The 30th

Annual International Conference of ISDRS on Sustainable Development Research

Linking Futures of Mountain and Ocean: Rescuing the SDGs 2030 for Sustainable Livelihood

PROCEEDINGS

June 10-14, 2024 | Kathmandu, Nepal

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Editors:
DR Bhuju, NM Sujakhu, DR Subedi

Editorial Assistance
Timila Bajracharya, Suvekchhya Tuladhar and Lahana Maharjan

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M Kapali

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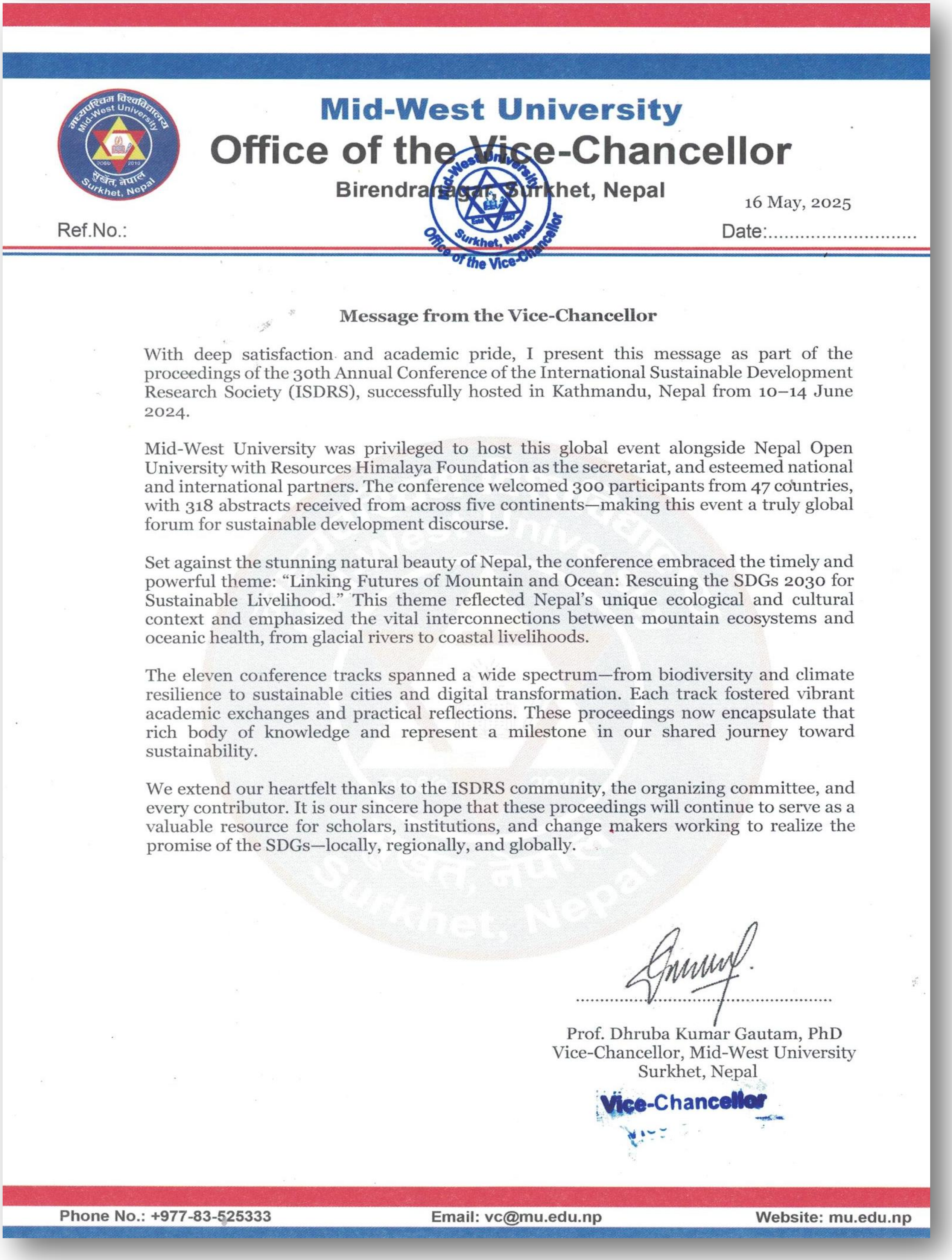

Mid-West University
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Message from the Vice-Chancellor

With deep satisfaction and academic pride, I present this message as part of the proceedings of the 30th Annual Conference of the International Sustainable Development Research Society (ISDRS), successfully hosted in Kathmandu, Nepal from 10–14 June 2024.

Mid-West University was privileged to host this global event alongside Nepal Open University with Resources Himalaya Foundation as the secretariat, and esteemed national and international partners. The conference welcomed 300 participants from 47 countries, with 318 abstracts received from across five continents—making this event a truly global forum for sustainable development discourse.

Set against the stunning natural beauty of Nepal, the conference embraced the timely and powerful theme: "Linking Futures of Mountain and Ocean: Rescuing the SDGs 2030 for Sustainable Livelihood." This theme reflected Nepal's unique ecological and cultural context and emphasized the vital interconnections between mountain ecosystems and oceanic health, from glacial rivers to coastal livelihoods.

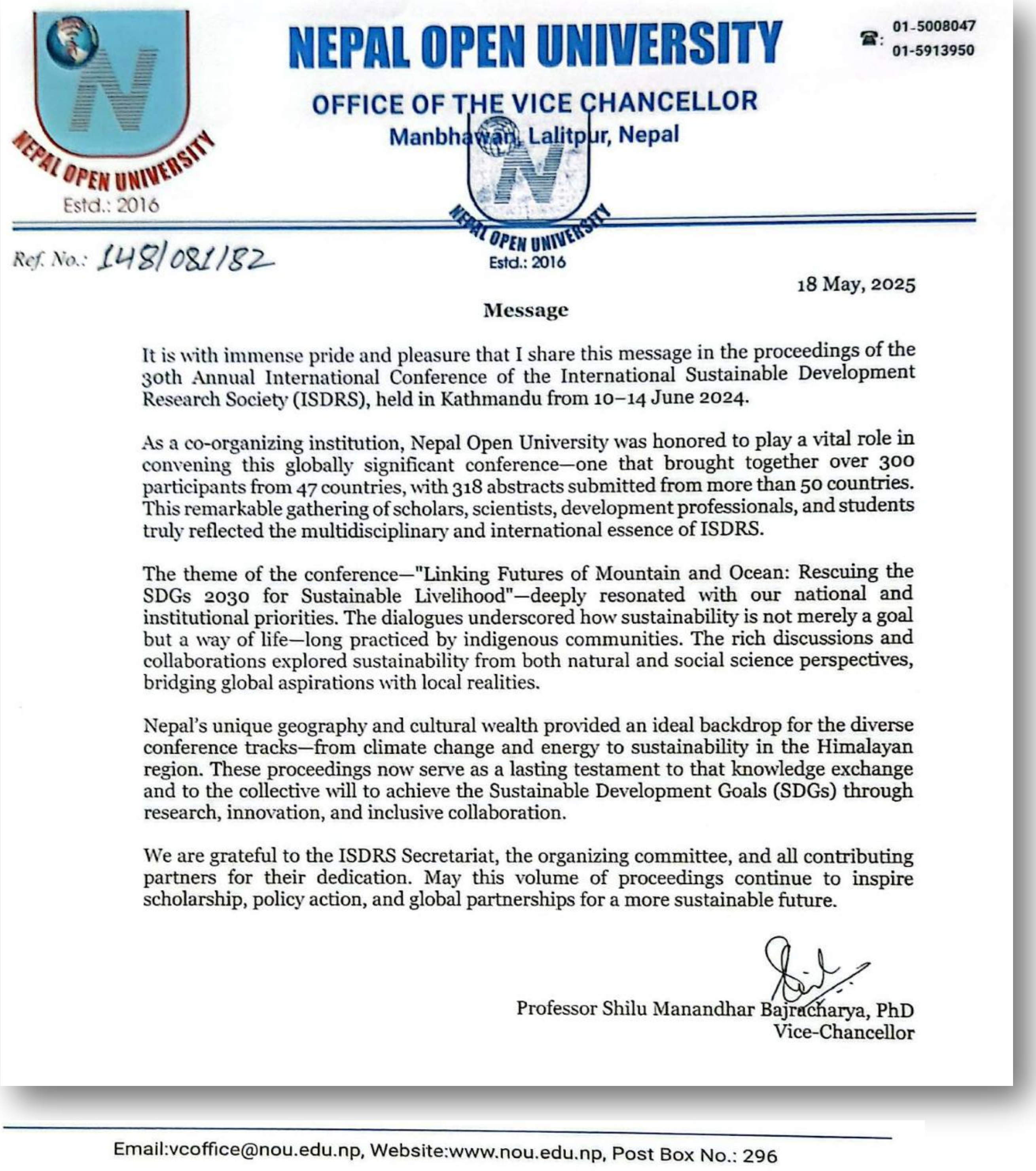
The eleven conference tracks spanned a wide spectrum—from biodiversity and climate resilience to sustainable cities and digital transformation. Each track fostered vibrant academic exchanges and practical reflections. These proceedings now encapsulate that rich body of knowledge and represent a milestone in our shared journey toward sustainability.

We extend our heartfelt thanks to the ISDRS community, the organizing committee, and every contributor. It is our sincere hope that these proceedings will continue to serve as a valuable resource for scholars, institutions, and change makers working to realize the promise of the SDGs—locally, regionally, and globally.

Prof. Dhruba Kumar Gautam, PhD
Vice-Chancellor, Mid-West University
Surkhet, Nepal

Vice-Chancellor

Phone No.: +977-83-525333 Email: vc@mu.edu.np Website: mu.edu.np



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OFFICE OF THE VICE CHANCELLOR
Manbhawan, Lalitpur, Nepal
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Message

It is with immense pride and pleasure that I share this message in the proceedings of the 30th Annual International Conference of the International Sustainable Development Research Society (ISDRS), held in Kathmandu from 10–14 June 2024.

As a co-organizing institution, Nepal Open University was honored to play a vital role in convening this globally significant conference—one that brought together over 300 participants from 47 countries, with 318 abstracts submitted from more than 50 countries. This remarkable gathering of scholars, scientists, development professionals, and students truly reflected the multidisciplinary and international essence of ISDRS.

The theme of the conference—"Linking Futures of Mountain and Ocean: Rescuing the SDGs 2030 for Sustainable Livelihood"—deeply resonated with our national and institutional priorities. The dialogues underscored how sustainability is not merely a goal but a way of life—long practiced by indigenous communities. The rich discussions and collaborations explored sustainability from both natural and social science perspectives, bridging global aspirations with local realities.

Nepal's unique geography and cultural wealth provided an ideal backdrop for the diverse conference tracks—from climate change and energy to sustainability in the Himalayan region. These proceedings now serve as a lasting testament to that knowledge exchange and to the collective will to achieve the Sustainable Development Goals (SDGs) through research, innovation, and inclusive collaboration.

We are grateful to the ISDRS Secretariat, the organizing committee, and all contributing partners for their dedication. May this volume of proceedings continue to inspire scholarship, policy action, and global partnerships for a more sustainable future.

Professor Shilu Manandhar Bajracharya, PhD
Vice-Chancellor

Email:vcoffice@nou.edu.np, Website:www.nou.edu.np, Post Box No.: 296

Preface and Acknowledgements

The International Sustainable Development Research Society (ISDRS) held its 30th annual international conference in Kathmandu, the capital of the Himalayan nation of Nepal. The conference marked a significant milestone in advancing the global sustainability agenda. Hosted in a hybrid format, the conference brought together over 250 participants from 47 countries, representing one of the most extensive international gatherings in the post-COVID-19 "new normal."

The conference was inaugurated by the Vice President of Nepal, while the Deputy Prime Minister and the Minister for Foreign Affairs participated in the valedictory session, underscoring the national significance of the event.

Nepal's new universities Mid-West University and Nepal Open University jointly hosted the conference. They established an inclusive academic platform by engaging five recently founded universities from across the country: Agriculture and Forestry University, Far-Western University, Madhesh University, Purbanchal University, and Rajarshi Janak University. This collaborative initiative laid the groundwork for stronger inter-university cooperation across Nepal.

In addition to the universities, the conference was supported by 12 key institutions, including the University Grants Commission (Nepal), the National Trust for Nature Conservation (Nepal), UNDP, and UNESCO. Serving as the conference secretariat, the Resources Himalaya Foundation played a central role in coordinating logistics and mobilizing resources.

The conference featured 220 research contributions across 10 thematic tracks, showcasing the interconnected and multifaceted nature of sustainable development. It highlighted the critical need for inter- and transdisciplinary collaboration, localized strategies, and inclusive approaches. Of particular significance was the strong participation of scholars from the Global South and women researchers, whose contributions emphasized the importance of addressing context-specific sustainability challenges and solutions.

The event called for the strengthening of research cultures in emerging academic institutions, improved science communication, and deeper engagement with issues of equity and planetary boundaries. These themes are especially relevant for Nepal—a Least Developed Country facing severe climate vulnerability. Melting Himalayan glaciers, rising frequency of wildfires, and increasingly erratic weather patterns are threatening livelihoods, particularly in rural farming communities. The timing of the conference was pivotal, as Nepal aspires to graduate to a developing nation status amidst these mounting sustainability challenges.

The conference served both as a challenge and an opportunity. It identified the urgent need to build robust platforms and mechanisms for collaboration among key actors in the Global South and emerging economies, reaffirming their crucial roles in achieving the Sustainable Development Goals (SDGs).

One of the key outcomes of the conference was the adoption of the Kathmandu Communiqué, which emphasized the importance of integrating the SDGs with planetary boundaries and understanding the socio-economic dimensions of sustainability—particularly equity, inclusivity, and the impacts of sustainability transitions on vulnerable populations.

We sincerely thank all partner organizations, volunteers, researchers, and scholars whose commitment and contributions were instrumental in making this conference a meaningful and memorable milestone in the global dialogue on sustainable development.

We extend special appreciation to the track reviewers, paper and poster presenters, and all participants, whose active engagement played a vital role in the conference's success.

Prof. Sjors Witjes, PhD
President
ISDRS 2024

Prof. Dinesh Bhuju, PhD
Convener
30th ISDRS Conference 2024 Kathmandu

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Assessing Circularity in the Agri-Food Sector: A Case Study

Federica Scandurra[1], Roberta Salomone[1], Sandra Caeiro[2, 3], Teresa Maria Gulotta[4]

[1]Department of Economics, University of Messina, Messina, Italy. [2]Center for Global Studies, Department of Science and Technology, Universidade Aberta, Lisbon, Portugal. [3]CENSE - Center for Environmental and Sustainability Research & CHANGE - Global Change and Sustainability Institute, NOVA School of Science and Technology, NOVA University of Lisbon, Lisbon, Portugal. [4]Department of Engineering, University of Messina, Messina, Italy

Abstract

The agri-food sector (AFS) faces challenges in providing affordable and healthy food for an increasing population. In this context, Circular Economy (CE) has gained interest as an approach to drive the food system to sustainability. However, circularity does not always lead to sustainability. The lack of a defined set of metrics to monitor CE in the sector makes it relevant to select assessment approaches that capture CE's contribution to sustainability. For this reason, the present study aims to support the dairy cooperative Fattoria della Piana, a best case of CE, in assessing its circular strategies. The study links Life cycle assessment (LCA) with circularity indicators collected in the literature. This preliminary study analyses the core of the circular exchanges of the cooperative, represented by the anaerobic digestion and combined heat and power plant (AD-CHP) plant. The study presents a valuable assessment approach for companies in the sector, highlighting the complexity of assessing CE. LCA evidenced valuable credits from avoiding mineral fertilizer and natural gas use thanks to their substitution with the treatment plant's outputs. Indicators suggest its ability to recirculate waste for energy purposes and nutrients. Future studies will explore the overall cooperative' system, evaluating the three dimensions of sustainability.

Introduction

Dairy products provide an essential source of nutrients; however, their intensive production and consumption contribute to environmental and health challenges (Stanchev *et al.*, 2020). Indeed, improper management of sewage and manure severely contributes to climate change and reduces biodiversity, threatening human health (Zhang *et al.,* 2021). Finding a sustainable venue for the sector is central to reducing its environmental footprint along the entire supply chain (Stanchev *et al.*, 2020). This brought attention to the Circular Economy (CE) model. Despite CE being widely explored in the dairy sector, the full recirculation of resources and waste is still far (Stanchev *et al.*, 2020). Thus, it is necessary to monitor how much the circular strategies implemented in the sector contribute to sustainability. Circularity metrics should support companies' decision-making in implementing efficient circular strategies in their businesses. Nowadays, the multitude of metrics available of the AFS makes selecting appropriate tools challenging for companies, limiting the quality of the information provided (Kounani *et al.*, 2023). The relevance of CE brought to the publication of relevant standards; at the national level, the UNI/TS proposed a set of indicators for CE assessment at the organizational level (UNI/TS 11820:2022); at an international level, the ISO published the ISO 59000 series, which standardized CE definition, application and assessment (ISO/FDIS 59020). However, the AFS deals with organic materials which dissipate after use (Møller *et al.*, 2023) and neither of the standards is sector specific. Thus, empirical studies applying CE metrics are relevant to identify metrics able to support circularity. Some studies observed that circularity should be monitored through a combined approach using LCA together with circularity indicators (Rigamonti and Mancini, 2021; Rufí-Salís *et al.,* 2021; Niero and Kalbar 2019). In this context, the present study aims to support companies of the AFS in assessing and monitoring the circularity and sustainability of their strategies. To this end, the study adopts a case study analysis of the dairy cooperative Fattoria della Piana. The cooperative represents a best case of circularity and industrial symbiosis for the South of Italy, which was awarded as a sustainable company (Impresa sostenibile) by the Sole 24 Ore (Il Sole 24 Ore, 2023). Moreover, the study was conducted within a six-month collaboration with Fattoria della Piana contemplated as an internship within the PhD scholarship PON No. 2. This allowed the collection of primary data through surveys and interviews onsite, increasing the reliability of data. Within the cooperative system, the Anaerobic Digestion and Combined Heat and Power (AD-CHP) plant has a central role in the symbiotic exchanges within the cooperative supply chains and other local businesses, contributing to closing the loop of waste and resources. For this reason, the present preliminary study focuses on the AD-CHP plant, exploring the circular strategies entailed.

System Description

Fattoria della Piana is a dairy cooperative in the province of Reggio Calabria (Italy) that closes the loop of resources and waste in its dairy chain. The cooperative has embodied CE's principles, generating symbiotic exchanges among the various supply chains and partners companies; The agricultural supply chain allows the company to produce on site a large part of the fodder for the livestock, using digestate produced via AD instead of mineral fertilizer on the fields. The breeding phase produces cattle milk for the cheese factory but also produces manure and sewage as waste which is then pumped to the treatment plant and used as input for the AD process. Moreover, in terms of energy, a photovoltaic system placed on the roof with a nominal power of400 kW, inclined at 14° facing South, provides electricity to the farm (https://fattoriadellapiana.it/). The cheese factory uses as input the cattle milk produced internally, plus sheep and goat milk provided by the Pastori Calabresi, who are partners of the cooperative. The heat used in the cheese production is generated by the AD-CHP plant, while the factory delivers whey, a subproduct of cheese production, to the treatment plant and delivers wastewater to the Phytodepuration plant. The cooperative also collects waste from partners companies which are in the neighborhood (main exchanges entail olive pomace and agrums pulp) providing back digestate to be used as organic fertilizer. Thus, the cooperative through the AD-CHP plant generates a self-sufficient ecosystem, where waste is turned into a resource and networking operations take place. This allows both to reduce the cost associated with the treatment of such waste and reduce the cost of e.g., providing heat, nor electricity to the system and reducing the environmental impact of the cooperative. Figure 1 summarizes the main exchanges within the system, which includes: Fattoria della Piana (the owner of the cheese factory, of one of the treatment plants, and of part of the distribution chain), Uliva (which deals with the breeding and agricultural productive chain and of one of treatment plants), Pastori Calabresi (a cooperative made of shepherds and agricultural producers of olives and citrus fruits), and Arriva fresco (which deals with the distribution activities).

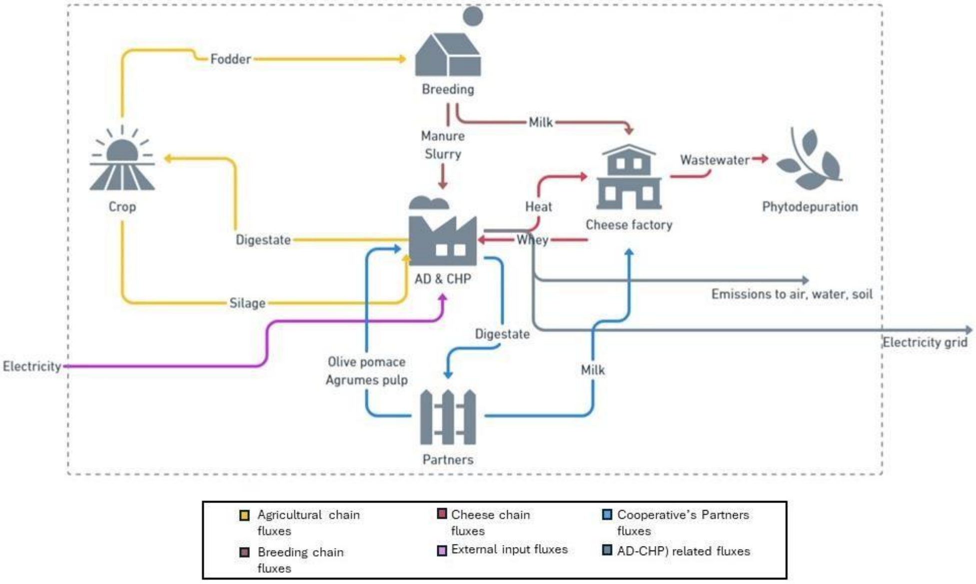

Figure 1. Main fluxes of the cooperative system. Source: own elaboration from data collected at "Fattoria della Piana".

The Anaerobic Digestion and the Combined Heat and Power Generation (AD-CHP) Plants

The AD-CHP treatment process consists of two main phases: i) anaerobic digestion, during which microorganisms decompose organic materials in a de-oxygenised space, producing biogas and digestate; ii) biogas reaches the Combined Heat and Power plant where it becomes electricity and thermal energy (Chowdhury, 2021). The cooperative has two equal AD-CHP plants with an electrical power of 998 kW each. The treatment plants are owned by Fattoria della Piana (plant a) and by Uliva (plant b). Plants are fed with internal waste, i.e. silage residues of wheat and corn, manure, sewage and bedding residue and whey. Additionally, the plants receive from external partners' inputs such as olive pomace, citrus pulp, molasses and chicken manure. All data here provided are primary information collected on site. In detail, in 2022 plant a) produced 5,342 ton of biogas, 2,779 ton of solid and 31,954 ton of liquid digestate. In the same year, plant b) produced 5,342 ton of biogas, 2,660 ton of solid and 30,594 ton of liquid digestate. Then biogas is burned in the CHP plant to produce electricity and thermal energy.

Methodology

To support companies of the AFS in circularity assessment, the present study proposes a case study analysis. This analysis allows us to explore an exemplary case of circularity applied to the dairy supply chain, grasping all the exchanges occurring among the various actors of the system in their original context (Eisenhardt, Graebner, & Sonenshein, 2016). The methodological approach chosen to assess the environmental profile and circularity of the AD-CHP plant is based on LCA and CE indicators. LCA defines the environmental load linked to the implementation of CE, while CE indicators measure the circularity of the system under analysis. Most of the data were collected at the company by administering surveys and conducting interviews with the cooperative's management and employees, while background or missing data were collected from scientific literature and databases.

CE Indicators

To assess the level of circularity of the treatment plant, some circularity indicators available in the literature and in line with the characteristics of the system under analysis were selected. Specifically, the following studies were considered in the selection process: i) Mancini and Raggi (2021), who explored the role of AD processes evaluation and assessment; ii) Poponi *et al.* (2022), who collected all the CE indicators available in literature, creating a dashboard; iii) Kounani *et al.* (2023), who collected CE indicators suitable for the olive oil supply chain; iv) Feiz *et al.* (2020), who selected indicators appropriate for the comparison of different biogas production contexts. The indicators selected concern the most critical aspects of the system analysed, namely energy, nutrients and organic waste, which were adapted to the case study context and presented in Table 1.

Table 1. CE indicators selected

Indicator	**Description**	**Reference**
Biogas efficiency	Energetic revalorization of waste	Mancini and Raggi (2021) Feiz *et al.* (2020)
Energy balance	Energy delivered (biogas) on primary energy of the process	Feiz *et al.* (2020)
Nitrogen recycling potential	Percentage of nitrogen recirculated in the system	Feiz et al. (2020)
Energy self-sufficiency	Capability of the system to cover its energy needs	Poponi *et al.* (2022) Kounani *et al.* (2023)

LCA Modelling

To assess the environmental profile of the AD-CHP plant, LCA is adopted according to the ISO 14040 and 14044 methodological guidelines (ISO 14040:2006/Amd 1:2020; ISO 14044:2006/AMD 2:2020). The analysis aims to define the environmental profile of the AD-CHP plant by measuring the potential environmental impacts through LCA, including avoided productions, thus including environmental credits associated with the avoided production of conventional fertilizers and natural gas. The treatment plant uses cattle sewage and manure (from the livestock phase), olive pomace, agrums pulp, chicken manure and molasses (from partners), corn and wheat silage (from fodder production), and cheese whey (from the cheese factory) as process inputs. The FU adopted is 1 MWh of electricity produced by the system, while the system boundaries allow a "gate to gate" perspective of analysis. Some cut-off criteria are included: i) no environmental impact is considered for cattle manure and sewage being wastes of the livestock supply chain; ii) the production of machinery, equipment and infrastructures is excluded from the study since the production of such capital is not significant in a life cycle context (Salomone and Ioppolo, 2012). To conduct the analysis, primary and secondary data were collected. Primary data relate to the 2022 productive year and report information regarding inputs (such as feedstock, electricity, and heat) and outputs (such as biogas, digestate, heat and electricity). These data were provided by the cooperative management and employees working on or with the treatment plant unit. Secondary data based on scientific literature and databases were used to fill in missing and background data, e.g., data on the plant production activity and electricity generation, were extracted from Ecoinvent (Wernet *et al.*, 2016). The treatment plant produces biogas and digestate, where the latter is then used by the cooperative as organic fertilizer in the agricultural supply chain and sent to partners who contribute their waste to the activity of the treatment plant. Following the ISO recommendations, the present study avoided the allocation process by adopting the substitution method, by including the avoided production of conventional production of heat and fertilizers. The heat produced in the treatment plant fulfils the needs of the treatment plant and the cheese factory. Thus, the heat produced by the system replaces the heat produced by conventional sources, e.g., natural gas produced by considering the reference linear scenario given the characteristics of the system. This implies that the environmental load related to the avoided heat can be considered a credit for the system, where the eco-profile of natural gas is derived from Ecoinvent (Wernet *et al.*, 2016).

Moreover, the study considers the digestate and the emissions connected as a replacement for conventional fertilizer. Thus, the environmental impacts associated with mineral fertilizer account for credits of the system. The LCA analysis is performed using SimaPro 8 software (PreConsultant, 2010), selecting appropriate impact categories and connected characterization factors. The methods used to estimate the environmental impacts of the plant are: i) CML IA baseline V3.07 (CML - Department of Industrial Ecology, 2016) method, selecting as impact categories abiotic depletion, abiotic depletion (fossil fuels), ODP, Human Toxicity, Freshwater aquatic ecotoX, Marine aquatic ecotoxicity, Terrestrial ecotoxicity, Abiotic Potential, Eutrophication Potential, and POFP; ii) IPCC 2021 GWP100 method (IPPC, 2021) which allows to evaluate the Global Warming Potential (GWP100); and iii) Cumulative Energy Demand (CED) to assess the total primary energy requirement, originated along the life cycle (Frischknecht *et al.*, 2007), adding impact category.

Results and Discussion

Inventory Data for Inventory Data for the AD-CHP Plants

The AD plant produces biogas and digestate. The biogas has 55% methane content for the volume of biogas produced, while the remaining portion is assumed to contain only CO_2 (Giuntoli *et al.*, 2017). Nevertheless, a small portion of biogas is lost, and the uncontrolled emissions represent >5% of biogas yield. The digestate is considered a co-product of the treatment plant. Specifically, digestate is moved from the digester to open tanks and then used as organic fertilizer without additional processing stages (Cusenza *et al.*, 2021). The open storage generates emissions of Nitrous oxide (N_2O) and methane (CH_4) caused by the residual organic matter content. Secondary data from the literature is used to estimate such emissions (Fusi *et al.*, 2016; Reichhalter *et al.*, 2011). Finally, the system considers the environmental credits associated with the prevention of production and use of mineral fertilizer, mainly composed of urea; thus, mineral fertilizer is considered a function of the amount of nutrients present in the digestate produced (Lijó *et al.,* 2014). Following Reichhalter *et al.* (2011) and Sedorovich *et al.* (2007), the avoided emissions associated with the conventional management of 1 tonne of cattle sewage and manure are 4.10 kg of CH_4 and 0.10 kg of N_2O per m^3 in a year. The CHP plant produces thermal and electric energy. Data on the emissions associated with the combustion process are based on secondary data and the macro-pollutants considered are nitrogen oxides and methane. The inventory data expressed per FU is reported in Table 2.

Table 2. Inventory data for AD-CHP plant's operation represented per 1 MWh of electricity produced

AD-CHP Plant	**Unit**	**Amount**	**Data source**
Input	t		
Bovine manure		3.76E-01	Primary data
Bovine slurry	t	2.35E-01	Primary data
Poultry manure	t	3.14E-01	Primary data
Whey	t	8.35E-01	Primary data
Silage waste	t	1.29E-01	Primary data
Olive pomace	t	2.89E+00	Primary data
Citrus pulp	t	1.68E+00	Primary data
Molasses	t	2.89E-02	Primary data
Electricity	kWh	2.94E+00	Primary data
Heat (from CHP)	kWh	1.16E+02	Mistretta *et al.*, 2022
Output			
Biogas	Nm^3	5.19E+02	Primary data
Electricity	kWh	1.00E+03	Primary data
Heat	kWh	2.76E+02	Mistretta *et al.*, 2022
Solid digestate	t	3.27E-01	Primary data
Liquid digestate	t	3.76E+00	Primary data
CO_2, biogenic	t	1.15E+00	FIPER, 2018
NOx	t	2.34E-04	FIPER, 2018
CH_4, biogenic	t	1.40E-02	FIPER, 2018
Heat waste	kWh	2.06E+01	Primary data
Avoided products Heat			
	kWh	1.58E+01	Calculated data
Mineral fertiliser	t	2.76E-01	Calculated data

CE Indicators

The biogas efficiency indicator (KPI_1) (Mancini and Raggi, 2021; Feiz *et al.*, 2020) monitors the energy valorisation of organic waste, by calculating the biogas generated during the AD process on the amount of organic waste used as input in the process. In this case, only organic waste was included in the system, thus the calculation was simplified focusing on just one type of waste (Salguero-Puerta *et al.*, 2019). As indicated in Table 3, the I_{bce} is 43.99 m^3 CH_4 /ton of waste. This indicates that every tonne of organic waste generated produces 43.99 m^3 CH_4 /ton of waste. This quantifies the valorisation of waste in terms of energy, but also suggests the efficiency of waste management within the system. Higher values suggest better performances for the system.

Table 3. KPI_1 calculations

Input	**Value**	**Unit**
Biogas produced	4.41E+06	m^3
Methane % in biogas	5.50E+01	%
Methane produced	2.43E+06	m^3CH_4
Waste collected	5.52E+04	ton
Ibce	4.40E+01	m^3 CH_4 /ton

The energy balance indicator provides an information regarding the energy performance of the biogas produced out of organic waste; it is given by the amount of energy produced as biogas on the amount of primary energy utilized to generate and distribute the same energy. The calculations are shown in Table 4.

Table 4. KPI_2 calculations

Input	Value	Unit
Biogas delivered	4.41E+09	m^3
Biogas lost	2.21E+09	m^3
Methane in net biogas	2.31E+09	m^3
KPI	1.91E+09	m^3

The self-sufficiency indicator (KPI_3) measures the self-sustaining capacity of the treatment plant as suggested in the literature (Poponi *et al.*, 2022; Kounani *et al.*, 2023). This is given by the energy produced and re-used by the treatment plant on the total amount of energy required by the plant for its functioning. In this case, the internal production of thermal energy and the electricity deriving from the electricity grid was considered. The AD-CHP plant of Fattoria della Piana covers 97.5% of its own thermal energy needs by the self-produced energy.

Digestate contains several macronutrients which are crucial for plant growth; the main ones are nitrogen (N), phosphorus (P) and potassium (K); using digestate as organic fertilizer allows for the recycling of such macronutrients (Feiz *et al.*, 2020). Thus, the nitrogen recycling potential (KPI_4) is chosen to verify the system's ability to recirculate nitrogen (Møller *et al.*, 2023; Feiz *et al.*, 2020). The indicator considers the quantity of nitrogen in the digestate and the quantity in the type of waste used as input in the AD process. Data concerning digestate nitrogen content were collected on the field being primary data, while the nitrogen average content of the various inputs was collected in literature, as indicated by Table 5. Finally, the indicator presents the percentage of nitrogen recirculated through the AD process. In this case, 21% of the nitrogen contained in the digestate is recycled.

Table 5. N content per type of waste stream

Input	Value	Unit	N %	Reference
Cattle manure	3.20E+03	ton	2.66E+00	Shah *et al.*, 2014
Sewage sludge	2.00E+03	ton	4.70E+00	Leone *et al.*, 2021
Whey	7.10E+03	ton	1.40E-01	Wasserman, 1960
Wheat	1.10E+03	ton	4.00E-01	Paritosh *et al.*, 2017
Olive mill pomace	1.26E+04	ton	8.70E-01	Leone *et al.*, 2021
Agrumes pulp (fruit waste)	1.13E+04	ton	1.36E+00	Shah *et al.*, 2014
Chicken manure	2.57E+03	ton	1.95E+00	Hachicha *et al.*, 2009
Melasso (fruit waste)	2.10E+02	ton	1.36E+00	Paritosh *et al.*, 2017

LCA Results

LCA's characterization results, displayed per FU, are presented in Table 6. The most relevant emissions associated with the AD-CHP plant functioning are GWP, Human Toxicity, Acidification Potential, Photochemical Oxidation and Eutrophication Potential. Relevant emissions for the treatment plant are associated with an increase of GWP related to pollutants like methane biogen and nitrogen oxides. In particular, when biogas is lost, it releases methane biogen, negatively impacting the production yield of the biogas while generating greenhouse gas emissions. On the contrary, emissions impacting Marine Aquatic Ecotoxicity, Abiotic Depletion-fossil fuels, and CED relate to the electricity consumed by the treatment plant. The most relevant environmental impacts relate to the use of electricity, which comes from the Italian electricity mix, where the contribution of fossil fuels is considerable. The analysis includes the environmental credits linked to the avoided production and use of conventional mineral fertilizer and natural gas. This is common in LCA analysis since the activity considered entails the avoided production of conventional products (Salomone *et al.*, 2018). The analysis of the environmental credits associated with the avoided use and production of urea (the main component of mineral fertiliser) envisages relevant positive impacts for the overall system. The most relevant credits are connected to GWP, Marine Aquatic Ecotoxicity, and Human Toxicity. The credits associated with the avoided use of gas from conventional sources are Marine Aquatic Ecotoxicity, Abiotic Depletion and CED. Thus, most of the benefits associated with avoided products analysed concern reductions of non-renewable, fossil impacts. In conclusion, the environmental profile of the AD-CHP plant evidenced significant reduction compared to a linear scenario in which heat is produced from natural gas and digestate is replaced by mineral fertilizer. Thus, the strategy adopted by the cooperative in terms of the treatment plant is environmentally consistent.

Table 6. Characterization results per 1 MWh of electricity produced

Impact category	**Unit**	**Impacts**		**Credits**	
		AD-CHP	**Electricity**	**Mineral fertiliser**	**Heat from natural gas**
Abiotic depletion	kg Sb eq	-1.27E-04	0.00E+00	1.94E-08	-1.20E-04
Abiotic depletion (fossil fuels)	MJ	-1.34E+04	0.00E+00	1.37E+01	-8.16E+03
Ozone layer depletion	kg CFC-11 eq	-1.08E-04	0.00E+00	1.27E-07	-5.97E-05
Human toxicity	kg 1.4-DB eq	-4.36E+01	2.80E-01	6.23E-02	-2.05E+01
Fresh water aquatic ecotox.	kg 1.4-DB eq	-3.02E+00	0.00E+00	2.49E-03	-2.08E+00
Marine aquatic ecotoxicity	kg 1.4-DB eq	-1.58E+05	0.00E+00	3.41E+02	-2.96E+04
Terrestrial ecotoxicity	kg 1.4-DB eq	-2.69E-01	0.00E+00	4.20E-04	-1.11E-01
Photochemical oxidation	kg C_2H_4 eq	-3.27E-02	8.39E-02	1.93E-04	-4.39E-02
Acidification	kg SO_2 eq	-2.42E+00	1.17E-01	3.96E-03	-1.04E+00
Eutrophication	kg PO_4--- eq	-2.32E-01	3.04E-02	3.45E-04	-1.33E-01
Global warming (GWP100a)	kg CO_2 eq	-1.34E+04	0.00E+00	1.37E+01	-8.16E+03
Cumulative Energy Demand	MJ	-1.76E+04	0.00E+00	2.31E+01	-9.34E+03

Circularity Indicators and LCA: A Combined Approach

The LCA analysis assessed the environmental profile of the AD-CHP plant of Fattoria della Piana, evidencing the benefits associated with the avoided use and production of mineral fertilizer and heat from natural gas, as shown in Figure 2. Focusing on energy production, the main impacts are related to the presence of methane biogenic, which impacts in terms of GWP and Photochemical Oxidation. If the environmental profile of the treatment plant assessed through LCA and of the environmental benefits of the system is clear, more complex is the evaluation of its level of circularity. On the one hand, the strategy implemented by the cooperative closes the resource loop by producing bioenergy and recycling nutrients (Møller *et al.*, 2023); on the other, considering the so-called “butterfly diagram” provided by the Ellen McArthur Foundation (Ellen McArthur Foundation, 2019), AD is associated with a lower level of circularity. One of the core principles of CE is to maintain resources at their maximum value for as long as possible (Korhonen *et al.*, 2018), whether energy recovery does not imply further use of the materials, thus is limitedly circular. However, as reported in Table 7, KPI_1 allows us to enrich the evaluation by assessing the energetic valorisation capacity of the treatment plant in terms of organic waste, which is 43.99 m^3 CH_4 /ton of waste. On the same line, KPI_3 showed the treatment plant's selfsupporting capacity in terms of heat, evidencing almost the full coverage of heat requirements. Thus, the AD-CHP system showed an efficient production of energy, which is recovered through waste. Considering the recirculation of nutrients, the use of digestate and organic fertilizer evidenced an environmental credit towards the treatment system, with particular attention in terms of Marine Aquatic Ecotoxicity, Abiotic Depletion and CED. Moreover, digestate presents a valuable quantity of nitrogen, in particular of ammonium nitrogen, compared to untreated waste. Thus, KPI_4 evidenced that 21% of nitrogen present in the digestate is recycled or recirculated from the initial waste source. This confirms that the credit evidenced during the LCA analysis is related to the recycling of the nutrients contained in the waste. In conclusion, the present analysis, consisting of the combined use of LCA analysis and circularity indicators, generated mutually consistent and coherent results. LCA and CE indicators entail different but complementary perspectives. LCA identifies and quantifies the potential environmental burden occurring along the life cycle of a product. On the contrary, CE indicators monitor if and how much specific circular practices may increase the overall circularity of a given system (Samani, 2023). Thus, LCA does not directly assess the circularity of a system but can support decision-making and drive circularity implementation in companies (Pena *et al.*, 2021). Ultimately, to avoid the presence of rebound effects within the system a competing but complementary approach is needed (Leipold *et al.*, 2023). Moreover, the boundaries of the system analysed should be evaluated; the symbiotic exchanges occurring inside and outside the cooperative system with its partners in terms of waste allow for to reduction of the overall quantity of waste produced, nor change waste into resources, increasing the circularity of the system. This implies that the evaluation of a system in terms of circularity and sustainability may be affected by the choice of instruments and by the system boundaries adopted. This makes it crucial to conduct case-by-case evaluations. In conclusion, the introduction of circularity principles within its activities supports the company in reducing and reusing the waste produced and received; thus, the cooperative, reduces disposal costs, generates thermal energy for the company itself and creates additional income related to the production of electricity for the national grid, taking advantage by the incentive present at national level for electricity production.

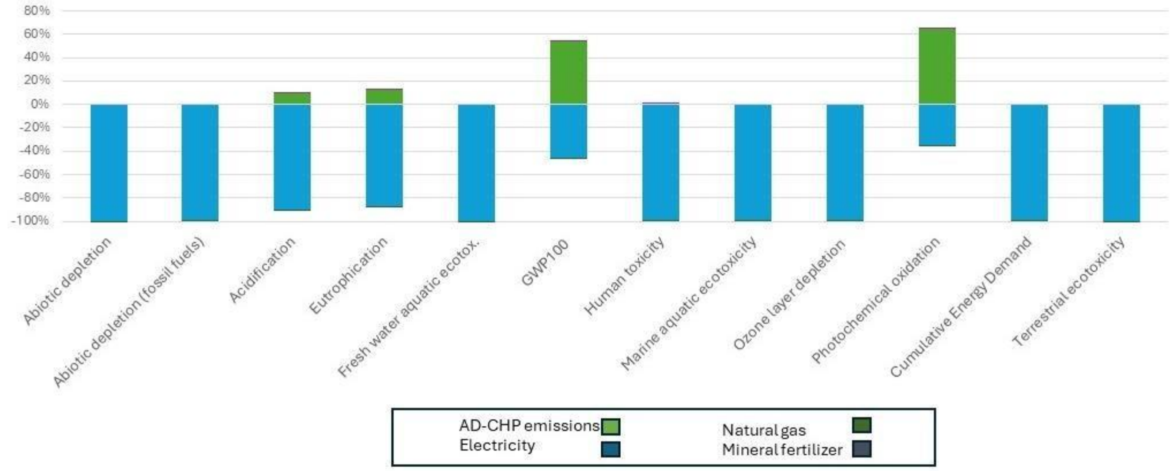

Figure 2. Characterization results per FU

Table 7. Overview of the KPIs measured

KPI$_1$	**KPI$_2$**	**KPI$_3$**	**KPI$_4$**
Biogas efficiency[a]	Energy balance[b]	Self-sustaining capacity[c]	Nitrogen recycling potential[d]
m^3 CH_4 /ton of waste	MJ/MJ	MWh	kg
4.40E+01	1.91E+00	9.75E+01 %	2.10E+01 %

[a] Higher values imply better performance. [b] Lower values imply better performance. [c] Higher values imply better performance. [d] Higher values imply better performance

Conclusion

The present preliminary analysis evidenced the environmental and circularity profile of the AD-CHP plant of the cooperative Fattoria della Piana by adopting a combined approach based on LCA and CE indicators. Circularity does not imply sustainability, so case-by-case evaluations are needed to ensure the sustainability of the circular strategies implemented. In this case, LCA and circularity analysis offered coherent outcomes. Despite being preliminary, the present study proposed an efficient approach that could guide companies of the sector towards circular and sustainable systems. LCA and circularity indicators outcomes are interpreted in a complementary way given that they provide different information, thus integration is not considered at this stage. In this preliminary study, the focus was on environmental sustainability, but CE embraces also economic and social sustainability. Thus, future developments of the study entail the monitoring and assessment of these two aspects Life Cycle Costing and Social-Life Cycle Assessment, completing the assessment with indicators targeted for the AFS. Moreover, future expansion of the study will evaluate all the supply chains of the cooperative. The current lack of unique metrics able to assess the circularity of the food system hampers circularity implementation at the company level and potentially generates greenwashing practices. Such a lack makes it challenging for food companies to include CE principles in their business. Finally, the ISO 59000 series is out, setting definitions, values and metrics to assess circularity, however, the ISO is not sector-specific, thus the path is still long since challenges in tackling the specificities of the food sector remain.

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