two material sinks (MPM and BARESI). It should be noted that BARESI is involved in two exchanges with two different roles. This is an interesting case to illustrate the use of SPI.

The reference scenario represents the hypothetical non-symbiotic system with no exchange of materials between the three companies. Moreover, it was assumed that MPM uses virgin PP to replace the by-products and that BARESI buys virgin PP to supply their customers. In the reference scenario, plastic wastes were considered disposed of in a landfill because, as informed by the companies, it was a traditional practice before the established exchanges.

3.4. Environmental assessment using LCA

As introduced in Section 3.2, the SPI indicator builds on the results of an LCA. For this reason, the first step in the assessment was to carry out an LCA following the ISO 14040 [43] and 14044 [44] standards. The goal of the LCA was first to quantify the environmental impacts (burdens and benefits) of the symbiotic and the reference scenarios, and second to provide the data to account for the SPI indicator. A cradle-to-gate analysis was performed using the system boundary described in Fig. 2. The cut-off approach was applied to model recycling in LCA [45]. This means that plastic waste was considered burden-free. The final handling of the products and by-products leaving the system was not included.

The environmental benefits of an IS network are accounted for by comparing the symbiotic scenario with a reference scenario. In this work, the methodological recommendations for setting the functional units proposed by Martin et al. [46] were adopted. The IS network produces several main products and by-products as it is a multifunctional system. Therefore, the functional units were set to the annual output (in tonnes per year) of PP and PE pellets, plastic posts, and plastic crates. As a result, both scenarios are designed to produce the same final functions and products. The values of the reference flows are listed in Table 2.

Regarding the inventory analysis, data were collected for the foreground and the background system. Data for the foreground system were collected in close collaboration with the companies involved in the plastic waste treatment system. In this study, the background system included the data on the production and distribution of diesel, tap water, electricity and virgin PP. It was modelled using the Ecoinvent 3.6 database [53] contained in the SimaPro® software (version 9.1.1.1). Infrastructure was not included due to unavailable data. Detailed information about the datasets from Ecoinvent is shown in Table S4 of the Supporting Information 1.

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[1] The chemical compound of this additive is pentaerythritol tetrakis (3-(3,5-di-tert-butyl-4-hydroxyphenyl)propionate).

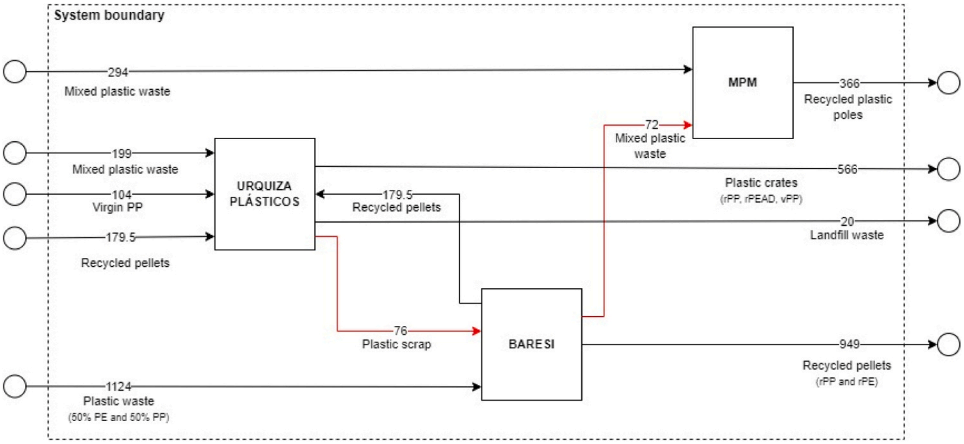

Fig. 2. Description of the IS case study in Mendoza (Argentina). All quantities are displayed in tonnes.

Table 2
Reference flows of entities in the industrial symbiosis network.

Entity	Flow	Annual production	Unit
BARESI	Plastic pellets	1128	Tonnes
MPM	Plastic posts	366	Tonnes
UP	Plastic crates	566	Tonnes

Two impact assessment methods were chosen to account for resource use and GHG emissions. Resource use was calculated using the Cumulative Exergy Extraction from the Natural Environment (CEENE) v. 2013 [21,22]. Although there is currently no consensus on assessing the impacts of resource use in LCA, Gonzalez Hernandez & Cullen [54] highlighted the main benefits of using exergy for resource accounting: exergy integrates material and energy into a single metric and evaluates the quality of resources. Therefore, the CEENE method was applied since it uses exergy to quantify all resources extracted from the natural environment over the life cycle of a product, and it is expressed in gigajoules of exergy (GJex). By definition, exergy is the maximum useful work that can theoretically be retrieved from a system or resource when it is brought into thermodynamic equilibrium with its surroundings through a reversible process [55]. The CEENE method covers the following categories: fossil energy, nuclear energy, metal ores, minerals, water resources, land use, abiotic renewable resources (including wind power, geothermal energy and hydropower) and atmospheric resources. More detailed information on the CEENE method can be found in Supporting Information 1.

The GHG emissions were estimated using the IPCC 2013 GWP 100a method, expressed in tonnes of CO_2 equivalents (tCO_2-eq). This was done for two main reasons. First, a reduction of GHG emissions may imply an increase in the use of resources. Therefore, it is relevant to develop a discussion around these statements. The second reason is that the accounting method proposed by IPCC is well consolidated and agreed upon among a diverse range of stakeholders, including policymakers, LCA practitioners and industry.

4. Results

In this work, the potential environmental impacts and savings of an IS network are expressed in terms of resource use and GHG emissions –calculated through LCA– by comparing a reference scenario with a symbiotic scenario. In the reference scenario, plastic waste streams are disposed of in a landfill, and companies consume virgin PP to meet their annual production demand. In the symbiotic scenario, virgin plastics are replaced by plastic by-products generated by two local entities. The results of the overall environmental impacts at the network level are presented in Section 4.1, while the results at the entity level are given in Section 4.2. The complete results of the calculations can be found in Supporting Information 2.

4.1. Environmental assessment of the IS network

The resource use and the GHG emissions of the reference and the symbiotic scenarios are presented in Table 3. The implementation of exchanges between the industries generates significant benefits in the IS network. The production of virgin PP and electricity are the most influential processes on the environmental burdens of both scenarios.

The IS network can lead to an annual reduction in resource use of nearly 19%. This reduction is primarily attributed to replacing almost 60% of virgin plastics with recycled plastics. Electricity consumption and transportation increase by 3% and 4%, respectively. However, their related impacts are offset by the substitution of virgin plastics. In the reference scenario, approximately 52% of the overall impacts of the system stem from electricity use, followed by the production of virgin PP with a contribution of 36%. In the symbiotic scenario, the electricity and the production of virgin PP are responsible for about 66% and 18% of the resource use, respectively. In both scenarios, the significant contribution of CEENE Fossil to CEENE Total results from the electricity mix, with fossil sources contributing 73% [56].

Regarding GHG emissions, the IS network illustrates environmental impact reductions of roughly 15%; once again, the largest impact reductions stem from the decrease in the amount of virgin PP. For the reference scenario, the most significant GHG emissions derive from the direct electricity consumed, with a share of 52%. The second most significant GHG emissions are from the production of virgin PP, with a contribution of 27%. For the symbiotic scenario, the primary cause of this environmental impact is electricity consumption, with a contribution of 64%, followed by transport of raw materials, products and waste materials, with a contribution of 18%.

4.2. SPI results for the by-product exchange between BARESI and MPM

In this by-product exchange, BARESI is considered the “source” and MPM defined as the “sink”. The SPI results in positive values for both entities with all three allocation methods. This suggests that both entities benefit from the exchange regarding the two impact categories assessed, as seen in Table 4. In the IS network, this synergy involves the exchange of 72 tonnes of mixed plastic waste, whereas in the reference scenario, MPM consumes 72 tonnes of virgin PP, and the mixed plastic waste is landfilled.

In the case of the 0:100 allocation method ($\lambda = 0$), the SPI has its lowest values for BARESI and the highest for MPM when assessing resources and GHG emissions. The source results are because the numerator only considers the landfilling process. The credits and the

Table 3
Results of the resource use (in Gigajoule of exergy) and the GHG emissions (in tonnes of CO_2-eq) of the Reference and the Symbiotic scenarios.

Scenario	CEENE																GHG emissions
	Metals		Minerals		Nuclear		Land		Renewables		Water		Fossil		Total		
	GJex	%	GJex	%	GJex	%	GJex	%	GJex	%	GJex	%	GJex	%	GJex	%	tonnes of CO_2-eq
Reference	0.25	0.0	22.5	0.0	2740	4.6	2690	4.5	5260	8.8	6530	11.0	42,400	71.1	59,600	100.0	2070
Symbiotic	0.15	0.0	11.5	0.0	2540	5.2	2720	5.6	5320	11.0	6170	12.8	31,700	65.4	48,500	100.0	1770

Table 4
Results of the SPI for the entities in the IS network using three different allocation methods, in terms of resource use (CEENE Total) and GHG emissions.

Allocation method	Entity	CEENE Total		GHG emissions	
		BARESI → MPM[a]	UP → BARESI[b]	BARESI → MPM[a]	UP → BARESI[b]
λ = 0 (0:100)	BARESI	0.07%	20.11%	1.17%	13.30%
	MPM	72.77%	-	65.32%	-
	UP	-	0.10%	-	1.54%
λ = 0.5 (50:50)	BARESI	11.25%	8.10%	8.88%	4.77%
	MPM	37.46%	-	34.13%	-
	UP	-	12.91%	-	11.56%
λ = 1 (100:0)	BARESI	22.43%	− 3.91%	16.58%	− 3.58%
	MPM	2.15%	-	2.94%	-
	UP	-	25.71%	-	21.59%

[a] BARESI → MPM represents the exchange between BARESI (source) and MPM (sink)
[b] UP → BAR represents the exchange between UP (source) and BARESI (sink)

environmental impacts of intermediate processing are not considered for BARESI who acts as a source entity in the 0:100 allocation method. Another explanation for these results is that the denominator of the source has a significant value because it is highly influenced by the electricity consumption of the company in the reference scenario. In the SPI of the MPM who acts as a sink entity, the numerator accounts for the difference between the recycling process of 72 tonnes of mixed plastic waste and the production of the same amount of virgin material. The numerator results in a positive value (160.7 tCO_2-eq and 6090.3 GJex), which indicates that the by-product exchange is environmentally feasible.

In the case of the 50:50 allocation method (λ = 0.5), the credits for avoiding virgin PP production are distributed equally between the source and the sink. The numerator of the source accounts for 50% of the credits and 50% of the environmental impacts of the intermediate processing; therefore, the results are 88.4 tCO_2-eq and 2972.7 GJex. The numerator of the sink accounts for nearly the same values as the source (83.9 tCO_2-eq and 3135.2 GJex). Although the numerators are virtually identical, the SPI results differ significantly; the difference in their denominators explains these results. The denominator of MPM is lower because, in contrast to BARESI, MPM accounts for 87% less electricity consumption.

Finally, using the 100:0 (λ = 1) allocation method, the SPI results of BARESI are higher than the SPI of MPM. The numerator of the source results in 165.2 tCO_2-eq and 5927.9 GJex, whereas for the sink, the results are 7.2 tCO_2-eq and 180.1 GJex. Although the sink does not account for the environmental impacts of the intermediate processing in the numerator, the lower results in its SPI are mainly because the source receives the total credits for avoiding raw material production.

4.3. SPI results for the by-product exchange between UP and BARESI

In this by-product exchange, UP is considered the “source” and BARESI defined as the “sink”. This by-product exchange benefits both companies when applying the 0:100 and 50:50 allocation methods. Nevertheless, the results for BARESI show that the SPI is negative for the two impact categories with the 100:0 allocation method, as shown in Table 4. The synergy implies the exchange of 76 tonnes of plastic scrap.

In the case of the 0:100 allocation method (λ = 0), the highest value in the numerator of BARESI is achieved. The results are 130.7 tCO_2-eq and 5316.1 GJex, whereas the numerator of UP has its lowest values (12.8 tCO_2-eq and 25.9 GJex). Clearly, BARESI has the most considerable reductions in environmental impacts stemming from reducing the production of 76 tonnes of virgin PP.

In the case of the 50:50 allocation method, credits are equally distributed between BARESI and UP, resulting in both companies achieving benefits from the exchange. The numerator of the sink reaches 47.5 tCO_2-eq and 2141.1 GJex. UP attains greater benefits from the exchange because the numerator results in 96.0 tCO_2-eq and 3200.9 GJex.

In the case of the 100:0 allocation method, the numerator of the sink results in negative values (−35.6 tCO_2-eq and −1033.8 GJex), and then it suggests that the entity does not achieve a reduction in GHG emissions and resource use. The negative value is mainly influenced by the net impact of the recycling process of the waste stream. Nevertheless, the source illustrates the largest impact reductions since the numerator results in positive values (179.2 tCO_2-eq and 6375.9 GJex).

5. Discussion

5.1. Benefits and limitations of using the Symbiotic Performance Indicator

In this paper, the environmental performance of the IS network is assessed through LCA by comparing a symbiotic scenario with a reference scenario. Results were calculated at both network and entity levels, which are crucial for assessing IS network performance. Policymakers would be interested in conventional network-level results when assessing the potential for environmental improvement in conventional industrial parks, municipalities, or regional areas where industrial activity concentrates. Conversely, the SPI indicator could be used for several ends by individual entities or companies operating in the IS network. They would be interested in accounting for their own environmental benefits, as this would help them decide to set and further promote the by-products exchanges. Indeed, this has been previously discussed by Fraccascia and Giannoccaro [20]. The SPI can help assess the environmental benefits attained by an entity according to its role (source or sink) in the exchange. For instance, BARESI’s assessment results in two SPI values as this entity is involved in two by-product exchanges. Since one exchange is independent of the other, both results should be separately evaluated. Therefore, the SPI helps to decide whether to participate in a specific exchange or not. Additionally, this indicator could attract LCA practitioners aiming to assess the potential environmental impact of IS networks, as the SPI is fully aligned with LCA framework and can be easily derived from conventional LCA results. From a methodological perspective, these findings are consistent with the multi-level approach developed by Kerdlap et al. [33].

The SPI is a scientifically sound indicator that is useful for guiding companies towards reducing their overall carbon footprint by establishing agreements for the material exchange at the local or regional level. As illustrated in the paper, this indicator has proven to be useful in measuring potential reductions at the entity level. These results help emphasize the role that material reuse can play in enhancing resource use and reducing GHG emissions at a broader geographical scale, particularly in the context of conventional industrial parks. One of the benefits of using the SPI compared to other indicators is that it quantifies the potential for environmental impact reduction feasible to be implemented locally and considering the use of resource and the generation of emissions from a life cycle perspective.

Despite its importance and potential usefulness, the SPI has some limitations. Further studies should be conducted to generalize the indicator's usefulness. Aspects that could be explored further include other processes, IS networks, typologies of industries and geographical locations. Case studies involving energy and/or water exchanges should be conducted to demonstrate the applicability of the indicator and the type of information managers can collect to support their decision-making. This will also provide a deeper understanding of the SPI and how it can be applied to other types of exchanges. Therefore, it would be beneficial to validate the indicator across other IS networks.

5.2. Implications on entities engaged in an IS network

The environmental performance assessment of IS networks has implications beyond quantifying overall impacts and benefits. A focus on the entities of the symbiosis could help identify those who gain from it or are mostly affected by the symbiotic activity [46]. Companies operating in the IS network could use the SPI to identify if the by-product exchanges provide benefits. Such information could offer data that motivates the initiation of new exchanges, especially when considering factors beyond just economic benefits. Additionally, the indicator can aid in promoting industrial symbiosis for business connections, process improvement and environmental performance communication [46]. Conversely, the SPI could identify if the by-product exchange is inconvenient for the entity from an environmental perspective. If benefits are not attained, the use of conventional raw materials would be the preferred option over exchanging materials and/or energy. This has been observed in the exchange where UP acts as a source and provides plastic waste to BARESI, and the allocation method only benefits the sourcing company (UP). In such cases, the results of the SPI were about –4%. Since BARESI did not attain a reduction in environmental impacts, they could be discouraged from participating in the by-product exchange. Alternatively, BARESI could potentially start a discussion regarding the pricing of the by-products or perform a more detailed assessment of the potential reuse of other materials to compensate for their environmental impact.

5.3. Allocation methods in SPI

As Kerdlap et al. [33] state, the LCA of IS networks should be flexible in selecting different allocation methods according to the context. Indeed, the allocation method chosen plays a significant role in the results of the SPI. In the 0:100 allocation method, each entity is assigned the environmental burdens of the processes in its life cycle, which assigns credits to the sink. When defining the boundary between the life cycle of the entities involved in the exchange, the boundary is set before the waste material is collected for the exchange. This approach benefits the entity using recycled material (sink) as long as the product made from virgin material has higher environmental burdens than those made from recycled material. When this allocation method is applied to the SPI of the source, the entity only benefits from the exchange if final disposal has a negative net impact on the environment ($r \bullet D_{\alpha_0} > 0$). However, the entity cannot have an incentive to participate in the exchange when waste disposal has a positive net impact on the environment ($r \bullet D_{\alpha_0} < 0$). For example, if final disposal is incineration with energy recovery, avoided burdens may be larger than the induced burdens. If this net impact results in a negative value, the SPI also results in a negative value, and then the exchange is not convenient for the source. This approach discourages waste suppliers from participating in by-product exchanges even when recycling has lower environmental burdens.

In the 100:0 allocation method, the SPI of the source accounts for the virgin material avoided through the by-product exchange. The greater the environmental burdens of virgin material production (V_{α_1}), the larger the benefits attained. Therefore, this method incentivizes the source to participate in the IS network even when waste disposal has lower environmental impacts than intermediate processing ($D_{\alpha_0} < I_{\alpha_0}$). The sink only benefits from the exchange when the product made from virgin material has higher environmental burdens than the one made from recycled material ($m \bullet M_\alpha > R_{\alpha_0} + M_\alpha$).

Regarding the 50:50 method, the source and the sink receive credits for the by-product exchange; however, this method could be questioned. Kim et al. [47] concluded that the allocation method should be chosen to distribute credits achieved by IS exchanges according to their contribution to exchange development and maintenance. Therefore, the 50:50 allocation method is recommended from the perspective of equivalent responsibility and benefit-sharing. Different allocation factors, such as 0.25 or 0.33, might be appropriate to reflect the different levels of commitment of the relevant entities. However, there is a need to set rules to assign value to the allocation factor for each analysis, as discussed by Viganò et al. [57]. They point out that this decision will fundamentally depend on the industries involved and the practitioner's experience.

6. Conclusions

A review of previous studies concluded that there is a lack of indicators for quantifying the benefits of IS at the entity level using a holistic approach. This paper provides an LCA-based indicator, defined as the environmental benefits that each entity ("source" and "sink") obtains from a by-product exchange, compared to a non-symbiotic reference scenario. The allocation of impacts and benefits was identified as an important methodological aspect. Thus, an allocation factor was introduced in the formulation to include the distribution of credits and impacts. To evaluate the influence of the allocation factor, three allocation methods were considered in this study: full allocation (100:0 and 0:100) and partial allocation (50:50).

The SPI was used in an IS case study about plastic waste treatment to illustrate its applicability. The IS network involves two exchanges of post-industrial plastic waste between three companies. At the network level, the results showed annual reductions in resource use and GHG emissions of 19% and 15%, respectively. These impacts were reduced due to a decrease in virgin plastic inputs, and also the related consumption of materials and energy from cradle to gate. At the entity level, each entity was assessed using the proposed indicator. The SPI for the three entities resulted in a positive value except for BARESI, when considering them as sink of the exchange and assigning the full environmental benefits to UP who acts as the source entity (100:0 allocation method). The SPI results indicated that the allocation factor significantly influences the individual environmental benefits.

Industry practitioners seeking to promote IS will find the practical implications of the SPI significant. The SPI can be used to make informed decisions about which synergies to implement. The indicator can also help companies identify areas where they need to improve their business model and quantify potential environmental savings. For example, by identifying potential improvements in production processes, intermediate processing, or waste management practices. Finally, the results of the SPI can serve as a way for companies to demonstrate and communicate their commitment to sustainability to consumers and other stakeholders, potentially gaining a competitive advantage in the market. The SPI supports the environmental management system already implemented by companies, by providing a more realistic measure of the benefits achieved. However, the challenge for future research will be to include an economic and social analysis to complement the environmental analysis of this study.

Funding

This research was funded by Consejo Nacional de Investigaciones Científicas y Técnicas-CONICET, Argentina.

CRediT authorship contribution statement

Fernando Arce Bastias: Conceptualization, Data curation, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Paula Daniela Rodríguez:** Methodology, Investigation, Validation, Writing – review & editing. **Alejandro Pablo Arena**: Investigation, Resources, Methodology, Validation, Writing – review & editing, Funding acquisition. **Laura Talens Peiró:** Investigation, Methodology, Validation, Writing – review & editing, Supervision, Funding acquisition.

Declaration of Competing Interest

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

Data Availability

Data can be found in the supporting materials.

Acknowledgements

The authors wish to thank Carlos Arce, Leonardo Cano y Pio De Amoriza from Madera Plástica Mendoza, Carlos Lara from BARESI, and Javier Chiappa from Urquiza Plástico for their support and the provided data. This article contributes to ICTA-UAB 'María de Maeztu Unit of Excellence' (MDM-2015–0552; MDM-2019–0940). and to the research group Sostenipra 2021SGR00734.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jece.2023.111023.

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