H2020 MSCA-ITN-2018

ReTraCE Project

Realising the **Tra**nsition towards the **C**ircular **E**conomy

D2.2

Environmental implications of Circular Economy implementation

A selection of micro level case studies

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie Innovative Training Network (H2020-MSCA-ITN-2018) scheme, grant agreement number 814247 (ReTraCE).

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List of acronyms

AD – Anaerobic Digestion

CBE – Circular Bioeconomy

CE – Circular Economy

CHP – Cogeneration of Heat and Power

EMA – EMergy Accounting

LCA – Life Cycle Assessment

LEAF – LCA and EMA Applied Framework

RNG – Renewable Natural Gas

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Executive summary

- This report provides an overview of several case studies in which circular economy pathways have been implemented at the micro level. Micro levels are to be considered the starting point to make CE closer to stakeholders' understanding, in so contributing to larger scale policy–making, based on deeper knowledge of benefits achievable and challenges to be faced.
- Investigated case studies provide a pragmatic environmental perspective of CE implementation pathways, also developing deeper understanding of positive and negative consequences.
- The application of different sustainability evaluation methods, including Life Cycle Assessment (LCA) and EMergy Accounting (EMA), emphasizes the need for methodological integration to capture different dimensions (see the methodological discussion paper by Oliveira et al., 2021a and ReTraCE Deliverable 2.1).
- The environmental benefits highlighted by the case studies showcase the need for supporting policies capable to promote a shift towards circular economy strategies as opposed to business as usual (linear model).
- Further studies looking at the impacts of circular strategies using non-reductionist approaches, as exemplified in this report, are needed to further develop knowledge around the transition towards a Circular Economy, to confirm claims for environmental benefit and sustainability (affected by markets and society) and finally to design win–win solutions in order to maximise net overall benefits.

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1 Introduction

The linear economic paradigm, heavily dominated by non-regenerative practices is not capable of maintaining the planetary system's capacity to support current human activities as well as future generations. The emerging Circular Economy (CE) paradigm is expected to provide a solution by increasing product and resource lifespan. The European Union is committed to making CE the main pillar of the EU Industrial Strategy, thus enabling circularity in new areas and sectors (European Commission, 2019). A CE can only be achieved through consistent (environmental, economic and social) science-based approaches, a much needed prerequisite to CE policy-making at all levels and promotion of viable technological solutions. Within this context, the ReTraCE project aims to further understanding about how the transition towards a CE can be successfully realised in the European context.

Although CE implementation is still in its infancy, its potential in reshaping production and consumption systems needs to be fully understood at different scales (i.e., micro, meso and macro) to assist in critical decision-making. According to several authors (Ferrara and De Feo, 2018; Linder et al., 2017; Ripa et al., 2017), most of the available indicators for measuring CE strategies refer either to macro (e.g. nation) or meso (e.g. supply chain) levels, ignoring site-specific micro level case studies. As highlighted by Oliveira et al. (2021a), multi-stakeholder, multi-dimensional and multi-criteria approaches to evaluate the transition towards a CE are needed, in order to evaluate performance across time, spatial scales, as well as multiple sustainability dimensions. Within this context and based on the previous deliverable (D2.1), this work showcases how the chosen methods (mainly Life Cycle Assessment and EMergy Accounting, with others to be integrated in future cases) are applied to evaluate the environmental consequences of CE implementation. While the importance of each method is acknowledged, we further contend that each method may not solve all problems and provide answers to all questions. As such, the synergistic application and integration of different methods is considered crucial in embracing and capturing social, environmental, and economic dimensions.

This report will focus on highlighting the environmental performance of several micro-level case studies[1] compiled within the ReTraCE project. In these case studies, non-reductionist approaches were utilised – such as Life Cycle Assessment (LCA) and EMergy Accounting (EMA) – to assess the performance of specific products and processes.

In addition to the identification of promising CE strategies, the report also provides scientific evidence on the environmental performance of circular vs linear strategies in multiple sectors. These sectors include, construction, agri-food, energy, and packaging, all in different geographical contexts. The report proceeds as follows: Chapter 2 provides an overview of the case studies, together with the results that were obtained and

[1] Case studies focusing on the meso and macro level are presented in deliverable 2.3.

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the implications of these results. Chapter 3 focuses on drawing together and summarising the implications from each case study, and how these implications can inform future perspectives as well as opportunities for further research.

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2 Circular Economy case studies at micro level

This chapter gives an overview of CE case studies developed within the ReTraCE project, which focused on assessing the environmental performance of linear and circular production systems. These micro level studies were primarily selected based on the relevance of the industrial sector under investigation for CE policy. According to the New CE Strategy (European Commission, 2020), construction and building, food, packaging and water are key sectors to achieve circularity. Furthermore, this report also highlights case studies conducted in non-EU locations (e.g., Zimbabwe and Canada) to expand the focus of CE research and to demonstrate the potential of CE in different geographical contexts. Therefore, each section of this chapter will focus on one case study, as detailed below:

- **Section 2.1:** Ncube et al. (2021a) (Moving towards resource efficiency and circular economy in the brick manufacturing sector in Zimbabwe), which was published in the *Journal of Cleaner Production*. The full paper is available at https://doi.org/10.1016/j.jclepro.2020.125238;
- **Section 2.2:** Ncube et al. (2021b) (Upgrading wineries to biorefineries within a Circular Economy perspective: An Italian case study), which was published in the journal *Science of the Total Environment*. The full text is available at https://doi.org/10.1016/j.scitotenv.2021.145809;
- **Section 2.3:** Ncube et al. (2021c) (Circular economy paths in the olive oil industry: A Life Cycle Assessment look into environmental performance and benefits), which was submitted to The International Journal of Life Cycle Assessment (Call for papers);
- **Section 2.4:** Oliveira et al. (2021b) (Circular Economy in the agro-industry: integrated environment assessment of dairy products), which was submitted to Renewable and Sustainable Energy Reviews (Call for papers);
- **Section 2.5:** Ncube et al. (2021d) (A circular and policy perspective on upgrading biogas. A case study in Ontario, Canada), which was submitted to the journal *Environmental and Sustainability Indicators* (Call for papers);
- **Section 2.6:** Catone et al. (2021) (Bio-products from algae-based biorefinery on wastewater. A review), which was submitted to the *Journal of Environmental Management*;
- **Section 2.7:** Miguel and Coleman (2021) (Accounting reuse from a life cycle perspective: A steel drum case study), *TATA Steel internal technical report*.

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2.1 Construction processes: brick manufacturing in Zimbabwe

2.1.1 Context and objectives

The exponential growth of Zimbabwe's urban population and increase in the demand for housing (ZIMSTAT, 2017) has led to a rise in the production of construction materials, such as bricks (Das, 2015). Clay is one of the main raw materials for brick production, and its unlimited and unregulated use has led to the removal of good quality clay from agricultural fields (Sahu and Kapre, 2017).

Environmental concerns over brick manufacturing have become more prevalent worldwide and triggered demands for coordinated and urgent action (Duce and Vosloo, 2017). China, the world's biggest manufacture of bricks, has limited the use of clay in brick production (Chen et al., 2011). Instead, various authors have recommended the use of by-products from other industries, in particular fly ash (Huarachi et al., 2020). Fly ash is a waste material produced from coal combustion in power generation plants, which can improve brick strength, substitute for clay and thus save valuable agricultural top soil (Yao et al., 2015; Moyo et al., 2019).

The environmental burdens arising from the operation of the clay brick industry are mainly related to air emissions (i.e., CO_2, CO, So_x) caused by the burning of fossil fuels for energy (Kumbhar et al., 2014; Nyambo, 2014). Therefore, a key measure for reducing environmental impacts associated with clay brick production is to decrease, as much as possible, the amount of coal and other fossil fuels used during the clay preparation and firing steps (Vosloo et al., 2016). Furthermore, the substitution of coal by means of alternative energy sources (e.g. biogas) can reduce process-related emissions and lower overall heat requirements by 30% (Moedinger, 2005).

Most of the Zimbabwean brick making facilities use a Hoffman kiln, the worst performing batch process kiln, due to the high amount of coal needed during the firing step (Rajarathnam et al., 2014). Thus, the brick manufacturing sector in Zimbabwe has contributed to the increased levels pollution in the country. To identify potential hotspots and pathways for improvement within the production of bricks, this study applies a Life Cycle Assessment (LCA) approach. In addition, the study contributes to raising environmental awareness within the brick manufacturing sector by using a case study in an African context.

2.1.2 Research methods

The study focused on ABC (Pvt) Ltd, one of the biggest brick manufacturing companies in Zimbabwe. The brick manufacturing process involves clay mining, brick moulding and drying of wet bricks in Hoffman kilns. The final products are common, paving and façade bricks. The company obtains clay and water on site, whereas coal is the main source of energy and is procured from Hwange and Chiredzi (Zimbabwe). This study assessed the potential for resource efficiency and cleaner production, focusing on clay use efficiency and air quality, and performed a LCA of the brick manufacturing process.

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2.1.2.1 Resource efficiency: Clay use assessment

To calculate the clay use efficiency in the production process, clay was quantified for each batch of bricks produced each month during a three-month period. For this purpose, the conveyor belt was stopped at each stage of production and the clay was weighed. The clay loss in production was accounted for by comparing the output (i.e., amount of clay at the final stage of production) and the input clay. In addition, the extraction of clay that occurs on site was evaluated by using images of ABC Pvt Ltd in 2008 and 2018, where the perimeter and area of the clay extraction pits were measured using ArcGIS software.

2.1.2.2 Air quality

Stack emissions were analysed by using a calibrated Testo 340 gas analyser to measure SO_2, CO, NO_x gas concentrations during a four-month period in 2018. Particulate matter was measured using a Casella micro pro dust analyser. The Air Quality Index (AQI) (2) converts air quality data of various pollutants into an index number; it is calculated based on the mean concentration of pollutants compared to the legal reference standard value of that pollutant, such as PM10, PM2.5, NO_2 and SO_2. The AQI Index is compared to a rating scale and the pollutant with the highest AQI score becomes the responsible pollutant.

2.1.2.3 Life cycle assessment

An LCA was performed to assess the environmental impacts of brick manufacturing (i.e. cradle to gate), assuming a functional unit of 1 kg of produced brick. The environmental impacts of the production system were modelled using SimaPro v9.0.0. Quantitative data was collected through personal interviews in 2018 and additional information was obtained through literature analysis and using SimaPro EcoInvent v3.5 databases.

As shown in Figure 2.1, the system boundaries include clay mining, brick moulding and roasting at the production site. We assumed that companies in proximity of ABC provided the fly ash, therefore, we considered that the environmental impacts arising from fly ash collection and transport were negligible. We also assumed that fly ash will replace the same amount of mined clay in different weight ratios, however, the brick manufacturing does not suffer any alterations. Finally, use and end-of-life phases were considered to be beyond the scope of this study and were therefore excluded.

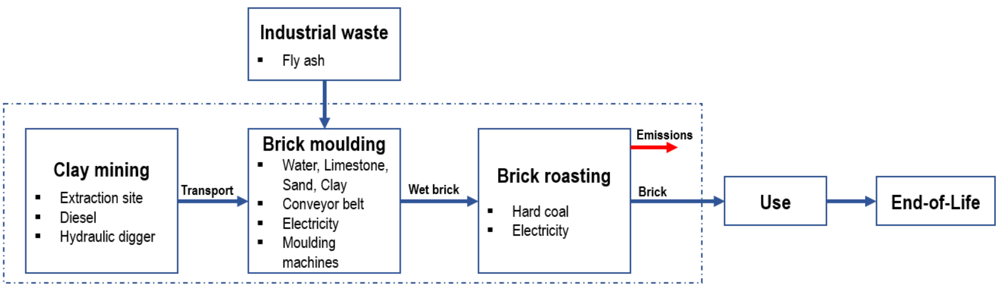

Figure 2.1 – System boundaries (adapted from Ncube et al., 2021a).

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2.1.3 Results and discussion

The field assessment demonstrated that the area around the clay pits is under threat, as current operations at ABC do not quantify the amount of clay mined, resulting in land loss due to pit expansion. High losses of clay were recorded between the extrusion and clamp stages during the brick moulding production phase. This continued loss has had a direct effect on pit expansion – in 10 years, the size of Pit 1 and Pit 2 increased 250% and 612%, respectively – based on the continuous production logic required to meet a standard number of bricks per amount of clay.

Regarding air quality, the use of low-quality coal has resulted in high emissions of SO_2, CO, NO_x and PM, normally above legal limits, as illustrated in Table 2.1. During the sampling period, CO had the highest concentrations levels, which can be attributed to incomplete combustion of bituminous coal (up to 85% more carbon content) used by ABC. In general, the Air Quality Index fell under the category "Severely polluted air quality", which has detrimental effects on human health and particularly that of the workers.

Table 2.1- Stacked emissions of SO_2, CO, NO_x and PM measured between August and November 2018 (adapted from Ncube et al., 2021).

		Months			
Pollutant	**Legal limit (mg/m³)**	**August (mg/m³)**	**September (mg/m³)**	**October (mg/m³)**	**November (mg/m³)**
SO_2	45	46.5	50.5	51	53.5
CO	80	481.5	481.5	476	492.5
NO_x	130	327.5	327.5	327.5	332.5
PM	100	33.3	39	30.2	60.6

The results from the preliminary LCA showed that clay mining is responsible for most of the environmental impacts (65.8%), followed by brick moulding (24.8%) and brick roasting (9.4%). When analysing the impact categories, it becomes evident that land use is the most affected category due to clay mining (responsible for 99.2% of the impacts), followed by fossil resource scarcity and global warming. The fossil resource scarcity category is mainly influenced by the transport of clay to the brick production plant (58%) and the global warming category is influenced by the emissions from the use of hydraulic diggers (40%) and the use of hauler trucks for clay transport (60%).

Four scenarios were developed to compare the use of clay and its replacement with fly ash: (1) 100% clay brick; (2) clay substitution and replacement with a 10% aggregate weight ratio of fly ash; (3) clay substitution and replacement with 25% aggregate weight ratio of fly ash; and (4) with 100% fly ash. Figure 2.2 shows the environmental benefits of replacing clay with fly ash for each scenario, considering global warming, land use, fossil resource scarcity, fine particulate matter formation and water consumption impact categories. Overall,

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substituting clay with fly ash in scenarios 2 and 3 lead to a slight decrease in environmental load, ranging between 31% and 27% respectively. Substituting 100% of clay with fly ash resulted in significant environmental load decrease (10%).

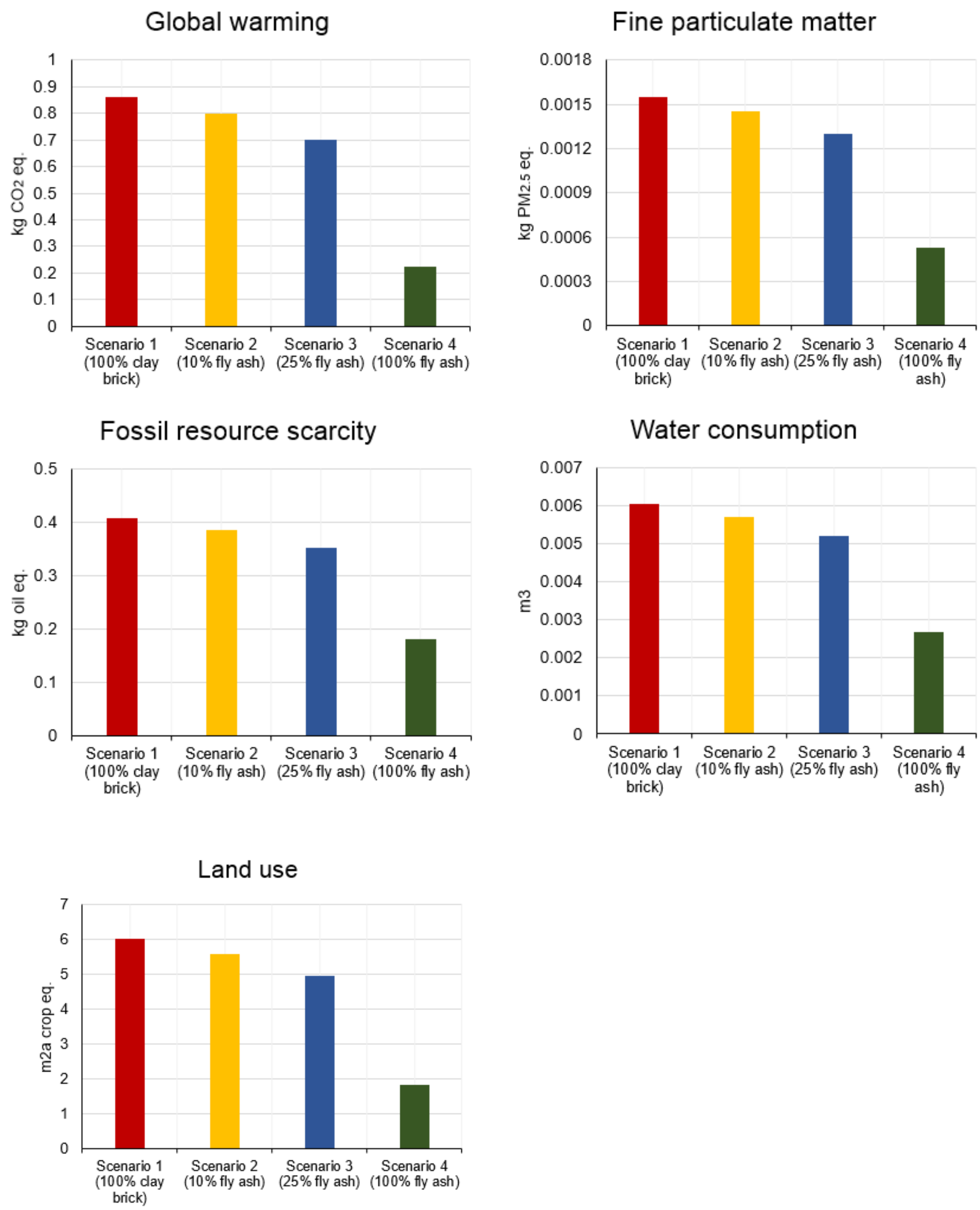

Figure 2.2 – ReciPe Midpoint characterised impacts calculated for the brick production scenarios with fly ash, considering a functional unit of 1kg of manufactured brick (adapted from Ncube et al., 2021a).

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Based on these results, the case study suggests that ABC Pvt should consider replacing clay with fly ash in order to improve the environmental performance of their activities. In addition, Table 2.2 presents additional cleaner production and circular strategies that can be implemented to address identified environmental issues and reduce pollution. Further evaluations on the environmental benefits provided by these measures are needed to fully understand their potential.

Table 2.2 – Environmental issues, cleaner production, and circular economy strategies to be implemented at ABC Pvt to reduce pollution.

Environmental issues	**Cleaner production and circular economy strategies**	
ABC currently uses Hoffman kiln technology to produce bricks, which is one of the worst environmental performing brick manufacturing technologies.	**New technology**	Replacing Hoffman kiln with more resource efficient kiln technologies.
There are high losses of brick during the firing process.	**Firing process changes**	Changing firing process from clamp kiln to fixed kilns will result in a reduction of brick loss.
ABC has air emissions higher than the legal limits.	**Investing in emission control devices**	Investment in emission control devices, such as fabric filters, bag house, electrostatic precipitators, and wet scrubbers. These devices could help lowering the PM, SO_2 and NO_x emissions.
Currently, ABC uses a vibrator to separate fine from lumpy clay. However, this leads to high losses of clay during the process.	**Investing in a clay grinding machine**	Investment in clay grinding machine to grind lumpy clay into fine clay, reducing the clay loss in the production process. This will also reduce the rate of clay extraction.
The brick wire cutter gets deformed due to lumpy clay, leading to the production of deformed and poor quality bricks	**Repair brick wire cutter at extrusion line**	Repair wire cutter deformed by lumpy clay, thus decreasing the number of bricks discarded due to deformations.
The use of coal as a source of energy has led to high air emissions.	**Renewable energy sources**	Replacement of fossil fuels by renewable alternatives (e.g. use of biomass to replace coal) to reduce GHG emissions.

2.1.4 Conclusions

The LCA demonstrated that clay mining and the use of coal as an energy source are the most significant contributors to the environmental impacts related to brick production. ABC Pvt Ltd has higher air emissions levels than those legally permitted for SO_2, CO, PM and NO_x, with CO being the most critical air pollutant. In addition, the resource efficiency assessment revealed that ABC faces significant clay wastage during the brick moulding phase and the rapid increase of the clay pit size has resulted in major land degradation. Hence, ABC could become more resource efficient if it applied circular economy principles, such as substituting clay with fly ash. Using fly ash in brick manufacturing would help solve its disposal issue, decrease brick manufacturing costs, increase brick quality, and reduce environmental impacts.

Nonetheless, additional studies focusing on human health, on the economic and social implications and the potential uses of agro-wastes are needed to improve the understanding of the brick making sector. At a policy level, the government of Zimbabwe could implement regulations on the use of fly ash for brick manufacturing.

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Resource efficiency and circular economy measures can lead to a cleaner environment and greener industry, increasing productivity whilst preventing agricultural land degradation. However, it should not be disregarded that the utilisation of fly ash may not stop the extraction of clay as production of and demand for bricks increases, thus leading to potential rebound effects (Zink and Geyer, 2017), which should be investigated in further research.

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2.2 Wine making: implementing a diffuse biorefinery in Italy

2.2.1 Context and objectives

Food waste is currently an important issue, both in developing and developed countries (FAO, 2018). It is estimated that about 1.2 billion tons of foods are lost or wasted globally, representing approximately one-third of the edible parts of food produced for human consumption (FAO, 2015).

According to the International Organization of Vine and Wine (OIV, 2019), Italy is the leading country in wine production. In addition to this, the Italian wine sector also deals with the enormous amount of by-products, which are challenging to manage, both from an economic and environmental perspective. The main challenge is transforming the waste into useful products that can be re-used in a circular perspective, also including the recovery of useful biobased products from agricultural and food waste which can be addressed by means of a sustainable and Circular Bioeconomy (CBE)(European Commission, 2018). Therefore, the Italian wine industry can represent a suitable example for the application of the bioeconomy principles, including the valorisation of agricultural and food waste.

There have been a substantial number of LCAs carried out in the agri-food sector, however, site-specific LCAs comparing linear and circular patterns within agri-systems are still scarce (Ferrara and De Feo, 2018). The present study addresses these concerns and deficiencies. In addition, the interrelationships between linear production systems and circular systems have not been extensively probed in literature, in particular, the evaluation of side processes for the recovery and valorisation of organic waste within agro-food production systems. Therefore, in this study, a site-specific LCA of traditional wine production and its alternative circular bioeconomy system (biorefinery) was performed. The biorefinery system was based on winery waste and aimed at recovering bio-based products, such as grapeseed oil and calcium tartrate.

2.2.2 Research methods

The company investigated represents a micro-level enterprise in the Campania Region, Italy. The data were collected from field visits and interviews with the involvement of company owners. Background and missing data were adopted (aligned to the functional unit) through scientific literature and specific databases such as EcoInvent version 3.5. For this case study, the functional unit was assumed to be one bottle of Asprinio wine and the main production processes were analysed (i.e., agricultural, vinification and bottling phases).

The specific goal of this study was to perform environmental evaluations on the winery case study from two perspectives (Figure 2.3): (i) an analysis of linear production leading to the production of the main product (blue flows) and by-products (residues that need further inputs to be upgraded and become usable, yellow flows) and (ii) the design and analysis of circular processes (green flows feeding back) based on the conversion of by-products into usable co–products, in so saving upstream resources and produce other value-added products.

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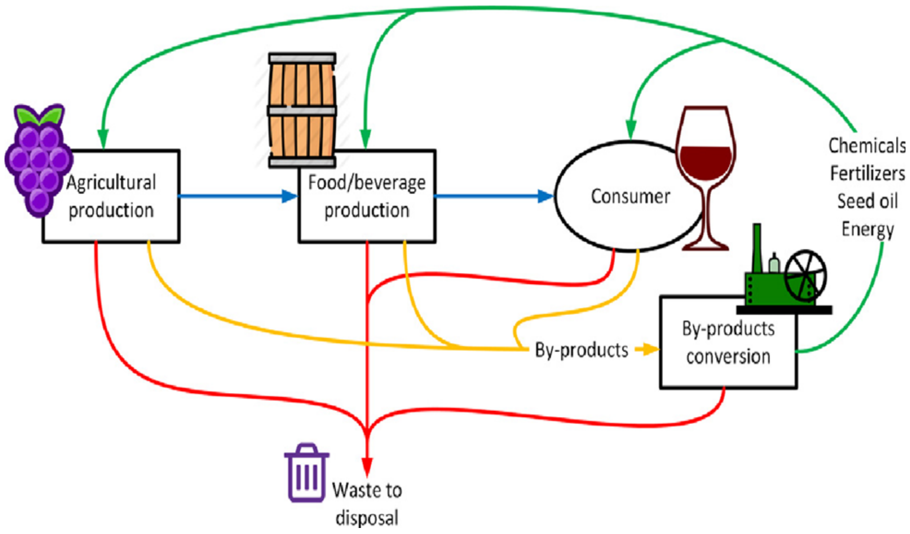

Figure 2.3 – Process flow chart and investigated system boundaries (adapted from Ncube et al., 2021b).

For the sake of clarity, products are the planned results of a process, usable without any other upgrade; co–products are additional unintended but still usable outputs that are not the main goal of the process (e.g. electricity and heat in a thermal power plant); by–products are unintended outputs that cannot be used as such, but require additional conversion to become usable secondary co–products (e.g. pomace to become chemicals, biogas, fertiliser); finally, wastes are unavoidable outputs and very difficult to be converted into usable secondary co–products (e.g. low temperature heat). In general, linear production only considers high economic value products and co–products, landfilling everything else; were as circular economy patterns plan the reduction or prevention of waste and low value by–products and converts by–products into usable co–products, to be fed back at different scales of the system.

In order to further decrease the unit costs and impacts of the by-products from the linear production, by-products were considered as feedstock to extract chemicals or produce secondary generation co-products as better detailed in Table 2.3.

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Table 2.3: A summary of the investigated subsystems, scenarios, and related activities (adopted from Ncube et al. 2021b)

Subsystem 1 (linear production chain) includes three production phases	
Production phase	**Activities**
Agricultural phase	• Removal of the new vine shoots from the previous harvest • Cultivation and vineyard treatment (fertiliser and chemical application) • Grape harvest
Wine production phase	• Crushing and destemming harvested grapes • Separation of the must from the pomace by pressing • Flotation, fermentation • Wine storage
Bottling phase	• Packaging of wine into glass bottles
Subsystem 2 (extended production biorefinery) includes two side production chains based on the utilization of the by-products from Subsystem 1	
Side Production chain	**Activities**
1 - Grape seed oil production (from grape pomace)	• Grape seed extraction and separation • Oil extraction (physical pressing) • Bottling
2 - Calcium tartrate production (from wine lees)	• Solid liquid separation • Acidification to remove the alcohol content from the wine lees • Precipitation and crystallization • Storage
Proposed circular winery scenarios for valuing winery waste	
Scenario 1 - Improved agricultural phase	• Substituting diesel used in the agricultural phase with a biofuel obtained by transesterification of grapeseed oil • 50% reduction of fertilisers
Scenario 2 - Improved vinification phase	• Replacing grid-electricity with steam obtained from prunings • Substituting protein feed, crude fodder yeast with yeast cells obtained from Subsystem 2
Scenario 3 - Improved calcium tartrate production	• Replacing industrial steam with bio-based steam recovered from stalks and prunings

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2.2.3 Results and discussion

Following the process flow structure, costs and impacts were allocated to the output flows of the linear production system. The linear and extended circular pathways were analysed separately to highlight the main hotspots calling for an improvement by closing the loop and ensuring sustainability of the system under study. The benefits of combining proposed scenarios with an enhanced degree of circularity were then expressed in the overall environmental load associated with the wine production processes. For example, when fossil-based inputs (diesel, electricity, steam, and chemicals) are replaced by bio-based resource flows recovered from by-products, the environmental burden of the production of wine sharply decreases. Figure 2.4 shows the environmental impact categories to produce 1 bottle of Asprinio wine, considering linear production with and without allocating costs among co–products and circular alternatives CP–A and CP–B. The alternative CP-A includes the combined environmental benefits and impacts deriving from the suggested improvement scenarios (Scenarios 1 to 3 in Table 2.3), allowing the replacement of fossil-based inputs with co-products recovered from the extended production system. CP–B is similar to CP-A in many aspects but differs in that grapeseed oil (Scenario 1) is sent to the market and considered for food purposes instead of fuel production.

The bottling phase, in particular, the production of packaging glass, is the process that contributes more to the generation of impacts in all categories (on average, 63%)) while the agricultural phase contributes around 14.3% and the vinification phase 22.7%. When results are normalised in order to allow comparison among impact categories, human carcinogenic toxicity, freshwater eutrophication, and fossil resource scarcity impact categories are the most affected ones.

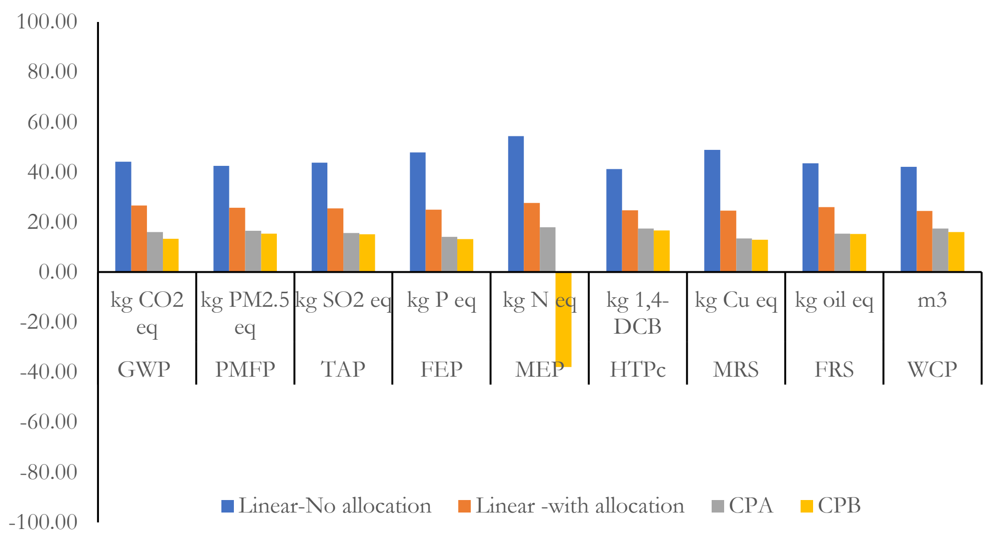

Figure 2.4 – Characterised impacts (%) of linear and circular production systems, referred to a functional unit of bottle of Asprinio wine.

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2.2.4 Conclusions

Environmental hotspots for the linear production system were identified and can be used as a starting point for future environmental improvement measures. By designing and implementing circular strategies in the traditional wine production system, calculated environmental impacts were on average three times lower for global warming, freshwater eutrophication, and mineral resource scarcity impact categories, when compared to the linear system.

The results achieved demonstrate the benefits of closing the loops in the wine industry. The reuse of bio-based residues as an alternative to fossil-based inputs and the integration of the traditional production system with new side production chains clearly led to more sustainable production patterns.

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2.3 Olive oil production: environmental performance of CE alternatives

2.3.1 Context and objectives

The European Union produces approximately 67% of the world's olive oil and the four major producing countries are Spain, Italy, Greece, and Portugal, (Eurostat, 2017). 80% of Italian olive production takes place in the southern zone and covers about 1 070 000 ha (International Olive Council, 2018). Despite this economic importance, olive production is still associated with several environmental impacts (Strano et al., 2014). The application of life cycle thinking perspectives and circular initiatives is expected to inform future sustainable behaviours and attitudes in the olive sector (Iofrida et al., 2018) According to Harris et al. (2021), there have not been enough attempts from researchers to evaluate the sustainability of circular processes compared to the linear paradigm. The recovery and transformation of the by-products can create a series of circular paths, in this way, obtaining new useful products and avoiding disposal impacts. Environmental impacts associated with the production of extra virgin olive oil could be decreased if by-products are converted into new feedstock material for other production processes (Guarino et al., 2019).

Therefore, in this study, the principles of circular economy are applied to the olive oil supply chain to improve the environmental sustainability of the sector. This work is based on an LCA study to compare and assess the environmental performance of two scenarios - Business-As-Usual (BAU) and circular (biorefinery) – to produce olive oil and other co–products as shown in Figure 2.5.

2.3.2 Research methods

The production chain of organically grown extra virgin olive oil, accompanied by by-products, such as pomace, seeds, and wastewater, was analysed using the Life Cycle Assessment method. To perform the analysis, primary data were collected from an oil farm and mill in the Campania region (Southern Italy). The type of analysis in this study is "gate to gate", since it only examined what was inside the "company gates". The evaluation of environmental impacts was made possible by using the SimaPro v9.0.0.0 LCA software tool and the ReCiPe 2016 Mid-point (H) Impact Assessment Method. The functional unit adopted is a 1-liter bottle (0.92 kg) of extra virgin olive oil. Figure 2.5 below shows the relevant system boundaries.

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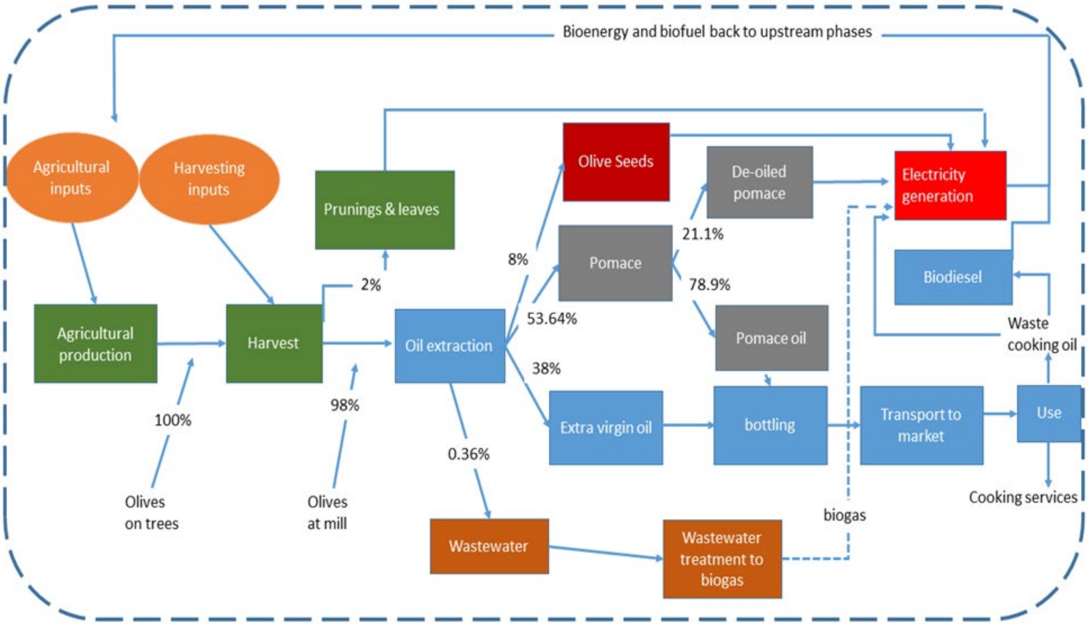

Figure 2.5 – Biorefinery process flow-chart to produce extra-virgin olive oil, with valorisation of co-products and feedback of some co-products to upstream phases (percentages refer to exergy allocation of co-products).

2.3.3 Results and discussion

The environmental impacts of the business-as-usual production pattern were identified and human carcinogenic toxicity, marine eco-toxicity, and terrestrial eco-toxicity were the most affected impact categories calling for further improvements along the production chain of organic extra virgin olive oil. As expected, the major contributions to almost all the analysed impact categories are determined by the agricultural phase (92.65%), followed by the bottling phase (7.13%) and, lastly, the oil extraction phase (0.22%).

The valorisation of co-products was considered by widening the system boundaries to ensure sustainability by developing circular patterns that feedback waste materials to upstream steps of the same process as shown in Figure 2.5 above. The environmental impacts were lower in almost all the impact categories, with benefits gained in the global warming and fossil depletion impact categories as shown in Figure 2.6. The linear system with a 100% allocation to the main product (scenario without valorisation of by products) has a much higher environmental load as compared to the Business as Usual (scenario with allocation of costs and impacts to all co-products) and other co-product reuse scenarios (Circular Scenario A-Only electricity reuse within the process and related avoided impacts; Circular Scenario B-with biofuel and electricity reuse within the process and related avoided impacts).

In almost all the considered impact categories of circular scenarios, the environmental load was about 2-3 times lower compared to the linear system with no allocation of co-products. The reuse of pomace, pruning and

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spent vegetable oil initially considered as waste resulted in some notable environmental benefits by replacing and substituting fossil based energy with bioenergy.

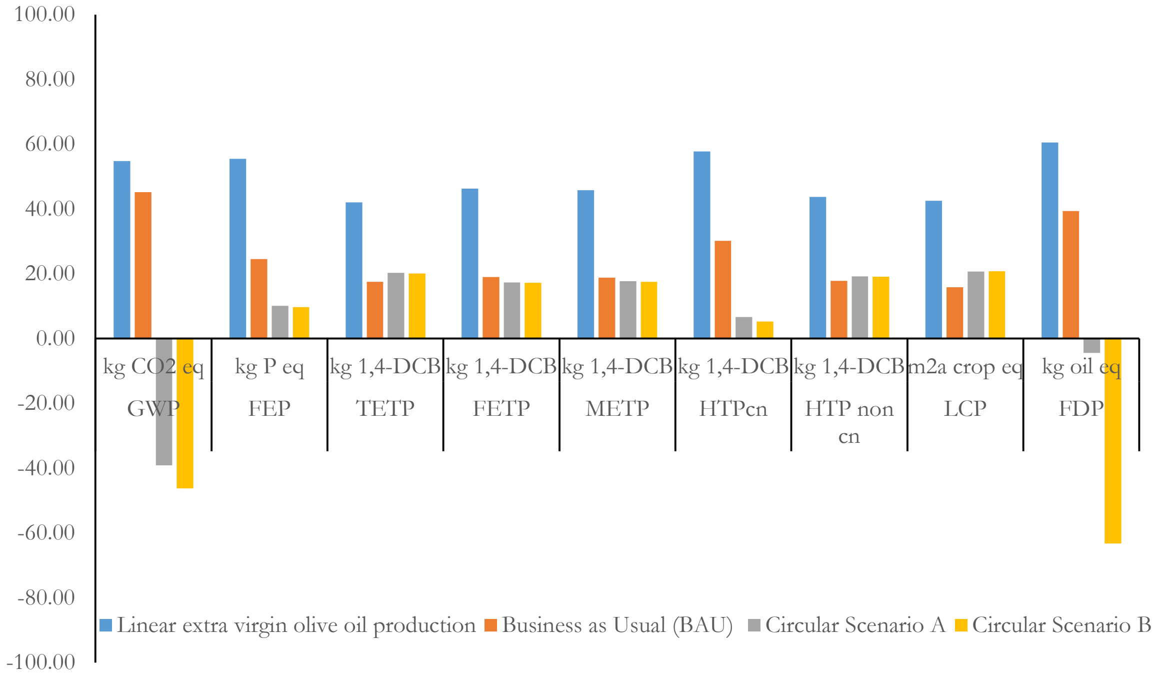

Figure 2.6 – Environmental impacts of linear and circular options, considering characterised impact (%) categories.

2.3.4 Conclusions

The olive oil sector in Italy has a significant socio-economic, environmental, and cultural relevance. In this study, the linear production of olive oil was analysed in order to identify potential hotspot areas needing further improvements such as the reliance and demand for large quantities of non-renewable resources (fuels, chemicals) and the costs of disposing residues. Human carcinogenic toxicity, marine eco-toxicity, and terrestrial eco-toxicity were identified as the most affected impact categories in all the olive oil production phases. The agricultural phase contributed to 92.7% of the environmental impacts, followed by the bottling phase (7.1%) and oil extraction phase (0.22%). To optimize and ensure sustainability within the sector, the valorisation of co-products by developing circular patterns that feedback waste materials to upstream steps of the same process was considered, resulting in significant environmental gains in the magnitude of 2-3 lower compared to the linear production system.

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2.4 Dairy sector: integrated environment assessment of dairy products

2.4.1 Context and objectives

Italian dairy sector accounts for 8.2% of European Union milk products which are known worldwide for their higher quality and variety. In the Campania Region, dairy production plays a significant role in the agri-food supply chain by generating economic benefits at both national and international markets.

Towards the optimisation of energy, materials, and environmental performance, within a circular economy perspective, a typical buffalo mozzarella cheese production in Campania Region (Italy) has been considered for environmental evaluation through the sequential application of LCA and EMA (Odum ,1996; Santagata et al., 2020). The integration of LCA and EMA followed a two-fold perspective: (1) evaluating the environmental performance of the buffalo mozzarella production chain and (2) suggesting methodological improvements to integrate LCA and EMA.

This work is one of the first attempt to integrate these methods aiming to provide a multi-perspective overview of the system being studied and suggest feasible solutions towards sustainability. Furthermore, EMA evaluations are particularly relevant for agricultural studies, as it is a system where natural and man-made contributions interact to obtain the final product, emphasising the role of ecological inputs that constitute to the basic life-support for living beings. Therefore, the dairy case study was selected as an example to demonstrate and show the integration of methods, as previously suggested by Oliveira et al. (2021a).

2.4.2 Research methods

In order to assess the environmental burden on ecosystems and human health along all the stages of a products' life cycle, the LCA methodology was employed, thus providing a consumer-side perspective. Instead, for a supply–side assessments and integration purposes, EMA was adopted to provide information relating to the support of the natural ecosystem in delivering and regenerating resources. LCA and EMA Applied Framework (LEAF, Figure 2.7) is an integrated procedure that provides a multiple-perspective analysis system through the sequential application of LCA and EMA evaluation methods (Santagata et al., 2020). Following the LEAF methodological procedure, the evaluation in this paper started with an ex-ante LCA, in order to identify the hotspots of the investigated case study. Then, a series of EMergy evaluations, aimed at investigating the environmental cost of feasible improvement scenarios was performed. The last step consisted of a series of ex-post Life Cycle Assessments, in order to confirm the reduction of the environmental burden. Three different scenarios were built in the paper based on the identified hotspots: (i) technological improvements; (ii) eco-efficiency perspective (fossil energy replaced with renewable alternatives); and (iii) viewpoint shifting scenarios (changing the allocation procedures: 1. No allocation at all (following the EMergy algebra); 2. economic allocation; 3. exergy allocation). Other scenarios could be built, according to the LEAF method, to test new proposed alternatives via EMA and LCA.

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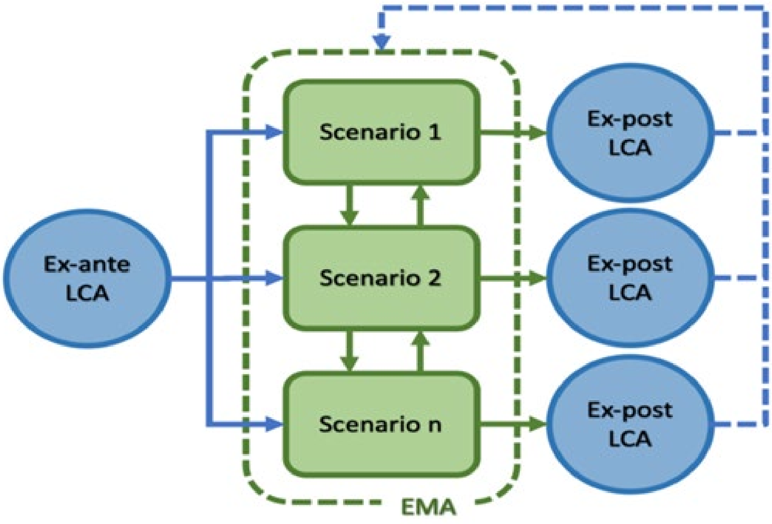

Figure 2.7 – LEAF framework (adapted from Santagata et al., 2020).

2.4.3 Results and discussion

Figure 2.8 shows the EMergy results from the comparison of the three scenarios. The sequential multi-perspective application of the two methods provides a deeper understanding of the system being investigated by suggesting feasible environmental solutions that can be achieved. Results showed that electricity from renewable resources provides the best environmental performance, with lower emissions and better EMergy indicators. However, technological improvements can deliver similar environmental gains, coupled with better work conditions. The change of perspective in the last scenario highlighted that multi-outputs issues should be carefully treated to avoid misleading results.

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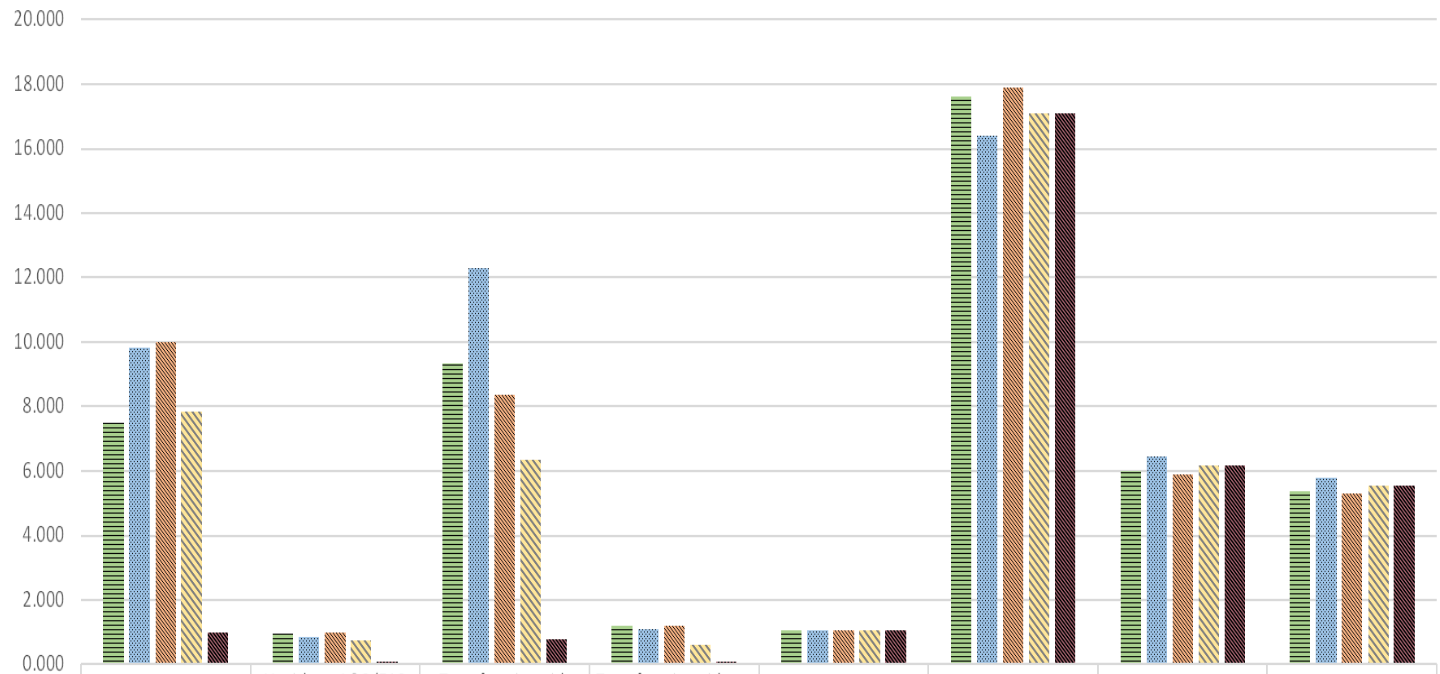

	U with L&S (E18 sej)	U without L&S (E18 sej)	Transformity with L&S (E6 sej)	Transformity without L&S (E6 sej)	EYR	ELR	ESI (E-2)	%REN
Scenario 1 - Technological Improvement	7.480	0.968	9.35	1.21	1.06	17.6	6.0	5.4
Scenario 2 - Eco-efficiency	9.833	0.858	12.29	1.07	1.06	16.4	6.4	5.8
Scenario 3 - Emergy Algebra rules	9.988	0.972	8.34	1.21	1.06	17.9	5.9	5.3
Scenario 3 - Economic Allocation	7.843	0.763	6.35	0.62	1.06	17.1	6.2	5.5
Scenario 3 - Exergy Allocation	0.978	0.095	0.79	0.08	1.06	17.1	6.2	5.5

Figure 2.8 – EMergy results from the comparison of three scenarios (adapted from Oliveira et al., 2021b).

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2.4.4 Conclusions

The integrated LEAF procedure was applied to dairy products through creating different scenarios to identify the most significant contributors to the environmental burdens namely, electricity and cleaning products. Scenario 2 presented the best environmental performance, showing that using renewable resources instead of fossil-based products reduces the total impacts. Although, Scenario 1 should also be considered as a successful option since it provides water and product savings coupled up to better labour conditions - the automation of the cleaning process gives the workers knowledge about the new process and safety from avoiding chemical manipulation. In general, the application of the LEAF procedure in the dairy case study has informed a better and more in-depth understanding of the improvement options for the considered processes. In addition, the sequential methodological application underlines the risks most often associated to the use of single methods in analysing complex systems, by allowing users to better understand how different options and scenarios can bring different and unexpected results.

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2.5 Energy sector: production of biogas and renewable natural gas in Canada

2.5.1 Context and objectives

The rapid development of some regions has led to an increase in the consumption of resources and the subsequent generation of large quantities of waste, thus creating enormous pressure on local waste management authorities (Sharholy et al., 2008; Zhou et al., 2018; Cerda et al., 2018).

Insights from different academic disciplines (in this case environmental performance evaluated through LCA to generate policy-oriented perspectives) are relevant when developing solutions for sustainable waste management and processing (e.g. Anaerobic Digestion (AD) facilities) in Canada and globally. Much of the scientific literature on AD has thus far been focused on China and Europe, creating knowledge gaps particularly on site-specific case studies in Canada (Horváth et al., 2016; Linville et al., 2015).

Moreover, interest in Renewable Natural Gas (RNG) has recently emerged in North America. As such, environmental performance evaluations capable of comparing existing AD with biogas upgrading technologies, such as (i) the commonly adopted Cogeneration of Heat and Power (CHP) and (ii) biogas valorisation systems to RNG, are much needed to inform policy and circular perspectives (Florio et al., 2019). Therefore, against this background, the aim of this study was to expand the focus from biogas production to its products such as heat, electricity, and RNG with a future outlook on waste management and the recovery of renewable energy. The identification of hotspot areas and the comparison of environmental benefits derived from the replacement of fossil-based energy with renewable counterparts (recovered from the AD facility), provided some additional insights for increased environmental awareness.

2.5.2 Research methods

The case study explored the production of biogas, electricity, heat, and RNG derived from an AD facility. The facility investigated is of commercial-scale and operates completely mixed wet anaerobic digesters to process the mixed organic waste stream. The facility accepts all kinds of Source Separated Organic (SSO) waste from residential, retail, and industrial areas, within approximately 100 km radius.

Three digester tanks are used for the anaerobic digestion process to produce biogas, which is immediately transferred to the on-site CHP facility with an electricity generation capacity of 2.5 MW. In addition to electricity, heat energy is captured for pasteurising the raw organic slurry, warming the digesters, and other on-site uses. Any remaining pathogens are destroyed during the drying process and the remaining material is then pelletised to make biofertiliser. A standardised LCA was carried out for comprehensive assessment of the environmental impacts associated with the AD facility. This included the upgrade of biogas to renewable natural gas and heat. The SimaPro 9.1.1.1 software was employed, along with TRACI 2.0 midpoint assessment method for North America (Bare, 2011). Figure 2.9 presents the system steps for this case study.

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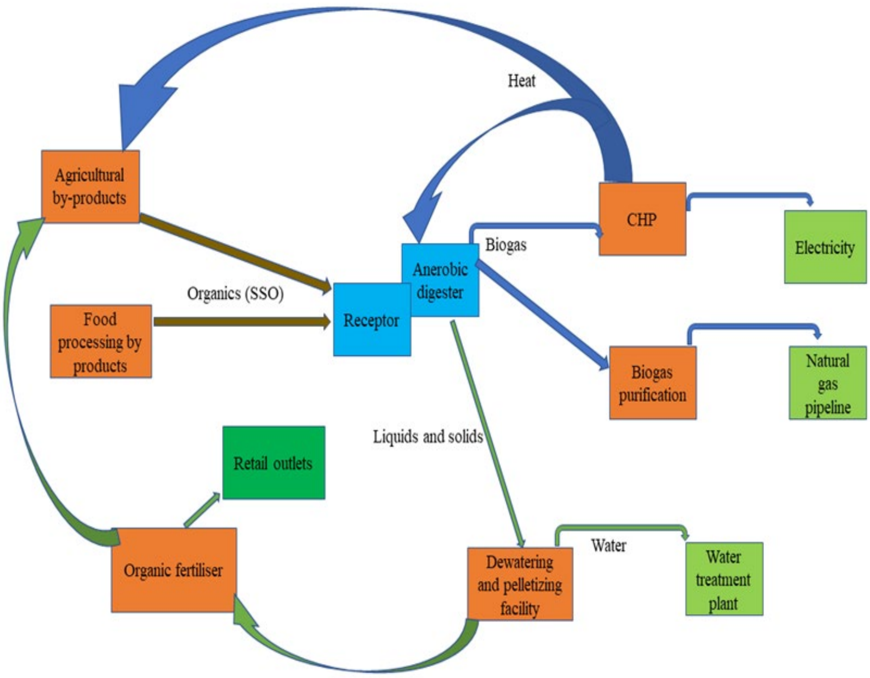

Figure 2.9 – System steps (adapted from Ncube et al., 2021d).

2.5.3 Results and discussion

The study expands the focus from using AD facilities for biogas production to other products (such as heat, electricity and RNG) while using a life cycle perspective to understand in critical terms the processing of organic waste and its potential to provide renewable energy. In addition, this case study also identified hotspots from different processing stages, highlighting additional environmental benefits that can be derived from the substitution of fossil-based natural gas, electricity, and heat for an increased circularity approach in the organic waste treatment facility in Ontario, Canada. Table 2.4 shows the selected impact categories, which were compared to highlight the benefits of avoiding the use of fossil derived energy sources. The Impact Assessment Method used is TRACI 2.0 (Bare, 2011), which allows the quantification of stressors that have potential effects on human health, e.g. cancer effects *(carcinogenics)* and non–cancer effects *(Non carcinogenics)*.

Table 2.4 – Comparison of selected characterised impacts of the production of renewables and their fossil derived counterparts (adapted from Ncube et al., 2021). Impact assessment method: TRACI 2.0 (Bare, 2011).

Impact category	Carcinogenics	Ecotoxicity	Eutrophication	Global warming	Fossil fuel depletion
Unit	CTUh*	CTUe#	kg N eq	kg CO_2 eq	MJ surplus

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Electricity-CHP	2.19E-06	1.81E+02	1.09E-01	1.18E+01	1.10E+01
Electricity-Grid {CA-ON}	1.26E-04	1.62E+04	5.45E+00	4.94E+03	9.68E+03
(+/-)	-57.49	-88.34	-48.91	-417.02	-879.21
Renewable Natural Gas	7.07E-06	6.17E+02	3.88E-01	4.41E+01	3.75E+01
Natural gas-High pressure {CA-AB}	2.93E-07	2.80E+01	3.61E-02	4.58E+00	5.00E+02
(+/-)	-0.04	0.95	0.91	0.90	-12.32
Heat-CHP	2.99E-06	2.48E+02	1.50E-01	1.62E+01	1.51E+01
Heat-Industrial {CA-QC}	9.74E-06	1.06E+03	1.09E+00	6.64E+03	1.59E+04
(+/-)	-3.25	-3.26	-6.26	-408.94	-1055.91
Biofertiliser-AD plant	4.68E-06	3.93E+02	2.55E-01	2.70E+01	2.22E+01
Phosphate fertiliser-{CA-QC}	6.34E-05	2.03E+04	2.35E+00	4.04E+02	4.75E+02
(+/-)	-13.54	-50.64	-8.20	-13.98	-20.44

*Comparative Toxicity Unit for humans
#Comparative Toxicity Units for ecotoxicity

The benefits of producing renewable electricity, heat, biomethane and biofertiliser can be appreciated in Table 2.3. The renewable co-products generated from the AD facility have significantly lower environmental impacts compared to their fossil derived counterparts. The corresponding substitution of fossil resource flows with renewable sources (namely electricity, renewable natural gas, renewable heat and biofertiliser) generates a reduction of the impacts. Such decreased impacts (negative values in Table 2.4) derive from the substitution of fossil-derived material with renewables.

For increased circularity, the production and provision of renewable energy needs a cautious approach as the supporting infrastructure and background production processes may not be entirely composed of renewable materials such as electricity, steel, concrete, and asphalt often derived from non-renewable sources (Zucaro et al., 2017). This paradox highlights one of the the challenges of implementing circular economy as the continous dependence on such material sources may not necessarily equate to greater sustainability (Figge et al., 2014; Harris et al., 2021).

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2.5.4 Circular and policy perspectives: compostable and conventional plastics in wastewater.

Growing concern over the environmental damage associated with conventional product packaging has led to keen interest in sustainable packaging (Herbes et al., 2018). Nonetheless, there is a lack of coordinated approaches to address the plastic challenge in Canada (including biogas plants). About 14% to 17% of the raw feedstock arriving at the AD facility is composed of plastics, which are removed and subsequently landfilled at the studied site, without distinguishing between compostable and conventional plastics. There was a significant increase in using plastic-based food packaging, containers, and ancillary items labelled as “compostable”, which the Canadian government has continued to vaguely endorse without adopting any standard. The presence of plastic material threatens the sustainability and operations of biogas plants. Further, the contaminated digestate, which might be used for agricultural purposes, may potentially affect food security due to its content of micro-plastics and heavy metals.

In parallel, the wastewater end usage requires a clear path forward and long-term strategies in order to realise the full benefits within a circular perspective in organic waste processing and treatment facilities. Current practices such as farm spreading, have largely been uncoordinated and have not created the necessary policy drivers for greater progress. This discussion framework for potential wastewater treatment pathways is further provided in the following Section 2.6.

2.5.5 Conclusions

The valorisation of biogas offers immense environmental and economic opportunities with an outlook based on restrictions upon fossil-based fuels and materials. The recovered co-products such as heat, electricity, and renewable natural gas (plus biofertilisers) performed exceptionally well with significant reductions in emissions and depletion of fossil fuels. Often overlooked, the production of biogas at AD facilities generates other by-products, such as digestate (containing plastics and other contaminants) and wastewater, which are of concern from a CE perspective and require appropriate policy measures. Therefore, cooperation between regulators (both provincial and federal) is needed to obtain coherent circular economy approaches to pursue organic waste reduction and biogas upgrade outcomes.

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2.6 Wastewater sector: recovering bio-products from a microalgae biorefinery in Italy

2.6.1 Context and objectives

Exploring alternatives to lowering consumers' footprint in developed countries and dependence on fossil fuels has prompted investments in the bio-based economy (or bioeconomy). The bioeconomy consists of producing and using biological resources, products, and processes as substitutes for fossil resources thus providing more sustainable goods and services (Bugge et al., 2016). Within this context, microalgae represent an emerging biological resource for its potential to produce high-value products, such as animal feeds, foods (e.g. supplements, vitamins), chemicals (e.g. cosmetics) and biofuels.

However, the production of microalgae biomass for biofuels is normally limited to areas with sufficient solar radiation, water, and nutrients, being both an energy- and freshwater-intensive process (Adarme-Vega et al., 2012; Bošnjaković and Sinaga, 2020; Feng et al., 2016). Therefore, the price of microalgae-based biodiesel remains high compared to fossil fuels and the intensive use of freshwater to grow microalgae on large scale can threaten freshwater availability in the future.

The CE model has led to a paradigm shift, reframing waste and wastewater not only as a problem, but also as sources of energy, bio-products, and water. For example, this has prompted investments in developing microalgae biofuels combined with wastewater treatment, since microalgae can bioremediate nutrients in wastewater avoiding eutrophication (significant water quality issue) and promoting water recycling (Feng et al., 2016). In this sense, microalgae grown in wastewater can be considered as diffuse biorefineries (Raheem et al., 2018). Biorefineries focus on the conversion of biomass materials into biofuels or bio-based products through biotechnology and physico-chemical technology (Park and Chertow, 2014), playing a key role in a Circular bioeconomy (CBE) context (Kershaw et al., 2020; Santagata et al., 2021; Stegmann et al., 2020). To this end, this study examines the scientific literature, identifying gaps and setting a future research agenda. In addition, the potential for microalgae grown on urban wastewater to recover bio-products, such as biofuels, is discussed through a theoretical example.

2.6.2 Research methods

A systematic literature review of 76 articles was conducted to identify knowledge gaps and potential bio-products that may be obtained from microalgae grown on urban wastewater. Thus, the study was organised according to the following criteria: to identify suitable microalgae species for growing on urban wastewater; to understand the main mechanisms driving microalgal product formation and how are affected by different environmental factors.

According to Papa et al. (2017), 60% of Italian wastewater treatment plants do not carry out any type of wastewater recovery, particularly in the Centre and South of Italy. The Campania Region, located in Southern Italy, has been sanctioned due to poor waste management (Ripa et al., 2017), with Sarno River being one of the

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most polluted rivers in Europe (Lofrano et al., 2015). Therefore, based on the results of the review and on public available data, the theoretical growth of microalgae was conceptualised on the total volume of urban treated wastewater in the Campania Region. To estimate the environmental impacts of implementing this system, two different CE pathways were hypothesised: production of energy and biochar from microalgae (*Scenedesmu*s and *Chlorella*) grown on urban wastewater.

2.6.3 Results and discussion

According to the body of literature, the most suitable microalgae genera for growing on wastewater are *Scenedesmus, Chlorella, Cyanobacteria* and *Desmodesmus*, but also marine microalgae, such as *Nannochloporis* and *Tetraselmis*.

Now, fertilisers and biochar are the only products that can be safely gained from microalgal biomass grown on wastewater. Other products, such as animal feed and high value molecules for cosmetic industry, are not safe to be extracted from microalgae grown on wastewater due to its absorption of pollutants (Leong and Chang, 2020). Additional research focusing on potential technologies to safely extract high value materials, for the cosmetic and pharmaceutical industries, is needed. Furthermore, larger and more extensive demonstration scale studies are required to demonstrate the potentials and improvements for cultivating microalgae on wastewater.

The recovery of bio-products, such as biofuels, from microalgae cultivated on wastewater are dependent of the lipid content of the microalgae biomass. Table 2.5 presents the theoretical biomass and lipid productivity assumed for Scenedesmus and Chlorella. In addition, Table 2.5 also estimates the total amounts of biodiesel, biomethane and biochar produced in one year in the largest wastewater plant in the Campania Region.

Table 2.5 – Theoretical biomass productivity, lipid content and productivity, as well as, estimated biodiesel, biomethane and biochar production for the largest wastewater treatment plant in Campania Region (adapted from Catone et al., 2021).

Microalgae	Urban treated wastewater (L/a)	Biomass productivity (ton/L_{tot})	Lipid content (%)	Lipid productivity (ton/L_{tot})	Biodiesel production (ton)	Biomethane production (m^3 CH_4)	Biochar production (ton)
Scenedesmus	$411{,}114 \times 10^6$	61,667 – 156,223	15.3 – 49.1	9,435 – 76,705	9,435 – 76,705	N/A	10,483.41 – 26,557.95
Chlorella		45,222 – 316,557	12.2 – 35.7	5,521 – 113,011	5,521 – 113,011	8,357,118 – 13,137,148	N/A

Based on these theoretical values, it was calculated that the production of biodiesel from microalgae cultivated on the largest wastewater treatment plant in the Campania Region could cover between 0.32 to 6.62% of the current consumption of diesel in the region. Furthermore, the anaerobic digestion of *Chlorella* could cover 0.29 to 4.69% of the total region's natural gas consumption (by using biomethane). Even though, it is unlikely that

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biofuel production from biorefineries would substitute completely fossil fuels, this theoretical experiment shows a contribution to the reduction of environmental impacts from harmful waste, whilst providing a small fraction of renewable energy to the community. Finally, it was estimated that the production of biochar from *Scenedesmus* could cover around 60% of the soil amendment used or, in the best-case scenario, the entire amendment consumption in Campania Region with a surplus of 53%.

2.6.4 Conclusions

This study showed that *Chlorella* and *Scenedesmus* are the most suitable microalgae to be cultivated in wastewater, because of their high growth rate and high resistance to pollutants. Nonetheless, other freshwater microalgae (*Cyanobacteria* and *Desmodesmus)* and marine microalgae *(Nannochloporis* and *Tetraselmis)* can also be grown in wastewater.

Biofuels, such as biodiesel and biogas, are the main bio-based products obtained from microalgae biomass, which are dependent of the lipid content of the microalgal biomass. Several studies have highlighted that stressful conditions (e.g., nutrient deficiency stress) favour the accumulation of lipids in microalgal biomass, improving their suitability for biofuel production. Microalgal biomass can also be used for production of animal feed, fertilisers, and high value molecules for the cosmetic and pharmaceutical industries. Overall, the treatment of wastewater with microalgae can bioremediate treated wastewater, decreasing the levels of nutrients (N and P) responsible for the eutrophication of aquatic environments, which lead to oxygen depletion and loss of aquatic flora and fauna.

Finally, the study details the need for further research, for example in the development of safe technologies for extracting high value materials from microalgal biomass. Growing microalgae in wastewater, requires further cooperation between regional and national actors in Italy, and policies are needed to enable a coherent CBE.

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2.7 Packaging sector: Steel Drum reuse

2.7.1 Context and Objectives

Currently, steel is the most recycled material in the world with 82.5% of steel packaging being recycled in 2018 (APEAL, 2021). In addition to the high levels of recycling, due to its durability, steel can also be reused or remanufactured (WorldSteel Association, 2019). Reuse can be defined "*as any operation by which products and components are used again for the same purpose for which they were conceived*" (EC, 2008). Therefore, reuse can only happen after repair or reconditioning (refurbishing) activities have taken place. Repair is the replacement of specific faulty components in a product, bringing the product back to "as-new" working condition, whilst reconditioning refers to a process of bringing an obsolete product to a working condition by repairing, replacing or refinishing all major components that are damaged, have failed or on the point of failure (den Hollander et al., 2017).

In general, reuse is perceived to have lower environmental impacts than recycling activities (Biganzoli et al., 2019) and therefore provides greater environmental benefits from a circular economy perspective. However, considering a CE scenario, introducing reuse strategies in a product system can lead to an increase of complexity and potential environmental impacts (e.g. transportation and reconditioning activities). Thus, when considering a product system, holistic approaches such as Life Cycle Assessment (LCA) should be used to account for environmental impacts associated with a product's life cycle (Oliveira et al., 2021a). In this study, the reuse of steel drums (used for storing chemical and petrochemical products) was modelled by taking an LCA approach. The LCA explored two methods for accounting for reuse, in order to gain insights into methods for evaluating the environmental benefits and impacts of reuse.

2.7.2 Research Methods

The main objective of this study was to evaluate the implications of two LCA accounting approaches (end-of-life and multiple life cycle) for assessing the environmental impacts associated with reusing steel drums, which are used for storing and transporting chemical and petrochemical products.

2.7.2.1 Steel reuse and how to account for steel reuse?

In a reuse scenario, the steel product is used again for the same initial purpose after repair or reconditioning operations. Thus, reuse can be considered as an extension of product life (Walker et al., 2018). In these circumstances, steel reuse can be modelled using different approaches from an LCA perspective, depending on the goal, scope of the study and functional unit. Due to the well-developed nature of steel recycling, industry organisations such as The World Steel Association have recommended accounting methods to be used when evaluating the benefits of recycling steel products, which can also be considered as a starting point to evaluate reuse and extended product life scenarios (Walker et al., 2018). These approaches were developed to align with

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the methods described in the International Standards on LCA (ISO, 2006, ILCD, 2010). To further understand the applicability of these methods, the study described here considered two approaches:

- **End-of-life approach** (also referred to as avoided burdens method), which is widely used to account for recycling (ISO 20915:2018) and assumes that the use of a certain amount of recycled material will displace the production and use of the same amount of primary material. This rationale can be extended to a product reuse scenario, where reusing a specific product will replace the production of a new product.
- **Multiple life cycle approach** considers the number of times a product has been reused and shares the environmental impacts associated to manufacturing and recycling by the number of times a product is used.

2.7.2.2 Life cycle assessment

The first stage of the research was to describe the processes involved in drum manufacture and reuse. Steel drums are manufactured from cold rolled coil, which is formed into a drum and then subsequently painted. In order to reuse the steel drum there is a reconditioning process. This reconditioning process involves washing the drums (both internally and externally) with hot water and a mixture of chemicals. The drums are then dried and reshaped in case of damage. After a quality check, the drums are repainted and become available for use again. On average, the steel drums can be reused up to 10 times (Biganzoli et al., 2019) before being considered no longer suitable for use and sent for recycling.

The function of this system is to provide ready-to-be-used steel drums, with an average empty weight of 20 kg, for the transport of chemical and petrochemical products within a European context. For this study, the functional unit was selected to be one steel drum. As shown in Figure 2.10, the system boundary for the study included steel production, drum production, reconditioning and recycling activities and the transport between different locations in the value chain. Due to the variability in storing and managing steel drums during the use phase, this was not included within the scope of the study. The environmental impacts of the system were modelled using GaBi 10 LCA software and background data sourced from its integrated professional database.

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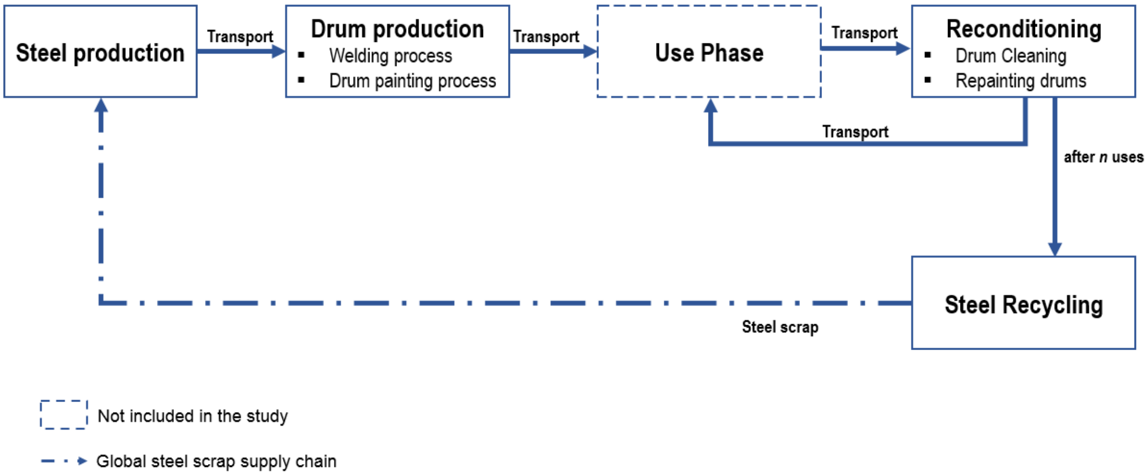

Figure 2.10 – Steel drum system boundaries.

2.7.3 Results and discussion

Considering that the steel industry is a significant carbon emitter and the existence of policy targets to implement a low-carbon steel industry in Europe (EC, 2020), it was decided to focus on the carbon footprint of the drum (given by the Global Warming Potential indicator) in this preliminary report.

Using the end-of-life approach, the reuse of a steel drum has an overall carbon footprint of 34 kg CO_2 eq compared to 58.7 kg CO_2 eq of a single-use steel drum, representing a reduction of almost 40% in carbon emissions. In the end-of-life approach, the main impacts are associated to cleaning and sorting of drums (22.9 kg CO_2 eq), followed by reconditioning activities (12.1 kg CO_2 eq) and transport (0.78 kg CO_2 eq). While any carbon emissions related to steel and drum production are assumed to be avoided by the reuse of the steel drum.

In contrast, with the multiple life cycle approach, the reuse of a steel drum has an overall carbon footprint of 47.1 kg CO_2 eq after two uses, and 37.9 kg CO_2 eq when used up to 10 times. Figure 2.11 shows the carbon emissions associated with each process of a steel drum life cycle, considering multiple uses. On average, the carbon footprint of a steel drum that is used twice is 80.2% of that of a system based on single use. As the number of times (n) the drum is reused increases the environmental impact reduces and when n=10 the impact reduces to 64.5% of a single use drum. The benefits of reusing increase with the number of uses. When looking at reusing of a steel drum in detail, the main environmental burdens are related to the cleaning and reconditioning (i.e. repainting) of drums, particularly the consumption of chemicals. Nonetheless, reusing steel drums is preferable to their single use followed by recycling.

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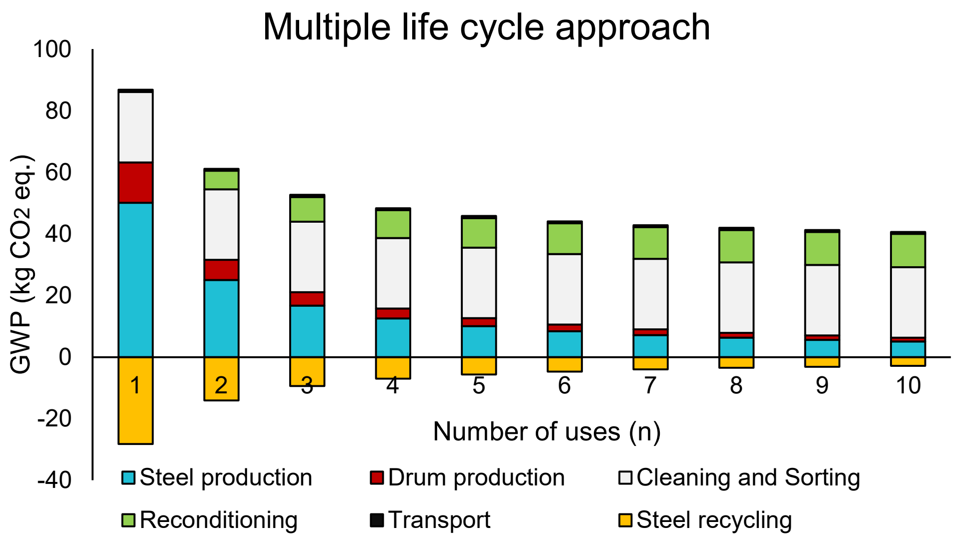

Figure 2.11 – Carbon emissions associated with each process of the steel drum life cycle throughout multiple uses.

Considering how the end-of-life method compares with the multiple life cycle method, Figure 2.12 shows the results of both accounting approaches and demonstrates how the multiple reuse method approaches a value similar to that of an end-of-life method where the number of uses is high. From this it can be concluded that where a product is only reused for a limited number of times, such as packaging, a multiple reuse method would provide a more accurate assessment of the environmental impacts of the drum. This would also help to demonstrate the environmental benefits of design for life extension through greater levels of reuse. This contrasts to the case of steel recycling, where the rationale for an end-of-life method is linked to the significant number of times steel can be recycled.

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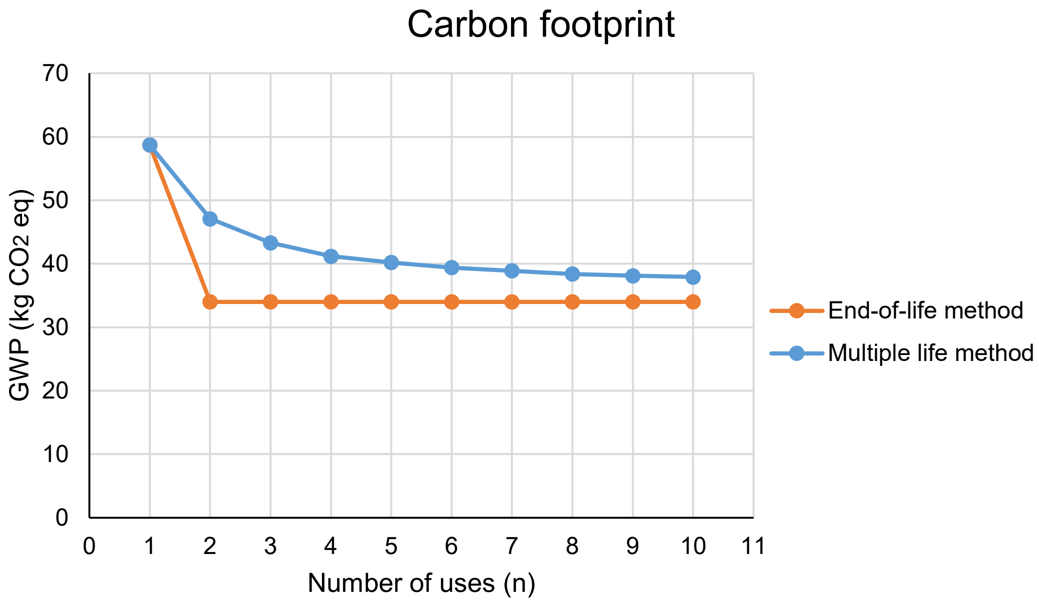

Figure 2.12 – Environmental benefits of reusing steel drums, based on global warming potential.

2.7.4 Conclusions

This preliminary study showed that the carbon emissions of reconditioning activities (i.e. transport, cleaning and repainting) are considerably lower than the production of new steel drums. In addition, the multiple life cycle approach can be a useful tool in a CE context to evaluate the benefits of reusing, as it allows us to calculate environmental burdens of different product systems (and associated business models) where there are variations in the number of times the product can be reused.

Based on a preliminary analysis and only considering the carbon footprint associated with the life cycle of a steel drum, reusing steel drums after reconditioning seems to be preferable to a single use followed by recycling. Further analysis considering other environmental impact categories is needed to fully understand the environmental impacts of both options. Finally, studies identifying and analysing potential rebound effects associated with business models promoting greater reuse of steel drums can provide a better picture of the consequences of implementing CE practices in a free-market scenario. Due to the lack of coordination, reuse of steel drums might not correspond to an immediate decrease in resource consumption in the supply chain.

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3 Final remarks and lessons learned

This report collects and explores the findings from multiple CE case studies in different sectors (i.e. construction, packaging, agri-food, energy and wastewater) and different geographical contexts (i.e. North America, Africa and Europe). By exploring a set of micro case studies and their environmental performance, we may point out their relation to circular economy. Decreased use of resources, decreased environmental emissions, increased planning, and design for more sustainable solutions (quality of know–how and information), increased awareness of resource and pollution problems, increased relation of production processes and well–being, are only a few of the aspects that must be dealt with, discussed and policy regulated in order to go beyond linear economy and Business–as–Usual production patterns. While it is very clear that there is no magic bullet to address resource consumption and environmental degradation problems, yet it is very clear that viable alternatives exist and deserve be explored.

Micro scale case studies do not provide a clear and full picture of the entire circular economy debate, nor can they ensure that circular economy is always a solution instead of becoming a new problem (just think of rebound effect, of the risk for greenwashing strategies, of developing new technologies without sufficient knowledge of their consequences). However, micro scale case studies may contribute to meso and macro scale policies towards the development of more informed production and consumption patterns as well as participatory roadmaps involving citizens and additional research involving academy, business, and policy makers.

After spending research efforts on micro scale case studies and understanding their benefits and limits, a set of take–home messages can be suggested (as listed below).

CE and environmental performance

The studies have highlighted potential CE interventions that might be relevant to different product systems and geographical contexts, as well as the environmental benefits of implementing CE practices in various sectors. For example, the brick manufacturing case study demonstrated that the substitution of fly ash for clay could increase brick quality and reduce environmental impacts, whilst the agri-food studies (i.e. wine, dairy and olive oil) highlighted that the implementation of circular strategies in traditional linear production systems leads to better environmental performance of those systems. Furthermore, the case studies raised relevant questions around, for example, the need for coordinated regulations and policies relating to the CE and the procedures to account for reuse using a life cycle perspective.

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Integration of methods

Most case studies used LCA to evaluate the environmental performance of micro level circular systems. However, the dairy milk case study used a combination of LCA and EMA for sustainability assessment, in order to provide a holistic view of the systems under study. The simultaneous application of different methods and appropriate allocation of environmental burdens between LCA (user-side) and EMA (donor-side) approaches has provided information in understanding CE implementation at micro-level (e.g. calculating the environmental cost of recycling and comparing with the advantages from recycling). For example, it is important to provide comprehensive information regarding indicators often disregarded by LCA. These include: renewable resources flows; labour and services contributions; the total EMergy of a process/product; other indicators of circularity and environmental cost.

Nonetheless, it should be cautioned that where necessary and depending on the scope and aims of the work, forced integration is not needed as it makes little sense to adopt the largest possible system boundary when the goal and scope of the analysis is intentionally reduced (e.g., when dealing with two alternative options for steel reusing). Thus, it is recommended to undertake some high-level screening of the relevant material or metrics before conducting a detailed study. Further studies looking at the impacts of circular strategies using non-reductionist approaches, as exemplified in this report, are needed to further develop knowledge around the transition towards a Circular Economy.

Policies: CE does not advocate new big biorefinery plants, but instead a diffuse biorefinery network

These micro-level case studies focused mainly on the environmental performance of technical aspects related to the implementation of CE strategies. However, some policy perspectives can be drawn from the results of these studies. The case studies do not advocate for building more infrastructures for biorefineries or recycling centres, but for the creation of collaborative and synergic systems, which would use existing infrastructures and require an improvement of the waste processing and recovering facilities. For the sake of clarity, when the possibility of converting a by–product into a new co–product comes out, this does not mean planning a new plant for large scale industrial conversion. Appropriate scale assessment is implicit in CE, as it has to do with distance, transportation costs, land use, resource density and many other aspects that come out of the waste generation and disposal processes, EMergy density, life cycle impact categories, degree of renewability of resources. Integration of processes and assessment methods are the basis for a diffuse exchange of resources, capable to minimize production and conversion costs, increase awareness, increase stakeholder's involvement at a scale that is appropriate to the goal and supported by local resources. Case studies did not show fully clean recovery processes. Each conversion step, each recovery, each reuse always shows a cost and an impact. When costs and impacts are diluted over a suitable area, the environmental services available locally and calculated via EMA provides sufficient support to the recovery process; instead, when concentration becomes excessive, the

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increase of the Empower Density and the Environmental Loading Ratio (two basic EMA landscape intensity indicators) put a limit to the possibility to increase the size and the power of even a recovery process, which would only be possible, one again, based on non-renewable resource flows.

CE and preventive design

Despite highlighting potential benefits of recycling, preventive design should be emulated instead of end-of-life measures. CE recommends designing for preventive outcomes and may force a change in policy and industry measures, moving away from only recycling towards preventive actions. Ultimately, potential rebound effects from the implementation of CE should be further analysed and assessed to fully comprehend the benefits of a circular transition. Rebound effect understanding do not come out of micro scale processes, but instead of regulatory policies that prevent (or not) the conversion of appropriate use of resources into misuse, under the perception that resources are unlimited and growth always possible in a limited planet. In such a situation, preventive design is a way to create and discuss roadmaps where the needed resources are compared to the available resources and the goal is compared to the costs. Preventive design is one of the most important aspects of CE, where technology improvements and efforts are applied to production and consumption processes, within the full perception that they are limited by resource availability and that producing more out of less does not mean unlimited production and consumption. Preventive design is also a process of removal of Business–as–Usual modalities towards innovation and acceptance of resource limits. This is already an outcome of micro scale case studies but requires convergence and expansion to larger regional and sectorial scales, to which resource policies can be tailored.

Need for regulatory and investment policies

As mentioned above, regional, national governments and European institutions should endorse investment policies to support emerging CE-based technologies, in order to counter the existing competition emanating from dominant linear supply chains. For example, by moving away from polluting fossil-based technologies that support linear systems, which should be replaced by technological interventions supported by circular mindsets.

Appropriate laws and standards can be put in place to support products and technologies that support CE. For example, standards to ensure the quality of secondary materials match the primary material. There is also a need to decrease the use of non-renewable resources, through degrowth mechanisms based on preventive design, use of renewable resources and recovery of materials, where prevention of waste is not possible. It is well known that every recycling or conversion process implies a loss of a fraction of materials and energy, so that 100% recovery is impossible. This means that CE does not advocate unlimited growth, nor does it claim that recycled materials are always of the same thermodynamic quality of primary materials (same exergy, same

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durability, same fit to the needs), but its very recovery process implicitly warns us that resources change their characteristics and so should our way of using them. However, society will have to adjust to the new features of materials (just think of construction materials, iron and steel, plastic, and paper) for new ways of using them. This will require an informed development of regulatory tools and a different way for investments, capable to develop diffuse activities instead of concentrated ones. Once again, this awareness does not come out of the strength of the investigated micro scale processes, but instead of their weakness that pushes towards new ways (smaller size, longer development times, more decentralization) for policy and decision making.

Stakeholders' engagement

Finally, in all cases studies, the accuracy of the data collection and modelling processes hugely depended on the active cooperation of actors from the whole production network. Therefore, stakeholder engagement is an important part to build upon collaborations and decision-making processes. Application of accounting methods (e.g. LCA, EMA, cost–benefits, waste generation) requires an informed and collaborative effort for data collection, data processing and data acceptance for discussion. When the problem is achieving a better understanding of the performance of a process, most of the time stakeholders think of economic performance. Instead, it is very frequent that environmental performance does not match the economic performance and needs an effort for deeper understanding of the large-scale effects of our small-scale activities. Every time a micro scale case study is investigated, the collaboration among the analysts and the supply chain actors is crucial for data to be complete, recent, accurate and, after processing, for interpretation to include multiple stakeholders' points of views and different abilities to look at the investigated system. This problem came out very clearly in the agricultural case studies, where the contact with farmers was more frequent and collaboration more effective.

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