SUN Symbiosis Users Network

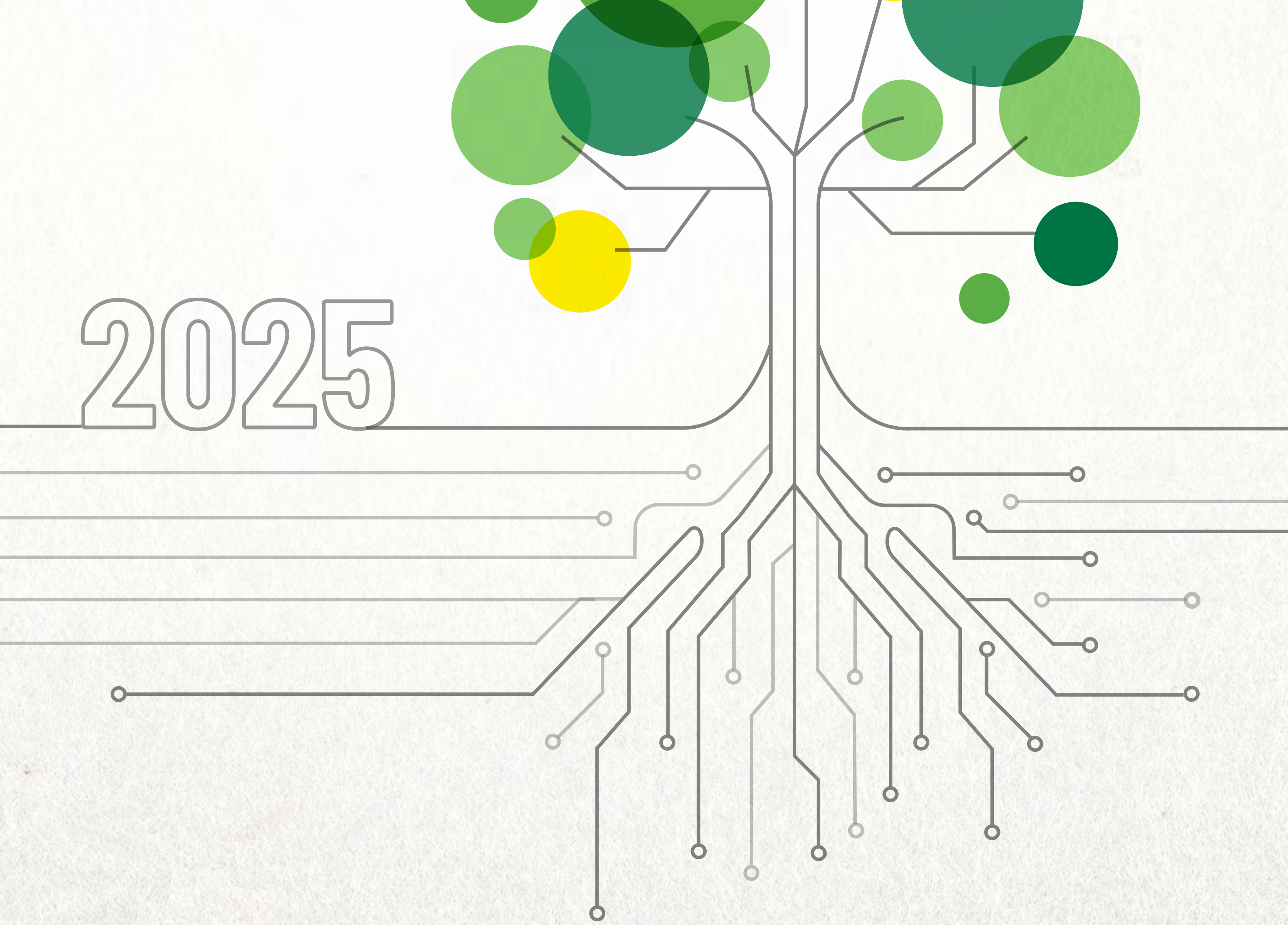
ENEA

INDUSTRIAL SYMBIOSIS IN THE TWIN TRANSITION ERA: a daily tool for systemic competitiveness, innovation and resource efficiency

LA SIMBIOSI INDUSTRIALE NELL'ERA DELLA TRANSIZIONE DIGITALE E VERDE: uno strumento sistemico per la competitività, l'innovazione e l'efficienza delle risorse

Symbiosis Users Network - SUN
Proceedings of the ninth
SUN Conference

November 5th 2025



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Edited by
Tiziana Beltrani and Marco La Monica

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a daily tool for systemic competitiveness,
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November 5th 2025

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National Agency for New Technologies, Energy
and Sustainable Economic Development

Edited by
Tiziana Beltrani and Marco La Monica

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Ecomondo 2025, Rimini – A moment from the SUN Conference

INTRODUCTION

Today, the productive landscape in Italy and Europe is experiencing a significant shift. The twin transition, ecological and digital, is no longer a future scenario; it is the reality that businesses, institutions, and territories must confront daily. Within this framework, industrial symbiosis is emerging as one of the most effective tools available to our country for combining economic competitiveness and environmental sustainability in a systemic way.

The proceedings of the ninth edition of the SUN Conference — Symbiosis Users Network, held on 5 November 2025 at Ecomondo, accurately reflect the vitality of a debate involving researchers, policymakers, entrepreneurs, and institutional representatives. The main idea is simple: industrial symbiosis should not just be a small-scale practice but should work as a key tool to lower environmental harm and boost the strength of production areas while creating value for everyone.

Despite occasional setbacks, the regulatory and programmatic contexts remain favourable. The National Strategy for the Circular Economy, adopted in 2022 and updated in its implementation schedule in March 2025, places industrial symbiosis at the heart of policies aimed at transforming the productive system, with measurable targets in 2035. At the European level, the Green Deal and the Clean Industrial Deal chart a further trajectory: the revival of industrial competitiveness, the decarbonisation of manufacturing processes, and access to energy at competitive prices. The agreement between the Ministry of Environment and Energy Security (MASE) and ENEA, mentioned in these discussions, shows that industrial symbiosis is becoming an important focus for governance, not just a topic for research.

For Italian businesses, adopting symbiosis-based approaches means, above all, reducing procurement and waste management costs while also valuing industrial residues that would otherwise be destined for disposal and improving secure access to raw materials—a particular consideration for critical and strategic resources. The case studies presented (spanning the textile supply chain, the construction sector, green hydrogen, regenerative agriculture, special hospital waste, and the recovery of critical raw materials from lithium batteries) demonstrate that industrial symbiosis cuts across all sectors and business scales. This is not a model reserved for large corporations or well-established industrial districts: projects such as Nodes, Percival, and Symba show how SMEs in both North-Western and Southern Italy can build networks capable of strengthening their structural competitiveness.

A particularly significant element emerging from these proceedings is the enabling role of the digital dimension. The National Meta-Platform for Industrial Symbiosis, currently under development by ENEA and MASE, represents a qualitative leap forward: not merely a matchmaking tool between resource supply and demand, but an infrastructure capable of monitoring the economic and environmental impacts of activated synergies. The digitisation of material flows, through the implementation of digital product passports and traceability systems, makes industrial symbiosis more measurable and transparent, facilitating its integration into corporate decision-making processes and enhancing its attractiveness to investors. At the same time, the development of the hub4ait web-GIS application, also by ENEA, enables a comprehensive and at the same time, the hub4ait web-GIS application developed by ENEA allows for a detailed and analytical mapping of Italy's various industrial systems, looking at not just their basic characteristics but also their industrial metabolism.

Through the SUN Conference, we have observed the growth of this ecosystem of practices and policies over many years. We believe that sharing existing experiences and disseminating knowledge are integral parts of the transition: every company that discovers a nearby success story, every local administrator who grasps the potential of circular eco-districts, and every student who studies industrial symbiosis as a tool for the future represents one piece of a broader transformation. The SUN network, with its multidisciplinary approach and its focus on local territories, continues to prove itself a valuable point of reference along this path.

These proceedings confirm that Italy is not embarking on a new journey. It has the expertise, and the people are already practicing industrial symbiosis with tangible results. What is now needed is to make symbiosis a common practice in management, backed by proper incentives and clear guidelines, along with a governance system that links different local areas. This is the challenge that the SUN community takes up each year, with scientific rigour and a collaborative spirit.

Laura Cutaia

President of SUN, ENEA – Circular Economy Division – Department for Sustainability

Alessandra De Santis

President of Editrice Circolare, *S.c.a.r.l* -EconomiaCircolare.com

INTRODUZIONE

Il panorama produttivo italiano ed europeo oggi si trova davanti a un momento di svolta decisivo. La doppia transizione, ecologica e digitale, non è più uno scenario futuro: è la realtà con cui imprese, istituzioni e territori devono confrontarsi ogni giorno. In questa cornice, la simbiosi industriale si afferma come uno degli strumenti più efficaci a disposizione del nostro Paese per coniugare competitività economica e sostenibilità ambientale in modo sistemico.

Gli atti della nona edizione del Convegno SUN, Symbiosis Users Network, tenutosi il 5 novembre 2025 a Ecomondo, restituiscono con precisione la vivacità di un dibattito che coinvolge ricercatori, policy maker, imprenditori e rappresentanti istituzionali. Il filo conduttore è chiaro: la simbiosi industriale non può essere una pratica di nicchia, ma uno strumento sistemico capace di ridurre l'impatto ambientale e rafforzare la resilienza dei territori produttivi generando valore condiviso.

Nonostante le battute di arresto, il contesto normativo e programmatico continua a essere favorevole. La Strategia Nazionale per l'Economia Circolare, adottata nel 2022 e aggiornata nel suo cronoprogramma nel marzo 2025, pone la simbiosi industriale al centro delle politiche di trasformazione del tessuto produttivo, con obiettivi misurabili fino al 2035. A livello europeo, il Green Deal e il Clean Industrial Deal tracciano una traiettoria ulteriore: il rilancio della competitività industriale, la decarbonizzazione dei processi manifatturieri, l'accesso a energia a prezzi competitivi. L'accordo di collaborazione tra il Ministero dell'Ambiente e della Sicurezza Energetica (MASE) ed ENEA, illustrato in questi atti, rappresenta un segnale concreto di come la simbiosi industriale stia diventando una priorità di governance, non solo un tema di ricerca.

Per le imprese italiane, adottare logiche di simbiosi significa innanzitutto ridurre i costi di approvvigionamento e di gestione dei rifiuti, ma anche valorizzare sottoprodotti altrimenti destinati allo smaltimento e aumentare la sicurezza dell'accesso alle materie prime, aspetto fondamentale soprattutto per quelle critiche. I casi presentati al convegno, dalla filiera tessile al settore delle costruzioni, dall'idrogeno verde all'agricoltura rigenerativa, dai rifiuti speciali ospedalieri al recupero di materie prime critiche dalle batterie al litio, dimostrano che la simbiosi industriale attraversa tutti i settori e tutte le dimensioni di impresa. Non si tratta di un modello riservato alle grandi aziende o ai distretti industriali consolidati: progetti come Nodes, Percival e Symba mostrano come anche le PMI del Nord-Ovest e del Sud possano costruire reti capaci di aumentare la propria competitività strutturale.

Un elemento di particolare rilievo che emerge da questi atti è il ruolo abilitante della dimensione digitale. La Metapiattaforma nazionale per la simbiosi industriale, in corso di sviluppo da parte di ENEA e del MASE, rappresenta un salto qualitativo: non solo uno strumento di "matchmaking" tra domanda e offerta di risorse, ma un'infrastruttura capace di monitorare gli impatti economici e ambientali delle sinergie attivate. La digitalizzazione dei flussi di materiali, grazie all'implementazione del passaporto digitale di prodotto e dei sistemi di tracciabilità rende la simbiosi industriale più misurabile e trasparente, facilitandone l'integrazione nei processi decisionali aziendali e rendendola più attraente per gli investitori. Analogamente, lo sviluppo dell'applicazione web-gis hub4ait, sempre da parte di ENEA, consente di mappare in maniera organica ed analitica i diversi sistemi industriali presenti in Italia, non solo dal punto di vista anagrafico ma anche dal punto di vista, ad es., del loro metabolismo industriale.

Attraverso il convegno SUN osserviamo da anni la crescita di questo ecosistema di pratiche e politiche. La convinzione è che il racconto delle esperienze esistenti e la diffusione della conoscenza siano parte integrante della transizione: ogni impresa che scopre un caso di successo vicino a sé, ogni amministratore locale che comprende il potenziale degli eco-distretti circolari, ogni studente che studia la simbiosi industriale come strumento del futuro, rappresenta un tassello del cambiamento. La rete SUN - con il suo approccio multidisciplinare e l'attenzione ai territori si dimostra un punto di riferimento prezioso in questo percorso.

Questi atti testimoniano che l'Italia non parte da zero. Ha competenze e persone che già praticano la simbiosi industriale con risultati tangibili. Ciò che serve ora è trasformare l'eccezione in norma: fare della simbiosi una prassi gestionale diffusa, sostenuta da incentivi adeguati e standard chiari, con una governance capace di connettere i diversi livelli territoriali. È questa la sfida che la comunità SUN raccoglie ogni anno, con rigore scientifico e spirito collaborativo.

Laura Cutaia

Presidente SUN, ENEA – Divisione Economia Circolare - Dipartimento "Sostenibilità circolarità e adattamento ai cambiamenti climatici dei Sistemi Produttivi e Territoriali"

Alessandra De Santis

Presidente Editrice Circolare *S.c.a.r.l* -EconomiaCircolare.com

Wednesday, 5 November 2025 10.00 – 13.00 Sala Mimosa Hall B6

TITLE: Industrial Symbiosis in the Twin Transition Era: A daily tool for systemic competitiveness, innovation and resource efficiency

Organized by: CTS Ecomondo, ENEA and SUN (Symbiosis Users Network).

CALL FOR PAPERS

The twin transition—ecological and digital—presents significant challenge that industrial symbiosis can effectively address by integrating both paradigms, which are reshaping the global industrial landscape. European and national policies, such as the European Green Deal, the Italian National Strategy for the Circular Economy, and the Draghi Report on revitalizing European industry, all emphasize the importance of creating a favourable environment for resource sharing and optimization of material and energy flows, leveraging technological innovation and investment support. The recent European Clean Industrial Deal provides further momentum, outlining urgent strategies to enhance the competitiveness of European industry against China and the United States while staying on course toward climate neutrality. The plan includes measures to secure access to competitively priced energy, decarbonize manufacturing, and incentivize investment in clean technologies, underscoring the critical role of industrial symbiosis in the transition to a more efficient and sustainable production model.
In this context, the 9th edition of the conference of the Italian Industrial Symbiosis network – Symbiosis Users Network (SUN) offers a value opportunity to explore tools, approaches, and case studies that can help integrate industrial symbiosis into strategies aimed at enhancing Italy's industrial system, making it more efficient, competitive and environmentally sustainable.

Session chairs
Alessandra De Santis, economiacircolare.com
Laura Cutaia, ENEA – SUN Symbiosis Users Network

Programme

10.00 – 10.10 **Introduction by the Chairs**

10.10 – 10.50 **Invited speakers**

Pietro Agrello - Ministry of Environment and Energy Security

Marco Calabrò - Ministry of enterprises and made in Italy

Maria Teresa Monteduro - Ministry of economy and finance

Maria Sabrina De Gobbi - International Labour Office

Claudio Perissinotti Bisoni – UNI

10.50-12.10 Speeches selected from the Call for Papers

La simbiosi industriale nelle megacostellazioni satellitari: un modello circolare per l'economia spaziale emergente

Francesco Ventura- CROWN Group INC.

Smart Leaf – Dalla raccolta intelligente alla circolarità: investimenti sostenibili per le smart city del futuro

Augusto Ferrentino - Smart Leaf S.r.l. - SARIM S.r.l.

CROSSTEX: Cross-sectoral Platform for Sustainable and Circular Textile

Debora Giorgi[1], Claudia Morea[1], Luca Incrocci[1], Matteo Bertelli[1], Maria Rosa Pizzo[2], Pierluca Cattaneo[2] - [1]University of Florence, [2]Italtel S.p.A.

Proposta di metodologia Diagnosi delle Risorse 2.0 e il modello di Eco-distretto Circolare

Tiziana Beltrani, Anna Rita Ceddia, Daniela Claps, Laura Cutaia, Emanuela De Marco, Arianna Dominici Loprieno, Fabio Eboli, Martina Iorio, Marco La Monica, Erika Mancuso, Silvia Sbaffoni, Francesca Testella - ENEA

A survey of industrial symbiosis practices and perceptions in the north-west regions of Italy

Giulia Lippi[1], Matteo Scacchi[2], Ila Stefania Maltese[2], Elena Maggi[2]; Enrica Vesce[1] - [1]University of Turin, [2]University of Insubria

I progetti Nodes e Percival due esempi di incremento della competitività delle imprese Italiane findate sulla simbiosi industriale

Elisa Aimo Boot, Giorgia Pellegrino, Paola Zitella - Environment Park S.p.A.

Mapping Industrial Symbiosis in the Textile Sector: A Data-Driven Network Analysis Using Gephi and R

Reza Vahidzadeh, Marta Domini, Giorgio Bertanza - University of Brescia

A case of industrial symbiosis for the circular and sustainable partial stabilization of hazardous waste

Giuseppe Mancini[1], Antonella Luciano[2], Dalila Bonanno[1], Francesco Palmeri[3], Giuseppe Benina[3], Debora Fino[4] - [1]University of Catania, [2]ENEA, [3]Siram, Cisma Ambiente S.p.A., [4]Polytechnic University of Turin

Simbiosi industriale, SNEC in ottica di sostenibilità: ottimizzazione dei processi produttivi e fundraising per transizioni digitale e verde.

Giovanni Moccia, Antonio Moccia – Centro Studi di Ricerche Economiche e Sociali Mondi Sostenibili.

12.10-12.55 Pitch Case study – Chairs Tiziana Beltrani and Marco La Monica

La simbiosi industriale può essere uno strumento di green marketing? Uno studio empirico su consumatori italiani

Luca Fraccascia[1], Rosa Maria Dangelico[2] - [1]Sapienza University of Rome; [2]Polytechnic University of Bari

La simbiosi industriale nel servizio di lava-noleggio di dispostivi tessili gestione dei rifiuti speciali in ambito ospedaliero

Felicia Ilgrande, Vincenza Poliandri, Daniela Antonioni, Luca Montermini - Intercent-ER Regione Emilia-Romagna

Business transition to industry symbiosis: the manager's perspective

Joanna Kulczycka, Dagmara Lewicka, Monika Pec - AGH University of Krakow, Poland

Da blue a green utility: il percorso delle aziende di gruppo CAP

Michele Falcone - Gruppo CAP

Industrial and rural partnerships underpinned by biomass-based solutions for carbon removal, chemicals, and renewable energy — the NET-Fuels project

D. Chiari[1], R. Soldati[1], S. Righi[1], E. Balugani[1], E. Pigni[1], C. Groves[2], Meiller M. [2], K. Petela[3], M. Proniewicz[3], F. Dargam[4], D. Molognoni[5], M. V. Paredes[5], D. Marazza[1]- [1]University of Bologna, [2]Fraunhofer Umsicht Sulzbach-Rosemberg, [3]Silesian University of Technology, [4]Innovation GmbHRI REACH Innovation, [5]LEITAT Technological Center

Developing industrial symbiosis networks: insights from southern Italy

Gabriella Fiorentino, Amalia Zucaro, Marco La Monica, Tiziana Beltrani, Antonella Luciano, Emanuela De Marco, Laura Cutaia - ENEA

SYMBA: Advancing Industrial Symbiosis for a Sustainable, Circular and Bio-based Europe

Antonietta Pizza[1], Marco de la Feld[1], Mirko Busto[1], Hector David Leiva Ñaupa[2], Abdulaziz Aldureid[3], Lucía González[4], Erica Locatelli[5] - [1]ENCO, [2]CIRCE, [3]AIMPLAS, [4]CETAQUA, [5]ICLEI

Il nuovo Science-Policy Panel su Sostanze Chimiche, Rifiuti e Inquinamento: percorso istitutivo e prospettive future.

Lucilla Baldassarri[1], Diana Corradi[2], Dario D'Angelo[2], Simone Marzeddu[3], Viola Pavoncello[4] -[1]Istituto Superiore di Sanità (ISS); [2]Ministero dell'Ambiente e della Sicurezza Energetica (MASE), [3]Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA), [4]Consiglio Nazionale delle Ricerche (CNR)

Mitigating Critical Raw Materials Supply Risk: A Global Perspective from Automotive Suppliers

Antonio Piepoli[1], Roberta Pellegrino[1], Francesco Arcidiacono[2], Pierpaolo Pontrandolfo[1], Florian Schupp[3] – [1] Polytechnic University of Bari, [2]Schaeffler Automotive Buehl & Co. KG; "Kore" University of Enna, [3]Schaeffler Automotive Buehl & Co. KG; Constructor University di Bremen gGmbH

12.55-13.00 Conclusions

Poster session - Chairs Marco La Monica and Francesca Testella

SUN - P1 *Criteri ambientali minimi nella pubblica amministrazione: implementazione di un modello di sviluppo industriale sostenibile*
Adriano Pistilli[1], Roberto Rana[2] - [1]Freelancer, [2]University of Foggia

SUN - P2 *Manutenere e igienizzare: le nanotecnologie a servizio di una attività quotidiana e conservativa*
Beatrice Carolina Iaia - Biotitan Nanotechnology

SUN - P3 *DIRAC - Innovativo paradigma per l'ottimizzazione energetica degli impianti di produzione e consumo dell'energia elettrica (fotovoltaici, cogeneratori, stazioni di ricarica veicoli elettrici, pubblica illuminazione, etc.) tramite Artificial Intelligence e Internet of Things*
Domenico Scarafile[1], Pietro Serafino[1], Davide Cascella[1], Giovanni Conte[1], Giuseppe Leonardo Cascella[2], Andrea Polichetti[3] - [1]Idea75 S.r.l., [2] Polytechnic University of Bari, [3]Free Energy Saving S.r.l.

SUN - P4 *Hydrogen-Powered Gensets for Electric Vehicle Charging*
Andrea Pivatello - Innio Jenbacher

SUN - P5 *Valorisation of CO_2 waste streams into polyester for a sustainable circular textile industry*
Luigi Ranza - PNO Innovation

SUN - P6 *PYROCO2: Demonstrating sustainable value creation from industrial CO2 by its thermophilic microbial conversion into acetone*
Anna Franciosini, Patrizia Circelli - PNO Innovation

SUN - P7 *ARISE: Ai-based medical swaRm learnIng prototype for SEcurity and analysis optimization on multicentric clinical data*
Domenico Scarafile[1], Davide Cascella[1], Giovanni Conte[1], Massimiliano Chirico[1], Giuseppe Leonardo Cascella[2], Nicola Vernacchia[3], Nadia Vernacchia[3] - [1]Idea75 S.r.l., [2]Polytechnic University of Bari, [3]VET S.r.l.

SUN - P8 *Tubino Rosso: Moda, Sostenibilità e Solidarietà*
Gian Nicola Specchio - AR2 Investment Be Change S.r.l.

SUN - P9 *Drawing Sectoral Symbiotic Profiles: what resources to which sectors?*
Giulia Lippi, Enrica Vesce – University of Turin

SUN - P10 *Models and Strategies for Environmental Emergency Response in a Seveso Framework*
Vitantonio Colucci, Romualdo Marrazzo - ISPRA

SUN - P11 *MAterie CRItiche e NObili (MA.CRI.NO.)*
Michela Reale[1], Nicola Bartucca[2] - [1]Rinnovative S.r.l.; [2]APEA Regionale Cartoneco Rete di Imprese Soggetto

SUN - P12 *Modelli di business circolari e innovazione eco-industriale: il caso POREM nella filiera dell'agricoltura rigenerativa*
Marco La Monica[1], Francesca Ceruti[2], Alice Dall'Ara[3], Alessandra Strafella[1], [1]ENEA, [2]University of Brescia, [3]ADA S.r.l.s.

SUN - P13 *MRA: Mutual Recogniyion Arrangement Pogramma nazionale contro il rischio di greenwashing*
Marta Tosetto - Carbon Footprint Italy S.r.l.

SUN - P14 *Advancing circular construction through innovative bio-based material and digital product passport*
Matteo Giovanardi, Alessandro Pracucci - Levery S.r.l. Società Benefit

SUN - P15 *Produzione di biometano con valorizzazione integrata della CO2*
Jessica Fabro - K-INN Tech S.r.l.

SUN - P16 *People-Driven Digital Transformation in Circular Economy: Lessons from Alia Servizi Ambientali*
Domenico Scamardella, G. Roberto Marseglia, Sonny Masoni, Alberto Irace - Alia Servizi Ambientali S.p.A.

SUN - P17 Studio sull'applicazione della disciplina del sottoprodotto per la simbiosi industriale. La proposta Enea.
Erika Mancuso, Laura Cutaia, Daniela Claps, Martina Iorio - ENEA

SUN - P18 *Dalla Valtiberina un'esperienza di sinergia tra aziende all'insegna della sostenibilità: il Consorzio ecoVprint*
Fabio Fantuzzi - Consorzio ecoVprint

SUN - P19 *Transizione digitale e mobilità sostenibile: il caso studio SFBM S.p.A.*
Manuela Iapaolo –Niccolò Cusano University

SUN – P20 *Dallo scarto siderurgico al cloruro ferrico: un'eccellenza circolare tutta italiana*
Davide Crippa - Altair Chemical S.r.l.

SUN – P21 *Cooperatives and SMEs in the Twin Transition: A Comparative Analysis*
Ginevra Coletti[1 2], Asia Guerreschi[1], Emy Zecca[1] - [1]University of Ferrara, [2]IUSS - School for Advanced Studies of Pavia

SUN - P22 *A circularity indicator in the construction sector*
Ottavio Spadaro[1], Agata Matarazzo[1], Massimo Costanzo[1], Francesco Garraffo[1], Mariusz Sołtysik[2] – [1]University of Catania, [2]Cracow University of Economics, Poland.

SUN – P23 *System Dynamics per la modellizzazione di sistemi eco-industriali: stato dell'arte e prospettive metodologiche*
Veronica Casolani, Alberto Simboli – "Gabriele d'Annunzio" University of Chieti-Pescara

SUN – P24 *Valorizzazione degli scarti industriali: l'Autorizzazione Integrata Ambientale strumento per l'economia circolare in Regione Basilicata.*
Maria Carmela Bruno, Fiorella Messina – Basilicata Region

SUN – P25 *Energy transition in Sicily: the strategic role of green hydrogen between technological innovation and material circularity*
Piero Guadagnino, Valentina Iacono, Federico Ursino, Salvo Mirabella, Agata Matarazzo – University of Catania

SUN – P26 *Upcycling mineral and timber-based waste from construction & manufacturing process industries through eco-design, advanced logistics, quality control and digital solutions*
Sotirios Grammatikos – NTNU Norwegian University of Science and Technology

SUN – P27 *Territorialità e circolarità della filiera ovina*

Raffaella Taddeo[1], Rosa Di Capua[2], Enrico Vagnoni[3], Valentino Tascione[1], Alberto Simboli[1], Andrea Raggi[1], Gianfranco Spizzirri[2], Pietro A. Renzulli[2], Bruno Notarnicola[2], Alessandra Piga[3], Sara Bortolu[3] - [1]"Gabriele d'Annunzio" University of Chieti-Pescara, [2] "Aldo Moro" University of Bari, [3]Consiglio Nazionale delle Ricerche

SUN – P28 *Caratteristiche, criticità e prospettive di circolarità della lana italiana*
Maria Gabriella Iacutone, Raffaella Taddeo, Andrea Raggi - "Gabriele d'Annunzio" University of Chieti-Pescara

SUN – P29 *BioSentinel: Algorithmic Modeling of Financial Risk Linked to Biodiversity Loss?*
Antonio Iuliano - Evoluzione aziendale LAB S.r.l.

SUN – P30 *Analisi prospettica del ciclo di vita della produzione fermentativa di Acido Glutarico da fonti di carbonio riciclate: un caso di simbiosi industriale per un approccio integrato ambientale ed economico*
Maria Ciotti[1,2], Jorge Benavides[1,3], Sara Daniotti[1], Maurizio Bettiga[4] - [1]Consorzio Italbiotec, Chalmers University of Technology, [3]Vela Tech SA, [4]Italbiotec S.r.l. Società Benefit

SUN – P31 *Starchy agro-industrial residues to energy self-sufficiency: a scalable disruptive approach*
Chiara Zanin[1], Rebecca My[1,2], Ameya Pankaj Gupte[1,2,] Lorenzo Favaro[1,2] – [1]University of Padova, [2]Agri-E

SUN – P32 *La sostenibilità per le persone*
Vincenzo Baraniello; Luciano Colantuono; Salvatore Faraci - Terravives S.r.l.

SUN – P33 *Indice composito ragionato sulle terre rare e il loro utilizzo in ambito delle nuove fonti rinnovabili*
Rosalia Ferri - Napoletana Plastica

SUN – P34 New circular strategies to reduce food waste.
Riccardo Pittalà, Chinnici Gaetano, Scuderi Alessandro, Costanzo Massimo Riccardo, Privitera Donatella, Zerbo Antonio, Matarazzo Agata – University of Catania

SUN – P35 *H2 Era Green Valley*
Federico Parma - H2 Era Green Valley

SUN – P36 *Recycling of critical raw materials in lithium-ion batteries: material flow analysis and economic analysis of the Italian industry*
Luca Giaccone[1], Marco La Monica[2], Luca Fraccascia[1,3] – [1]Sapienza University of Rome, [2]ENEA, [3]University di Twente

SUN – P37 *AR2 Investment Be Change S.r.l.*
Gian Nicola Specchio - AR2 Investment Be Change S.r.l.

SUN – P38 *From Circular Economy to Regenerative Agriculture: The Case of POLLINA PAV*
A. Dall'Ara[1], P. Grandini[1], M. Bellomo[2], F. Marianini[3] - [1]ADA S.r.l.s., [2]TAUA S.r.l., [3]Agrofertil Società Cooperativa Agricola

SUN – P39 *Reverse Flow e biometano: il progetto Italgas ad Avetrana*
Regas S.p.A., Italgas S.p.A., SAFE S.p.A.

Mercoledì, 5 novembre 2025 ore 10.00 – 13.00 Sala Mimosa pad.B6

TITOLO: ***La simbiosi industriale nell'era della transizione digitale e verde: uno strumento sistemico per la competitività, l'innovazione e l'efficienza delle risorse***

Organizzato da: CTS Ecomondo, ENEA e SUN (Symbiosis Users Network)

CALL FOR PAPERS

La sfida della doppia transizione, ecologica e digitale, vede nella simbiosi industriale una efficace strategia in grado di integrare entrambi i paradigmi, che stanno ridefinendo il panorama industriale globale. Le politiche europee e nazionali, come il Green Deal, la Strategia Nazionale per l'Economia Circolare (SNEC) e rapporto Draghi sul rilancio dell'industria europea, convergono nella necessità di creare un contesto favorevole alla condivisione delle risorse e all'ottimizzazione dei flussi materiali ed energetici, sfruttando l'innovazione tecnologica e il sostegno agli investimenti. Un ulteriore impulso arriva dal recente Clean Industrial Deal europeo, che definisce strategie urgenti per rilanciare la competitività dell'industria europea rispetto a Cina e Stati Uniti, mantenendo il percorso verso la neutralità climatica. Il piano prevede misure per l'accesso all'energia a prezzi competitivi, la decarbonizzazione del settore manifatturiero e l'incentivazione degli investimenti in tecnologie pulite, evidenziando il ruolo chiave della simbiosi industriale nella transizione verso un modello produttivo più efficiente e sostenibile.

In questo scenario, la IX edizione del Convegno della rete italiana di simbiosi industriale - Symbiosis Users Network (SUN) offre un'importante occasione per approfondire strumenti, approcci e casi studio utili ad integrare la simbiosi industriale in percorsi capaci di rendere il sistema industriale italiano più efficiente, competitivo e a minore impatto ambientale.

Presidenti di sessione

Alessandra De Santis, economiacircolare.com
Laura Cutaia, ENEA - SUN Symbiosis Users Network

Programma

10.00 – 10.10 **Introduzione**

10.10 – 10.50 **Interventi ad invito**

Pietro Agrello - Ministero dell'Ambiente e della Sicurezza Energetica

Marco Calabrò - Ministero delle imprese e del Made in Italy

Maria Teresa Monteduro - Ministero dell'Economie e delle Finanze

Maria Sabrina De Gobbi - International Labour Office

Claudio Perissinotti Bisoni – UNI

10.50-12.10 Presentazioni da call for paper

La simbiosi industriale nelle megacostellazioni satellitari: un modello circolare per l'economia spaziale emergente

Francesco Ventura - CROWN Group INC.

Smart Leaf – Dalla raccolta intelligente alla circolarità: investimenti sostenibili per le smart city del futuro

Augusto Ferrentino - Smart Leaf S.r.l., SARIM S.r.l.

CROSSTEX: Cross-sectoral Platform for Sustainable and Circular Textile

Debora Giorgi1, Claudia Morea1, Luca Incrocci1, Matteo Bertelli1, Maria Rosa Pizzo2, Pierluca Cattaneo2 - 1Università degli Studi di Firenze, 2Italtel S.p.A.

Proposta di metodologia Diagnosi delle Risorse 2.0 e il modello di Eco-distretto Circolare

Tiziana Beltrani, Anna Rita Ceddia, Daniela Claps, Laura Cutaia, Emanuela De Marco, Arianna Dominici Loprieno, Fabio Eboli, Martina Iorio, Marco La Monica, Erika Mancuso, Silvia Sbaffoni, Francesca Testella - ENEA

A survey of industrial symbiosis practices and perceptions in the north-west regions of Italy.

Giulia Lippi[1], Matteo Scacchi[2], Ila Stefania Maltese[2], Elena Maggi[2]; Enrica Vesce[1] - [1]Università degli Studi di Torino, 2Università degli Studi dell'Insubria

I progetti Nodes e Percival due esempi di incremento della competitività delle imprese Italiane fondate sulla simbiosi industriale

Elisa Aimo Boot, Giorgia Pellegrino, Paola Zitella - Environment Park S.p.A.

Mapping Industrial Symbiosis in the Textile Sector: A Data-Driven Network Analysis Using Gephi and R

Reza Vahidzadeh, Marta Domini, Giorgio Bertanza - Università degli Studi di Brescia

A case of industrial symbiosis for the circular and sustainable partial stabilization of hazardous waste

Giuseppe Mancini[1], Antonella Luciano[2], Dalila Bonanno[1], Francesco Palmeri[3], Giuseppe Benina[3], Debora Fino[4] - [1]Università degli Studi di Catania, [2]ENEA, 3Siram, Cisma Ambiente S.p.A., [4]Politecnico di Torino

Simbiosi industriale, SNEC in ottica di sostenibilità: ottimizzazione dei processi produttivi e fundraising per transizioni digitale e verde.

Giovanni Moccia, Antonio Moccia – Centro Studi di Ricerche Economiche e Sociali Mondi Sostenibili.

12.10-12.55 Pitch Casi studio – Coordinatori Tiziana Beltrani e Marco La Monica

La simbiosi industriale può essere uno strumento di green marketing? Uno studio empirico su consumatori italiani

Luca Fraccascia[1], Rosa Maria Dangelico[2] - [1]Sapienza Università di Roma; [2]Politecnico di Bari

La simbiosi industriale nel servizio di lava-noleggio di dispostivi tessili gestione dei rifiuti speciali in ambito ospedaliero

Felicia Ilgrande, Vincenza Poliandri, Daniela Antonioni, Luca Montermini - Intercent-ER Regione Emilia-Romagna

Business transition to industry symbiosis: the manager's perspective

Joanna Kulczycka, Dagmara Lewicka, Monika Pec - Università della Scienza e della Tecnologia di Cracovia, Polonia

Da blue a green utility: il percorso delle aziende di gruppo CAP

Michele Falcone - Gruppo CAP

Industrial and rural partnerships underpinned by biomass-based solutions for carbon removal, chemicals, and renewable energy — the NET-Fuels project

D. Chiari[1], R. Soldati[1], S. Righi[1], E. Balugani[1], E. Pigni[1], C. Groves[2], Meiller M. [2], K. Petela[3], M. Proniewicz[3], F. Dargam[4], D. Molognoni[5], M. V. Paredes[5], D. Marazza[1] - [1]Alma Mater Studiorum Università di Bologna, [2]Fraunhofer Umsicht Sulzbach-Rosemberg, [3]Politecnico della Slesia, [4]Innovation GmbHRI REACH Innovation, [5]LEITAT Technological Center

Developing industrial symbiosis networks: insights from southern Italy

Gabriella Fiorentino, Amalia Zucaro, Marco La Monica, Tiziana Beltrani, Antonella Luciano, Emanuela De Marco, Laura Cutaia - ENEA

SYMBA: Advancing Industrial Symbiosis for a Sustainable, Circular and Bio-based Europe

Antonietta Pizza[1], Marco de la Feld[1], Mirko Busto[1], Hector David Leiva Ñaupa[2], Abdulaziz Aldureid[3], Lucía González[4], Erica Locatelli[5] - [1]ENCO, [2]CIRCE, [3]AIMPLAS, [4]CETAQUA, [5]ICLEI

Il nuovo Science-Policy Panel su Sostanze Chimiche, Rifiuti e Inquinamento: percorso istitutivo e prospettive future.
Lucilla Baldassarri[1], Diana Corradi[2], Dario D'Angelo[2], Simone Marzeddu[3], Viola Pavoncello[4] -[1]Istituto Superiore di Sanità (ISS); [2]Ministero dell'Ambiente e della Sicurezza Energetica (MASE), [3]Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA), [4]Consiglio Nazionale delle Ricerche (CNR)

Mitigating Critical Raw Materials Supply Risk: A Global Perspective from Automotive Suppliers
Antonio Piepoli[1], Roberta Pellegrino[1], Francesco Arcidiacono[2], Pierpaolo Pontrandolfo[1], Florian Schupp[3] – [1]Politecnico di Bari, [2]Schaeffler Automotive Buehl & Co. KG; Università "Kore" di Enna, [3]Schaeffler Automotive Buehl & Co. KG; Constructor University di Brema GmbH

12.55-13.00 Conclusioni

Sessione poster – Coordinatori Marco La Monica e Francesca Testella

SUN - P1 *Criteri ambientali minimi nella pubblica amministrazione: implementazione di un modello di sviluppo industriale sostenibile*
Adriano Pistilli[1], Roberto Rana[2] - [1]Libero Professionista, [2]Università degli Studi di Foggia

SUN - P2 *Manutenere e igienizzare: le nanotecnologie a servizio di una attività quotidiana e conservativa*
Beatrice Carolina Iaia - Biotitan Nanotechnology

SUN - P3 *DIRAC - Innovativo paradigma per l'ottimizzazione energetica degli impianti di produzione e consumo dell'energia elettrica (fotovoltaici, cogeneratori, stazioni di ricarica veicoli elettrici, pubblica illuminazione, etc.) tramite Artificial Intelligence e Internet of Things*
Domenico Scarafile[1], Pietro Serafino[1], Davide Cascella[1], Giovanni Conte[1], Giuseppe Leonardo Cascella[2], Andrea Polichetti[3] - [1]Idea75 S.r.l., [2]Politecnico di Bari, [3]Free Energy Saving S.r.l.

SUN - P4 *Hydrogen-Powered Gensets for Electric Vehicle Charging*
Andrea Pivatello - Innio Jenbacher

SUN - P5 *Valorisation of CO2 waste streams into polyester for a sustainable circular textile industry*
Luigi Ranza - PNO Innovation

SUN - P6 *PYROCO2: Demonstrating sustainable value creation from industrial CO2 by its thermophilic microbial conversion into acetone*
Anna Franciosini, Patrizia Circelli - PNO Innovation

SUN - P7 *ARISE: Ai-based medical swaRm learnIng prototype for SEcurity and analysis optimization on multicentric clinical data*
Domenico Scarafile[1], Davide Cascella[1], Giovanni Conte[1], Massimiliano Chirico[1], Giuseppe Leonardo Cascella[2], Nicola Vernacchia[3], Nadia Vernacchia[3] - [1]Idea75 S.r.l., [2]Politecnico di Bari, [3]VET S.r.l.

SUN - P8 *Tubino Rosso: Moda, Sostenibilità e Solidarietà*
Gian Nicola Specchio - AR2 Investment Be Change S.r.l.

SUN - P9 *Drawing Sectoral Symbiotic Profiles: what resources to which sectors?*
Giulia Lippi, Enrica Vesce – Università degli Studi di Torino

SUN - P10 *Models and Strategies for Environmental Emergency Response in a Seveso Framework*
Vitantonio Colucci, Romualdo Marrazzo - ISPRA

SUN - P11 *MAterie CRItiche e NObili (MA.CRI.NO.)*
Michela Reale[1], Nicola Bartucca[2] - [1]Rinnovative S.r.l.; [2]APEA Regionale Cartoneco Rete di Imprese Soggetto

SUN - P12 *Modelli di business circolari e innovazione eco-industriale: il caso POREM nella filiera dell'agricoltura rigenerativa*
Marco La Monica[1], Francesca Ceruti[2], Alice Dall'Ara[3], Alessandra Strafella[1], [1]ENEA, [2]Università di Brescia, [3]ADA S.r.l.s.

SUN - P13 *MRA: Mutual Recogniyion Arrangement Pogramma nazionale contro il rischio di greenwashing*
Marta Tosetto - Carbon Footprint Italy S.r.l.

SUN - P14 *Advancing circular construction through innovative bio-based material and digital product passport*
Matteo Giovanardi, Alessandro Pracucci - Levery S.r.l. Società Benefit

SUN - P15 *Produzione di biometano con valorizzazione integrata della CO2*
Jessica Fabro - K-INN Tech S.r.l.

SUN - P16 *People-Driven Digital Transformation in Circular Economy: Lessons from Alia Servizi Ambientali*
Domenico Scamardella, G. Roberto Marseglia, Sonny Masoni, Alberto Irace - Alia Servizi Ambientali S.p.A.

SUN - P17 Studio sull'applicazione della disciplina del sottoprodotto per la simbiosi industriale. La proposta Enea.
Erika Mancuso, Laura Cutaia, Daniela Claps, Martina Iorio - ENEA

SUN - P18 *Dalla Valtiberina un'esperienza di sinergia tra aziende all'insegna della sostenibilità: il Consorzio ecoVprint*
Fabio Fantuzzi - Consorzio ecoVprint

SUN - P19 *Transizione digitale e mobilità sostenibile: il caso studio SFBM S.p.A.*
Manuela Iapaolo - Università degli Studi Niccolò Cusano

SUN – P20 *Dallo scarto siderurgico al cloruro ferrico: un'eccellenza circolare tutta italiana*
Davide Crippa - Altair Chemical S.r.l.

SUN – P21 *Cooperatives and SMEs in the Twin Transition: A Comparative Analysis*
Ginevra Coletti[1 2], Asia Guerreschi[1], Emy Zecca[1] - [1]Università degli Studi di Ferrara, [2]Scuola Universitaria Superiore IUSS Pavia

SUN - P22 *A circularity indicator in the construction sector*
Ottavio Spadaro[1], Agata Matarazzo[1], Massimo Costanzo[1], Francesco Garraffo[1], Mariusz Sołtysik[2] – [1]Università di Catania, [2]Università di economia di Cracovia, Polonia.

SUN – P23 *System Dynamics per la modellizzazione di sistemi eco-industriali: stato dell'arte e prospettive metodologiche*
Veronica Casolani, Alberto Simboli - Università degli Studi G. D'Annunzio Chieti-Pescara

SUN – P24 *Valorizzazione degli scarti industriali: l'Autorizzazione Integrata Ambientale strumento per l'economia circolare in Regione Basilicata.*
Maria Carmela Bruno, Fiorella Messina - Regione Basilicata

SUN – P25 *Energy transition in Sicily: the strategic role of green hydrogen between technological innovation and material circularity*
Piero Guadagnino, Valentina Iacono, Federico Ursino, Salvo Mirabella, Agata Matarazzo – Università di Catania

SUN – P26 *Upcycling mineral and timber-based waste from construction & manufacturing process industries through eco-design, advanced logistics, quality control and digital solutions*
Sotirios Grammatikos – NTNU Università Norvegese della Scienza e della Tecnologia

SUN – P27 *Territorialità e circolarità della filiera ovina*
Raffaella Taddeo[1], Rosa Di Capua[2], Enrico Vagnoni[3], Valentino Tascione[1], Alberto Simboli[1], Andrea Raggi[1], Gianfranco Spizzirri[2], Pietro A. Renzulli[2], Bruno Notarnicola[2], Alessandra Piga[3], Sara Bortolu[3] - [1]Università degli Studi "G. d'Annunzio" di Chieti-Pescara, [2]Università degli Studi di Bari Aldo Moro, [3]Consiglio Nazionale delle Ricerche

SUN – P28 *Caratteristiche, criticità e prospettive di circolarità della lana italiana*

Maria Gabriella Iacutone, Raffaella Taddeo, Andrea Raggi - Università degli Studi "G. d'Annunzio" di Chieti-Pescara

SUN – P29 *BioSentinel: Algorithmic Modeling of Financial Risk Linked to Biodiversity Loss?*
Antonio Iuliano - Evoluzione aziendale LAB S.r.l.

SUN – P30 *Analisi prospettica del ciclo di vita della produzione fermentativa di Acido Glutarico da fonti di carbonio riciclate: un caso di simbiosi industriale per un approccio integrato ambientale ed economico*
Maria Ciotti[1,2], Jorge Benavides[1,3], Sara Daniotti[1], Maurizio Bettiga[4] - [1]Consorzio Italbiotec, Università di tecnologia Chalmers, [3]Vela Tech SA, [4]Italbiotec S.r.l. Società Benefit

SUN – P31 *Starchy agro-industrial residues to energy self-sufficiency: a scalable disruptive approach*
Chiara Zanin[1], Rebecca My[1,2], Ameya Pankaj Gupte[1,2,] Lorenzo Favaro[1,2] – [1]Università degli Studi di Padova, [2]Agri-E

SUN – P32 *La sostenibilità per le persone*
Vincenzo Baraniello; Luciano Colantuono; Salvatore Faraci - Terravives S.r.l.

SUN – P33 *Indice composito ragionato sulle terre rare e il loro utilizzo in ambito delle nuove fonti rinnovabili*
Rosalia Ferri - Napoletana Plastica

SUN – P34 New circular strategies to reduce food waste.
Riccardo Pittalà, Chinnici Gaetano, Scuderi Alessandro, Costanzo Massimo Riccardo, Privitera Donatella, Zerbo Antonio, Matarazzo Agata – Università degli Studi di Catania

SUN – P35 *H2 Era Green Valley*
Federico Parma - H2 Era Green Valley

SUN – P36 *Recycling of critical raw materials in lithium-ion batteries: material flow analysis and economic analysis of the Italian industry*
Luca Giaccone[1], Marco La Monica[2], Luca Fraccascia[1,3] – [1]Sapienza Università di Roma, [2]ENEA, [3]Università di Twente

SUN – P37 *AR2 Investment Be Change S.r.l.*
Gian Nicola Specchio - AR2 Investment Be Change S.r.l.

SUN – P38 *From Circular Economy to Regenerative Agriculture: The Case of POLLINA PAV*
A. Dall'Ara[1], P. Grandini[1], M. Bellomo[2], F. Marianini[3] - [1]ADA S.r.l.s., [2]TAUA S.r.l., [3]Agrofertil Società Cooperativa Agricola

SUN – P39 *Reverse Flow e biometano: il progetto Italgas ad Avetrana*
Regas S.p.A., Italgas S.p.A., SAFE S.p.A.

INVITED SPEAKERS

The development of environmental policies for industrial symbiosis in Italy - Pietro Agrello – Ministry of the Environment and Energy Security

Industrial symbiosis has become one of the most prominent themes within national environmental and industrial policy, serving as a concrete lever to enhance sustainability, innovation, and territorial competitiveness. It is fully aligned with the circular economy paradigm, which aims to move beyond the linear model of production and consumption by fostering synergies among businesses, institutions, and local communities. The circular economy goes far beyond waste management; it requires a systemic transformation of the productive and social fabric based on resource efficiency, material regeneration, and cooperation among economic actors. Within this framework, industrial symbiosis plays a strategic role as an engine of innovation and a catalyst for collaborative processes that reduce waste and generate shared value.

The evolution of Italian national circular economy policies

In recent years, the circular economy has become a cornerstone of both Italian and European environmental strategies. A key milestone was the National Recovery and Resilience Plan (NRRP), which dedicates Mission 2 to the ecological transition and includes a specific component on circular economy and sustainable agriculture. In line with the NRRP, the Italian National Strategy for the Circular Economy (NSCE) was approved in 2022. This strategic document sets out general and sector-specific goals, actions, and instruments to accelerate the transition toward sustainable production systems. An implementation roadmap — updated in March 2025 — defines the targets to be achieved by 2035.

The NSCE provides an overarching framework that integrates several operational tools, including:

- Minimum Environmental Criteria (MEC), mandatory for public contracting authorities to guide procurement toward sustainable goods and services. Recent examples include MEC for Roads (Decree of 5 August 2024), MEC for Energy Services for Buildings (Decree of 12 August 2024), MEC for Waste Management (Decree of 7 April 2025), and MEC for Catering and Vending (Decree of 9 April 2025).

- The Ecodesign Working Table, established in November 2024, which promotes a systemic life-cycle approach to products and includes working groups on reuse and repair.
- The national waste traceability system R.E.N.T.RI (Italian Ministry of the Environment and Energy Security Decree No. 59 of 4 April 2023), which enhances the transparency and management of material flows.
- Fiscal incentives supporting recycling and the use of secondary raw materials, such as tax credits for alternatives to single-use plastics (DL 196/2021) and for the use of recovered materials (Law 197/2022).
- Environmental taxation reform, which eliminated an environmentally harmful subsidy (EHS): the reduced VAT rate for landfilling and incineration without energy recovery (Law 207/2024).
- The growing policy focus on industrial symbiosis, formalized through a collaboration agreement between Italian Ministry of the Environment and Energy Security and ENEA.

The Italian Ministry of the Environment and Energy Security-ENEA agreement and the development of industrial symbiosis

To implement the NSCE, Italian Ministry of the Environment and Energy Security signed a collaboration agreement with ENEA under Article 15 of Law 241/1990, aimed at developing regulatory, economic, and technical instruments to support the practical application of industrial symbiosis. The agreement is structured into ten Work Packages designed to create a national infrastructure for industrial symbiosis. Key activities include applying symbiosis principles to regenerate brownfield sites and develop circular eco-districts; designing and implementing a digital meta-platform to match resource, material, and skills supply and demand; analysing and designing incentive mechanisms; developing dedicated standards and certifications; monitoring economic, environmental, and social impacts; and promoting training and capacity building to disseminate a culture of sustainable industrial cooperation.

The digital meta-Platform for industrial symbiosis

The digital meta-platform is one of the most innovative instruments introduced by the NSCE. Its purpose is to facilitate exchanges of resources, monitor the implementation of industrial symbiosis across Italy, and provide insight into the environmental, economic, and social impacts generated. Although several industrial symbiosis platforms already exist in Italy, their functionalities are often fragmented. Developed in collaboration with ENEA, the meta-platform seeks to integrate and enhance these initiatives, creating a dynamic, cooperative system driven by user participation.

Companies, consultants, and platform operators can register, complete resource sheets (detailing origin, use, and valorisation methods), and share best practices validated by an expert panel. All information will be made publicly available through a continuously updated database, acting as an engine of collaboration across diverse industrial sectors. A beta version of the meta-platform is already available on the ENEA website and is entering an advanced development phase, with planned extensions for resource-flow monitoring and interoperability with existing systems.

Conclusions

In the coming months, the Italian Ministry of the Environment and Energy Security and ENEA will begin drafting the National Programme for Industrial Symbiosis, which will provide the policy and operational framework for coordinated implementation in this field. The Programme will define the regulatory and technical tools needed to scale industrial symbiosis practices, the accompanying economic support measures, and the pathways for developing specialised professional skills.

Digitalisation — a cross-cutting pillar of all circular economy policies — remains a key enabler of sustainable growth. The ability to collect, manage, and share information along circular supply chains underpins new product-as-a-service business models and fosters more responsible consumption patterns. In this context, industrial symbiosis emerges not only as a virtuous practice for resource management but also as a structural pillar of ecological and digital transition, strengthening the resilience, innovation capacity, and competitiveness of Italian companies in the European and global arena.

Lo sviluppo delle politiche ambientali per la simbiosi industriale in Italia - Pietro Agrello – Ministero dell'Ambiente e della Sicurezza Energetica

La simbiosi industriale rappresenta oggi uno dei temi di maggiore rilievo nell'ambito delle politiche ambientali e industriali nazionali, in quanto strumento concreto per promuovere sostenibilità, innovazione e competitività territoriale. Essa si inserisce pienamente nel paradigma dell'economia circolare, che mira a superare il modello lineare di produzione e consumo attraverso la valorizzazione delle sinergie tra imprese, istituzioni e territorio. L'economia circolare non riguarda esclusivamente la gestione dei rifiuti, ma implica una trasformazione sistemica del tessuto produttivo e sociale, incentrata sull'efficienza delle risorse, sulla rigenerazione dei materiali e sulla cooperazione tra attori economici. In questo quadro, la simbiosi industriale assume un ruolo strategico come motore di innovazione e come catalizzatore di processi collaborativi che consentono di ridurre gli sprechi e generare valore condiviso.

L'evoluzione delle politiche nazionali per l'economia circolare

Negli ultimi anni, l'economia circolare è diventata un pilastro delle politiche ambientali italiane ed europee. Una tappa fondamentale di questo percorso è rappresentata dal Piano Nazionale di Ripresa e Resilienza (PNRR), che dedica la Missione 2 alla transizione ecologica, includendo una componente specifica per l'economia circolare e l'agricoltura sostenibile. In coerenza con il PNRR, nel 2022 è stata approvata la Strategia Nazionale per l'Economia Circolare (SEC), uno strumento programmatico che definisce obiettivi generali e specifici, azioni e strumenti per accelerare la transizione verso modelli produttivi sostenibili. Alla Strategia è seguito un cronoprogramma di attuazione – aggiornato nel marzo 2025 – che individua i target da raggiungere entro il 2035.

La SEC costituisce una cornice strategica che integra diversi strumenti operativi. Tra questi:

- I Criteri Ambientali Minimi (CAM), obbligatori per le stazioni appaltanti pubbliche, con l'obiettivo di orientare gli acquisti verso beni e servizi sostenibili. Tra i più recenti figurano i CAM Strade (D.M. 5 agosto 2024), i CAM Servizi energetici per edifici (D.M. 12 agosto 2024), i CAM per la gestione dei rifiuti (D.M. 7 aprile 2025) e quelli per il ristoro e distributori automatici (D.M. 9 aprile 2025).

- Il Tavolo Ecodesign, istituito nel novembre 2024, promuove un approccio sistemico al ciclo di vita dei prodotti, includendo gruppi di lavoro su riutilizzo e riparazione.
- Il nuovo sistema di tracciabilità dei rifiuti R.E.N.T.RI (Decreto MASE 4 aprile 2023, n. 59) migliora la gestione e la trasparenza dei flussi di materiali.
- Gli incentivi fiscali a sostegno delle attività di riciclo e utilizzo di materie prime seconde, come il credito d'imposta per prodotti alternativi alle plastiche monouso (DL 196/2021) e quello per l'impiego di materiali recuperati (L. 197/2022).
- La riforma della tassazione ambientale, nell'ambito della quale è stato abolito il sussidio ambientalmente dannoso (SAD) rappresentato dall'IVA agevolata per il conferimento in discarica e per l'incenerimento senza recupero energetico (L. 207/2024).
- Il tema della Simbiosi industriale, nell'ambito della quale è stato stipulato un Accordo di collaborazione tra il Ministero dell'Ambiente e la Sicurezza Energetica (MASE) ed ENEA

L'accordo MASE-ENEA e lo sviluppo della simbiosi industriale

In attuazione della SEC, il MASE ha stipulato con ENEA un accordo di collaborazione ex art. 15 della Legge 241/1990, volto a creare strumenti normativi, economici e tecnici per l'applicazione concreta della simbiosi industriale. L'accordo si articola in dieci Work Package, finalizzati a realizzare un'infrastruttura nazionale a supporto della simbiosi industriale, attraverso l'applicazione dei principi di simbiosi per la rigenerazione delle brown area e la creazione di ecodistretti circolari; la progettazione e implementazione di una metapiattaforma digitale per favorire l'incontro tra domanda e offerta di risorse, materiali e competenze; l'analisi e la definizione di meccanismi incentivanti; lo sviluppo di standard e certificazioni specifiche; il monitoraggio degli impatti economici, ambientali e sociali; la promozione di competenze e formazione per diffondere la cultura della cooperazione industriale sostenibile.

La metapiattaforma digitale per la simbiosi industriale

La metapiattaforma digitale rappresenta uno degli strumenti più innovativi previsti dalla Strategia nazionale per l'economia circolare. Essa nasce con l'obiettivo di facilitare l'incontro tra domanda e offerta di risorse, monitorare lo stato di implementazione della simbiosi industriale in Italia e informare sugli impatti generati in termini ambientali, economici e sociali. Attualmente in Italia esistono diverse piattaforme dedicate alla simbiosi industriale, ma con funzionalità spesso frammentate. La metapiattaforma, sviluppata in collaborazione con ENEA, si propone di integrare e valorizzare queste esperienze, creando un sistema dinamico e cooperativo basato sulla partecipazione attiva degli utenti. Le imprese, i consulenti e i gestori di piattaforme potranno registrarsi, compilare schede informative sulle risorse disponibili o ricercate (specificando origine, uso e modalità di valorizzazione) e condividere buone pratiche validate da un gruppo di esperti. Le informazioni saranno rese pubbliche in un database consultabile e costantemente aggiornato, fungendo da motore di collaborazione tra realtà produttive diverse. La versione beta della metapiattaforma è già disponibile sul sito ENEA (https://metapiattaforma.enea.laserromae.it/) e sta entrando in una fase avanzata di sviluppo, che prevede nuove funzionalità di monitoraggio dei flussi di risorse e interoperabilità con sistemi esistenti.

Prospettive e sviluppi futuri

Nei prossimi mesi, il MASE e l'ENEA avvieranno la redazione del Programma Nazionale per la Simbiosi Industriale, che costituirà il quadro di riferimento per l'attuazione coordinata delle politiche e degli strumenti in materia. Il Programma definirà gli strumenti normativi e tecnici necessari a favorire la diffusione delle pratiche di simbiosi industriale, le misure economiche di supporto e i percorsi di sviluppo delle competenze professionali. La digitalizzazione, elemento trasversale a tutte le politiche di economia circolare, si conferma un fattore abilitante per la crescita sostenibile del Paese. La capacità di raccogliere, gestire e condividere informazioni lungo le catene di approvvigionamento circolari costituisce la base per nuovi modelli di business "product-as-a-service" e per un consumo più consapevole. In questo scenario, la simbiosi industriale emerge non solo come pratica virtuosa di gestione delle risorse, ma come architrave della transizione ecologica e digitale, in grado di rendere le imprese italiane più resilienti, innovative e competitive nel contesto europeo e globale.

Towards a symbiotic industrial model: the role of the Italian Ministry of Enterprises and Made in Italy in the twin transition - Gabriele Scabbia – Ministry of Enterprise and Made in Italy

The Italian Ministry of Enterprises and Made in Italy is firmly committed to advancing an industrial model that brings together innovation, sustainability, and competitiveness. Today, the twin transition — digital and ecological — represents both a strategic challenge for the national production system and a concrete opportunity for growth and renewal across the industrial landscape.

A new industrial vision

Industrial symbiosis stands as one of the pillars of this new vision. It is founded on the idea that businesses should not only strive to reduce their environmental impact but should also cooperate to generate shared value. In a symbiotic system, the waste of one company becomes a resource for another; energy can be exchanged, water reused, and knowledge shared. This is not an abstract notion, but a practical strategy of collaboration built on trust, integration, and collective intelligence.

In this sense, symbiosis means creating territorial and industrial networks in which companies, institutions, and local communities share material resources, energy, and expertise. This approach not only reduces environmental impact but also reinforces business competitiveness by improving production efficiency, resilience, and innovation capacity. Increasingly, competitiveness is measured by the ability to integrate technology, sustainability, and cooperation.

Italian Ministry of Enterprises and Made in Italy's role in the twin transition

The Italian Ministry of Enterprises and Made in Italy supports the transformation of the production system along two main lines:

- Incentive measures to encourage investment and the adoption of digital and energy-efficient technologies.
- Cultural transformation to promote a new industrial vision grounded in sustainability, innovation, and shared responsibility.

In this framework, the Italian Ministry of Enterprises and Made in Italy coordinates a network of 50 active entities, funded with approximately 350 million euros from the National Recovery and Resilience Plan (NRRP), that support companies in their digitalization and sustainability efforts. The objective is to foster a more aware and capable production ecosystem, where the transition is viewed not as a constraint but as an opportunity for growth.

The Transition 5.0 Plan

Among the Ministry's most significant initiatives is the Transition 5.0 Plan, the natural evolution of the previous Industry 4.0 framework. The Plan integrates technological innovation, energy efficiency, and environmental sustainability in a synergistic way, offering a concrete response to the demands of the twin transition.

In recent months, there has been a remarkable surge in demand from Italian companies for digital and energy-transition measures. In just a few days, both Transition 5.0 and the 4.0 Plan experienced unprecedented acceleration.

In early November, the resources allocated to Transition 5.0 were fully booked, reaching over 3 billion euros in reservations. Soon after, the 4.0 Plan also saw a rapid increase, quickly reaching its ceiling of 2.2 billion euros.

These figures clearly demonstrate the confidence of Italian companies in the technological and energy transition and their need for stability and continuity — a need to which the Ministry's actions directly respond.

They also confirm that businesses have fully embraced the logic of the measures: investing in digital technologies to innovate, reduce energy consumption, and enhance competitiveness.

The Transition 5.0 Plan consolidates Italy's commitment to a modern industrial policy capable of combining productivity with sustainability. The new incentive framework, included in the 2026 Budget Law, will ensure continuity beyond 2025 and introduces several key elements, including:

- The introduction of hyper-depreciation, replacing the tax credit, to simplify and streamline procedures;
- Increased rates of up to 40% for companies achieving significant reductions in energy consumption;
- Stronger integration between digitalization and energy efficiency, reinforcing the link between innovation and sustainability.

The result is a unified instrument designed to tackle the digital and environmental transitions in a coordinated manner, fostering a more efficient, circular, and resilient industrial system.

Conclusions

The ecological and digital transition is not an obstacle, but an opportunity to strengthen the competitiveness of the national production system. Italian Ministry of Enterprises and Made in Italy's policies aim to foster a profound cultural shift: investing in sustainable innovation is not only an ethical choice but a winning economic strategy.

By promoting industrial symbiosis, the Ministry seeks to consolidate a Made in Italy model that integrates environment, industry, and technology. Only through a collaborative and circular approach can we build a modern, competitive, and sustainable production system capable of driving the transition toward a more equitable and regenerative economy.

Verso un'industria simbiotica: il ruolo del MIMIT nella doppia transizione - Gabriele Scabbia – Ministero delle Imprese e del Made in Italy

Il Ministero delle Imprese e del Made in Italy (MIMIT) partecipa con convinzione al percorso verso un modello industriale capace di coniugare innovazione, sostenibilità e competitività. La doppia transizione – digitale ed ecologica – rappresenta oggi una sfida strategica per il sistema produttivo nazionale, ma anche un'opportunità concreta di crescita e di rinnovamento del tessuto industriale.

Una nuova visione industriale

La simbiosi industriale costituisce uno dei pilastri di questa nuova visione. Essa si fonda sull'idea che le imprese non debbano limitarsi a ridurre il proprio impatto ambientale, ma possano cooperare per creare valore condiviso. In un contesto simbiotico, i rifiuti di un'impresa diventano risorse per un'altra, l'energia viene scambiata, l'acqua riutilizzata e le informazioni condivise. Non si tratta di un concetto astratto, ma di una concreta strategia di collaborazione fondata su fiducia, integrazione e intelligenza collettiva.

Simbiosi, in questo senso, significa costruire reti territoriali e industriali in cui imprese, istituzioni e comunità locali condividono risorse materiali, energetiche e conoscenze. Tale approccio non solo consente di ridurre l'impatto ambientale, ma rafforza la competitività delle aziende, favorendo l'efficienza produttiva, la resilienza e la capacità di innovazione. La competitività contemporanea si misura sempre più nella capacità di unire tecnologia, sostenibilità e cooperazione.

Il ruolo del MIMIT nella doppia transizione

Il Ministero delle Imprese e del Made in Italy accompagna la trasformazione del sistema produttivo lungo due direttrici principali:

1. Misure incentivanti, volte a sostenere gli investimenti e l'adozione di tecnologie digitali ed efficienti dal punto di vista energetico.

2. Cambiamento culturale, necessario per diffondere una nuova visione industriale fondata su sostenibilità, innovazione e responsabilità condivisa.

In questa prospettiva, il MIMIT coordina una rete di 50 soggetti attivi, finanziata con circa 350 milioni di euro del PNRR, che supporta le imprese nel percorso di digitalizzazione e sostenibilità. L'obiettivo è creare un ecosistema produttivo più consapevole, in cui la transizione non venga percepita come un vincolo, ma come un'opportunità di crescita.

Il Piano Transizione 5.0

Tra gli strumenti più significativi promossi dal Ministero figura il Piano Transizione 5.0, evoluzione naturale del precedente Industria 4.0. Il Piano integra in modo sinergico innovazione tecnologica, efficienza energetica e sostenibilità ambientale, offrendo una risposta concreta alle esigenze della duplice transizione.

Negli ultimi mesi si è registrato un fenomeno di grande rilievo: la domanda delle imprese italiane verso la transizione digitale ed energetica è cresciuta in modo esponenziale. In pochi giorni le misure Transizione 5.0 e Piano 4.0 hanno subito un'accelerazione senza precedenti.

Nella prima settimana di novembre è stato comunicato l'esaurimento delle risorse disponibili per Transizione 5.0, con prenotazioni che hanno raggiunto l'obiettivo di oltre 3 miliardi di euro. A seguire, si è verificata una forte accelerazione anche sul Piano 4.0, che ha rapidamente raggiunto il tetto di 2,2 miliardi.

Questi dati evidenziano in modo inequivocabile la fiducia delle imprese italiane nella transizione tecnologica ed energetica e la loro richiesta di stabilità e continuità. La risposta offerta va esattamente in questa direzione.

Le cifre confermano inoltre come le aziende abbiano compreso appieno la logica delle misure: investire in tecnologie digitali per innovare, ridurre i consumi energetici e aumentare la competitività.

Il Piano Transizione 5.0 consolida l'impegno verso una politica industriale moderna, in grado di coniugare produttività e sostenibilità. Il nuovo schema di incentivi, previsto dalla Legge di Bilancio 2026, garantirà continuità al programma anche oltre il 2025, introducendo elementi di rilievo tra i quali:

- l'introduzione dell'iper-ammortamento in sostituzione del credito d'imposta, con l'obiettivo di semplificare e rendere più flessibili le procedure;
- aliquote incrementate fino al 40% per le imprese che conseguono riduzioni significative dei consumi energetici;
- una maggiore integrazione tra digitalizzazione ed efficientamento energetico, a rafforzamento del legame tra innovazione e sostenibilità.

Si configura, in definitiva, un unico strumento pensato per affrontare in modo coordinato la duplice transizione, digitale e ambientale, promuovendo un sistema industriale più efficiente, circolare e resiliente.

Conclusioni

La transizione ecologica e digitale non rappresenta un ostacolo, ma un'occasione per rilanciare la competitività del sistema produttivo nazionale. Le politiche del MIMIT mirano a favorire un cambio di cultura: investire in innovazione sostenibile non è soltanto una scelta etica, ma anche una strategia economica vincente.

Attraverso la promozione della simbiosi industriale, il Ministero intende consolidare un modello di Made in Italy capace di integrare ambiente, industria e tecnologia. Solo grazie a un approccio collaborativo e circolare sarà possibile costruire un sistema produttivo moderno, competitivo e sostenibile, in grado di guidare la transizione verso un'economia più equa e rigenerativa.

The role of fiscal policy in supporting industrial symbiosis - Maria Teresa Monteduro – Italian Ministry of Economy and Finance

The ongoing ecological and digital transition represents a transformational challenge that calls for careful reflection on economic policy and on the fiscal instruments required to guide companies toward more sustainable and collaborative production models. In this context, industrial symbiosis stands out as a key strategy for combining environmental sustainability, resilience, and competitiveness by fostering cooperation among firms through the efficient exchange of resources, energy, infrastructure, and knowledge.

Fiscal policy as a driver of transition

Tax incentives play a decisive role in stimulating innovation and encouraging the adoption of industrial symbiosis practices, provided they are well designed and aligned with sustainability objectives. These measures can help reduce operating costs, enhance firms' adaptive capacity, and accelerate the shift toward more sustainable production systems.

International experience offers valuable examples of effective fiscal policy. The well-known case of Kalundborg in Denmark—often cited as the global benchmark for industrial symbiosis—demonstrates how collaboration among businesses, local authorities, and the community can create an integrated system for reusing and repurposing resources, supported by favourable public policies.

In Italy, one of the most significant initiatives is the Industry 5.0 tax credit, which broadens previous incentives focused on digitalisation and now directs them toward environmental sustainability and production resilience. The new regulatory framework provides enhanced tax deductions for firms investing in sustainable technologies and processes, aiming to balance competitiveness with the need to reduce environmental impact. However, as with any innovative measure, early implementation may involve high administrative costs and access barriers that limit full take-up, particularly among small and medium-sized enterprises.

Opportunities for regions and businesses

Another important incentive is the tax credit for the Single Special Economic Zone (Single SEZ), designed to concentrate economic activities and promote territorial synergies. The SEZ tax credit—which can be combined with other incentives—supports the development of shared infrastructure and facilitates the creation of cooperative industrial ecosystems, especially in Southern Italy. This measure not only fosters local development but also contributes to reducing territorial disparities by encouraging new firms to locate in disadvantaged areas.

The latest Budget Bill also introduces a new deductible-base mechanism inspired by the former hyper-depreciation scheme, featuring a declining surcharge on amortisable costs as investment levels rise. Backed by €4 billion in resources, the measure includes maximum thresholds to encourage SME participation and introduces a specific bonus for environmental investments, marking a step toward a more equitable and sustainability-oriented incentive framework.

Toward a system of collaborative incentives

Despite the progress achieved, a crucial question remains: do current fiscal instruments genuinely reward collaboration, or are they still largely focused on the performance of individual firms? Most existing policies tend to incentivise the results of single economic operators, overlooking the shared forms of innovation that are fundamental to industrial symbiosis.

A rethinking of fiscal incentive design is therefore needed—one that places greater emphasis on inter-firm cooperation, resource sharing, and the strengthening of business networks. Such an approach would promote more resilient and sustainable production models, in line with the European strategy for climate neutrality and with the principles of the circular economy.

Another important aspect is ensuring that incentives are accessible and inclusive, with adequate technical assistance and support tools to facilitate participation, particularly for smaller companies. Support policies should incorporate mechanisms for pooling resources and collaborative platforms that make it easier to engage in joint projects, thereby expanding the reach and effectiveness of fiscal measures.

Conclusions

The challenge of the coming years will be to transform the industrial system into an ecosystem where collaboration becomes the rule rather than the exception. Fiscal incentives must evolve from instruments that reward individual performance to strategic levers that promote collective innovation, supporting not only those who invest but, above all, those who innovate together.

Only through an integrated approach—combining targeted fiscal policies, effective governance tools, and cooperative models among businesses and territories—will it be possible to accelerate the transition toward a truly circular, competitive, and sustainable economy.

Il ruolo della leva fiscale a supporto della simbiosi industriale - Maria Teresa Monteduro – Ministero dell'Economie e delle Finanze

La transizione ecologica e digitale in corso rappresenta una sfida epocale che impone una profonda riflessione sulle politiche economiche e sugli strumenti fiscali necessari per accompagnare le imprese verso modelli produttivi più sostenibili e collaborativi. In questo quadro, la simbiosi industriale si configura come una strategia chiave per coniugare sostenibilità ambientale, resilienza e competitività, promuovendo la cooperazione tra imprese attraverso lo scambio efficiente di risorse, energia, infrastrutture e conoscenze.

La leva fiscale come strumento di transizione

Gli incentivi fiscali rappresentano una leva determinante per stimolare l'innovazione e favorire la diffusione di pratiche di simbiosi industriale, a condizione che siano ben progettati e coerenti con gli obiettivi di sostenibilità. Possono infatti contribuire a ridurre i costi operativi, rafforzare la capacità di adattamento delle imprese e accelerare la trasformazione dei modelli produttivi.

L'esperienza internazionale mostra esempi significativi di politiche fiscali efficaci. Emblematico è il caso di Kalundborg, in Danimarca, spesso considerato il modello di riferimento per la simbiosi industriale, dove la collaborazione tra imprese, enti locali e comunità ha permesso di creare un sistema integrato di riuso e valorizzazione delle risorse, sostenuto anche da politiche pubbliche favorevoli.

In Italia, una delle iniziative più rilevanti è il credito d'imposta per Industria 5.0, che amplia i precedenti incentivi legati alla digitalizzazione, indirizzandoli ora verso obiettivi di sostenibilità ambientale e resilienza produttiva. Il nuovo impianto normativo prevede deduzioni fiscali potenziate per le imprese che investono in tecnologie e processi sostenibili, cercando di bilanciare le esigenze di competitività con la necessità di ridurre l'impatto ambientale. Tuttavia, come per ogni strumento innovativo, le fasi iniziali possono presentare costi amministrativi elevati e difficoltà di accesso che limitano la piena fruizione del beneficio, soprattutto per le piccole e medie imprese.

Le opportunità per i territori e le imprese

Un altro incentivo significativo è il credito di imposta per la Zona Economica Speciale (ZES) Unica, disegnato per favorire la concentrazione di attività economiche e promuovere sinergie territoriali. Il credito d'imposta ZES, cumulabile con altri incentivi, può sostenere lo sviluppo di infrastrutture condivise e agevolare la creazione di ecosistemi industriali cooperativi, soprattutto nel Mezzogiorno. Tale misura contribuisce non solo alla crescita locale, ma anche alla riduzione delle disuguaglianze territoriali, incentivando la localizzazione di nuove imprese in aree svantaggiate.

Il disegno di legge di Bilancio più recente ha inoltre introdotto un nuovo meccanismo di deduzione dall'imponibile, ispirato ai principi dell'iperammortamento, che prevede una maggiorazione decrescente del costo ammortizzabile all'aumentare dell'investimento. Questa impostazione, accompagnata da tetti massimi per favorire la partecipazione delle PMI, dispone di risorse pari a 4 miliardi di euro e introduce una premialità specifica per gli investimenti ambientali, segnando un passo avanti verso un sistema di incentivi più equo e orientato alla sostenibilità.

Verso un sistema di incentivi collaborativi

Nonostante i progressi compiuti, resta aperta una questione cruciale: gli strumenti fiscali attuali premiano realmente la collaborazione o si concentrano ancora sulla performance individuale delle imprese? La maggior parte delle politiche finora adottate tende a valorizzare i risultati dei singoli operatori economici, trascurando le forme di innovazione condivisa che sono alla base della simbiosi industriale.

È quindi necessario un ripensamento del disegno degli incentivi fiscali, orientandoli maggiormente verso la cooperazione interaziendale, la condivisione delle risorse e la valorizzazione delle reti di impresa. Questo approccio consentirebbe di promuovere modelli produttivi più resilienti e sostenibili, in linea con la strategia europea per la neutralità climatica e con i principi dell'economia circolare.

Un altro aspetto da considerare è l'esigenza di rendere gli incentivi più accessibili e inclusivi, garantendo assistenza tecnica e strumenti di accompagnamento che facilitino l'adesione delle imprese, in particolare quelle di piccole dimensioni. Le politiche di sostegno dovrebbero prevedere meccanismi di mutualizzazione delle risorse e piattaforme collaborative in grado di favorire la partecipazione a progetti congiunti, ampliando così la portata e l'efficacia delle misure fiscali.

Conclusioni

La sfida dei prossimi anni sarà quella di trasformare il sistema industriale in un ecosistema in cui la collaborazione diventi la norma e non più l'eccezione. Gli incentivi fiscali dovranno evolversi da meri strumenti di premialità individuale a leve strategiche per l'innovazione collettiva, capaci di sostenere non solo chi investe, ma soprattutto chi innova insieme.

Solo attraverso un approccio integrato, che combini politiche fiscali mirate, strumenti di governance efficaci e modelli di cooperazione tra imprese e territori, sarà possibile accelerare la transizione verso un'economia realmente circolare, competitiva e sostenibile.

Industrial symbiosis and its employment effects in developing countries - Maria Sabrina De Gobbi – International Labour Office

Industrial symbiosis is one of the most effective strategies for advancing the transition toward a circular economy, enhancing resource efficiency, and reducing environmental impacts. However, its implications for labour markets remain insufficiently explored, particularly in developing countries. Against this backdrop, the International Labour Organization (ILO) conducted a research project between 2021 and 2024 to assess the quantitative and qualitative employment effects of industrial symbiosis (De Gobbi, 2024). The study contributes to the broader framework of the 2030 Agenda for Sustainable Development, particularly Sustainable Development Goal (SDG) 8 ("Decent work and economic growth") and SDG 12 ("Responsible consumption and production").

Research objectives and methodology

The project covered six countries: Argentina, Benin, Colombia, Costa Rica, South Africa, and Tanzania. A simplified operational definition of industrial symbiosis was adopted to facilitate the identification of relevant networks: industrial symbiosis occurs when the by-products or waste materials of one enterprise are used as productive inputs by another.

Two complementary methodological approaches were employed to evaluate employment impacts:

- the method developed by Martin & Harris (2018), used to quantify the number of direct jobs created or maintained;
- the model by Abriata & Masut (2021), used to estimate indirect and induced employment effects along the value chain through input-output analysis.

The research relied on primary data collected through structured questionnaires and interviews with entrepreneurs, workers, and local experts, as well as secondary sources such as censuses, enterprise surveys, and national sector studies.

Key findings

Examples of industrial symbiosis networks. One of the most illustrative case studies emerged in Colombia, where three firms—two agricultural exporters of flowers and one manufacturing company—established a network for exchanging discarded plastic materials. The agricultural enterprises supply unusable plastic panels to the manufacturing firm, which regenerates and repurposes them into new panels or remunerates the providers financially. This network generated 30 new jobs and maintained an additional 14, highlighting the potential of industrial symbiosis to create local employment and foster new economic linkages.

Quantitative employment effects. The quantitative assessment involved 35 enterprises in Benin, Colombia, Costa Rica, and Tanzania, primarily in the agricultural and agri-food sectors. Results show a median employment increase of 1.1% in large firms, while small and medium-sized enterprises (SMEs) experienced substantially higher growth, averaging 30%. Value chain analyses in Argentina and South Africa also revealed positive indirect and induced effects, with a minimum overall employment impact of 19%. A noteworthy outcome is the emergence of new microenterprises providing consulting, logistics, and material treatment services: one in Colombia, four in Costa Rica, and seven in Tanzania. This demonstrates that industrial symbiosis can also act as a catalyst for local entrepreneurship and the creation of new occupations.

Quality of employment. Job quality varied significantly according to enterprise size. In large firms, industrial symbiosis generated formal and stable positions aligned with ILO decent work standards. Conversely, in SMEs and microenterprises, new jobs were often temporary or informal, reflecting the structural characteristics of local labour markets. From a gender perspective, most new positions were filled by men, especially in manufacturing and agricultural activities where female participation has historically been lower. However, women were more represented in research, innovation, and flexible service roles, which tend to offer better work–life balance.

Policy recommendations

The analysis highlights several key policy recommendations to enhance the positive employment and sustainability effects of industrial symbiosis:

- Develop national strategies specifically targeting the circular economy and industrial symbiosis, ensuring alignment with broader sustainable development policies.
- Introduce economic and fiscal incentives for enterprises adopting symbiotic practices, facilitating investments in technologies for by-product and waste processing.
- Promote active labour market policies to increase women's participation, particularly in manufacturing and environmental sectors.
- Strengthen information systems and data collection on industrial symbiosis networks to monitor economic, environmental, and employment impacts.

- Engage public institutions and social partners—employers and trade unions—in promoting a culture of recycling and waste valorisation, which is essential for the widespread adoption of sustainable and competitive practices.

Conclusions

The ILO's research shows that industrial symbiosis, beyond being a cornerstone of the circular economy, can significantly contribute to the creation of decent work, the growth of SMEs, and the development of new skills. To ensure these benefits are sustained over time, it is crucial to integrate industrial symbiosis policies with labour market and vocational training strategies, while fostering a systemic approach that combines environmental sustainability, social inclusion, and economic competitiveness.

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La simbiosi industriale e i suoi effetti occupazionali nei Paesi in via di sviluppo - Maria Sabrina De Gobbi – International Labour Office

La simbiosi industriale rappresenta una delle strategie più efficaci per promuovere la transizione verso un'economia circolare, migliorando l'efficienza delle risorse e riducendo gli impatti ambientali. Tuttavia, gli effetti di queste pratiche sul mercato del lavoro restano ancora poco esplorati, in particolare nei Paesi in via di sviluppo. In tale contesto, l'Organizzazione Internazionale del Lavoro (ILO) ha condotto tra il 2021 e il 2024 un progetto di ricerca volto ad analizzare gli effetti quantitativi e qualitativi della simbiosi industriale sull'occupazione (De Gobbi, 2024). Lo studio si inserisce nel quadro degli Obiettivi di Sviluppo Sostenibile dell'Agenda 2030, in particolare l'Obiettivo 8 ("Lavoro dignitoso e crescita economica") e l'Obiettivo 12 ("Consumo e produzione responsabili").

Obiettivi e metodologia della ricerca

Il progetto ha interessato sei Paesi: Argentina, Benin, Colombia, Costa Rica, Sudafrica e Tanzania. La definizione operativa di simbiosi industriale adottata è stata volutamente semplificata per facilitare l'individuazione delle reti da analizzare: la simbiosi industriale si verifica quando i sottoprodotti o i rifiuti di un'impresa vengono utilizzati come input produttivi da un'altra impresa.

Per valutare l'impatto occupazionale sono stati applicati due approcci metodologici complementari:

- il metodo elaborato da Martin & Harris (2018), utilizzato per quantificare i posti di lavoro diretti creati o mantenuti;
- il modello sviluppato da Abriata & Masut (2021), adottato per stimare anche gli effetti indiretti e indotti lungo la catena del valore, basato sull'analisi delle tabelle input-output.

La ricerca si è avvalsa di dati primari, raccolti tramite questionari strutturati e interviste a imprenditori, lavoratori ed esperti locali, e di fonti secondarie, tra cui censimenti, indagini d'impresa e studi di settore nazionali.

Risultati principali

Esempi di reti di simbiosi industriale. Uno dei casi studio più significativi è stato rilevato in Colombia, dove tre imprese – due agricole specializzate nell'esportazione di fiori e una manifatturiera – hanno dato vita a una rete di scambio di materiali plastici dismessi. Le due aziende agricole forniscono all'impresa manifatturiera i pannelli di plastica non più utilizzabili, che vengono rigenerati e riutilizzati come nuovi pannelli o remunerati economicamente. In questa rete, la simbiosi industriale ha generato 30 nuovi posti di lavoro e ne ha mantenuti 14, dimostrando la capacità di tali pratiche di generare occupazione locale e stimolare nuove relazioni economiche.

Effetti quantitativi sull'occupazione. La valutazione quantitativa è stata condotta su 35 imprese distribuite in Benin, Colombia, Costa Rica e Tanzania, appartenenti prevalentemente ai settori agricolo e agroalimentare. I risultati mostrano un incremento mediano dell'1,1% dei posti di lavoro nelle grandi imprese e un impatto molto più marcato nelle piccole e medie imprese (PMI), dove la crescita occupazionale raggiunge in media il 30%. L'analisi delle catene di valore in Argentina e Sudafrica ha evidenziato inoltre effetti indiretti e indotti positivi, con un impatto minimo del 19% sull'occupazione complessiva. Un risultato rilevante è la nascita di nuove microimprese legate ai servizi di consulenza, logistica e trattamento dei materiali: una in Colombia, quattro in Costa Rica e sette in Tanzania. Ciò dimostra come la simbiosi industriale possa agire anche come catalizzatore di imprenditorialità locale e di nuove forme di occupazione.

Qualità dell'occupazione. La qualità dei posti di lavoro creati varia sensibilmente in base alla dimensione delle imprese coinvolte. Nelle grandi imprese, la simbiosi industriale ha generato occupazione formale e stabile, in linea con gli standard di lavoro dignitoso promossi dall'ILO. Al contrario, nelle PMI e microimprese i nuovi impieghi risultano spesso temporanei o informali, riflettendo le caratteristiche strutturali dei mercati del lavoro locali. Dal punto di vista di genere, la maggior parte delle posizioni create è stata occupata da uomini, soprattutto nei settori manifatturiero e agricolo, dove la presenza femminile è tradizionalmente minore. Tuttavia, le donne tendono a essere maggiormente impiegate in attività di ricerca, innovazione e servizi flessibili, che consentono una migliore conciliazione tra vita lavorativa e familiare.

Raccomandazioni di policy

Dall'analisi emergono alcune raccomandazioni chiave per potenziare l'impatto positivo della simbiosi industriale sull'occupazione e sulla sostenibilità:

1. Definire strategie nazionali specifiche per l'economia circolare e la simbiosi industriale, assicurando coerenza con le politiche di sviluppo sostenibile.
2. Introdurre incentivi economici e fiscali per le imprese che adottano pratiche simbiotiche, facilitando gli investimenti in tecnologie per il trattamento dei sottoprodotti e dei rifiuti.

3. Promuovere politiche attive del lavoro volte ad aumentare la partecipazione femminile, soprattutto nei settori manifatturiero e ambientale.
4. Rafforzare i sistemi informativi e la raccolta di dati sulle reti di simbiosi industriale, al fine di monitorarne gli impatti economici, ambientali e occupazionali.
5. Coinvolgere istituzioni pubbliche e parti sociali – datori di lavoro e sindacati – nella promozione di una cultura del riciclo e della valorizzazione dei rifiuti, elemento cruciale per la diffusione di pratiche sostenibili e competitive.

Conclusioni

La ricerca dell'ILO evidenzia come la simbiosi industriale, oltre a rappresentare un pilastro dell'economia circolare, possa contribuire in modo significativo alla creazione di lavoro dignitoso, alla crescita delle PMI e allo sviluppo di nuove competenze. Perché questi benefici si consolidino nel tempo, è essenziale integrare le politiche di simbiosi industriale con quelle del mercato del lavoro e della formazione professionale, promuovendo al contempo una visione sistemica che unisca sostenibilità ambientale, inclusione sociale e competitività economica.

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Standardization for Industrial Symbiosis - Claudio Perissinotti Bisoni – UNI (Italian Standards Body)

In recent years, industrial symbiosis has become a central pillar of European strategies supporting the transition towards a circular economy. In this context, technical standardization plays a key role in facilitating the uptake and scalability of symbiosis practices, promoting integration among businesses, territories, and public policies. UNI's activities—conducted in coordination with European and international standardization bodies (CEN, ISO)—aim to translate research and innovation outcomes into shared technical references that can be readily adopted by the market.

European initiatives for the standardization of industrial symbiosis

A first example is the RISERS project (A Roadmap for Industrial Symbiosis Standardisation for Efficient Resource Sharing), funded by the European Union under Horizon Europe and promoted by CEN and CENELEC. Launched in January 2024 with a three-year timeline, the project seeks to develop a comprehensive standardization roadmap for industrial symbiosis—an essential strategic tool to plan and coordinate the development of future European technical standards over the medium to long term.

RISERS aims to identify standardization priorities for industrial symbiosis, ensuring alignment with EU policies and market dynamics; to map key challenges and regulatory gaps through input from multi-sector experts; and to guide future standardization activities in critical areas such as waste-heat recovery, steel-slag valorization, electric-vehicle batteries, packaging, textiles, biomass, energy-data management, and end-of-waste criteria. The project will also contribute to thematic technical reports that will form the basis of the final roadmap, providing practical guidance for companies and public authorities involved in the circular transition.

UNI also participates in the United Circles project, likewise funded under Horizon Europe, which focuses on developing urban–industrial symbiosis. Cities—responsible for generating over two billion tonnes of waste each year—represent a strategic setting for advancing the circular economy. United Circles promotes cooperation between urban and industrial systems through "Hub4Circularity": innovation ecosystems that integrate new technologies, collaborative models, and governance tools for efficient resource management.

Each Hub will develop advanced governance frameworks, methodologies for financial sustainability, digital tools, social and environmental innovations, and a permanent observatory on materials and products. Among the pilot cases, the Italian initiative in the Veneto region is particularly notable, centred on converting used cooking oil into bioplastics and bio-based materials—an example of industrial symbiosis that effectively connects production sectors with urban contexts.

The standardization landscape for industrial symbiosis

While only a limited number of technical standards currently address industrial symbiosis directly, the topic is already partially embedded within the broader framework of circular-economy standardization, particularly in standards defining principles, terminology, business models, and performance indicators.

The ISO 59000 series provides the overarching reference framework for the circular economy. ISO 59010, in particular, explores business models and collaborative approaches, including industrial symbiosis, recognizing it as one of the key transition pathways alongside servitization and other innovative paradigms.

At the national level, Italy has taken a pioneering role with two key documents:

- UNI/TR 11821, a technical report that compiles 41 best practices of circular economy—including three on industrial symbiosis—and provides a methodological framework for documenting and assessing them;
- UNI/TS 11820, a technical specification introducing 68 circularity indicators, nine of which are specifically dedicated to symbiotic exchanges of materials, by-products, water, energy, and services, enabling quantitative assessment of industrial-symbiosis performance.

At the European level, CWA 17354 "Industrial Symbiosis: Core Elements and Implementation Approaches" represents the first technical document fully dedicated to industrial symbiosis. Published in 2018, it defines fundamental principles, enabling factors, implementation models, and conditions that support the adoption of industrial symbiosis, highlighting its contribution to competitiveness, innovation, and regional development.

Given its relevance and the evolving technological and policy context, CEN/TC 465 "Sustainable Cities and Communities" established in 2025 a new Working Group (WG 5) tasked with transforming CWA 17354 into a European standard. This marks the start of the first formal standardization process focused specifically on industrial symbiosis, with the objective of ensuring methodological consistency, data traceability, and replicability of practices.

Conclusions

Standardization is a crucial enabler for transforming industrial symbiosis from an experimental approach into a systemic and scalable practice. Shared standards foster a common language among businesses, public institutions, and the scientific community, improving measurability, comparability, and mutual trust.

Through European projects and ongoing technical work led by UNI and international standardization bodies, a solid foundation is being built to support the transition to fully circular production models—where industrial symbiosis becomes not only an environmental opportunity but also a driver of innovation, competitiveness, and regional cohesion.

La normazione per la simbiosi industriale – Claudio Perissinotti Bisoni – UNI (Ente Italiano di Normazione)

Negli ultimi anni la simbiosi industriale ha assunto un ruolo centrale nelle strategie europee di transizione verso l'economia circolare. In questo contesto, la normazione tecnica rappresenta uno strumento essenziale per supportare la diffusione e la replicabilità delle pratiche di simbiosi, favorendo l'integrazione tra imprese, territori e politiche pubbliche. L'attività di UNI, in coordinamento con gli organismi europei e internazionali di normazione (CEN, ISO), si inserisce pienamente in questo scenario, con l'obiettivo di tradurre i risultati della ricerca e dell'innovazione in riferimenti tecnici condivisi e utilizzabili dal mercato.

Progetti europei per la normazione della simbiosi industriale

Un primo esempio è il progetto RISERS (A Roadmap for Industrial Symbiosis Standardisation for Efficient Resource Sharing), iniziativa finanziata dall'Unione Europea nell'ambito del programma Horizon Europe e promossa da CEN e CENELEC. Avviato nel gennaio 2024 con una durata triennale, il progetto mira a sviluppare una vera e propria roadmap di normazione per la simbiosi industriale, uno strumento strategico volto a pianificare e coordinare lo sviluppo delle future norme tecniche europee nel medio-lungo periodo.

RISERS intende definire le priorità normative per la simbiosi industriale, assicurandone la coerenza con le politiche europee e le tendenze di mercato; individuare, con il contributo di esperti multisettoriali, le principali sfide e lacune regolatorie; orientare la futura produzione normativa in ambiti cruciali come il recupero del calore di scarto, la valorizzazione delle scorie di acciaieria, le batterie dei veicoli elettrici, gli imballaggi, i tessili, la biomassa, i dati energetici e i criteri di end-of-waste; contribuire alla redazione di rapporti tecnici tematici che confluiranno nella roadmap finale, offrendo strumenti operativi per le imprese e le amministrazioni impegnate nella transizione circolare.

UNI partecipa anche al progetto United Circles, anch'esso finanziato da Horizon Europe, dedicato allo sviluppo della simbiosi urbano-industriale. Le città, responsabili ogni anno di oltre due miliardi di tonnellate di rifiuti, rappresentano infatti un nodo strategico per l'attuazione dell'economia circolare. UnitedCirclespromuove la collaborazione tra sistemi urbani e industriali attraverso i cosiddetti Hub4Circularity, ecosistemi di innovazione che integrano nuove tecnologie, modelli collaborativi e strumenti di governance per la gestione efficiente delle risorse.

Ciascun Hub svilupperà framework di governance avanzati, metodologie per la sostenibilità finanziaria, strumenti digitali, innovazioni sociali e ambientali e un osservatorio permanente sui materiali e sui prodotti. Tra i casi pilota, spicca l'esperienza italiana in Veneto, dedicata alla trasformazione degli oli da cucina esausti in bioplastiche e materiali bio-based, a dimostrazione del potenziale della simbiosi industriale nel connettere filiere produttive e contesti urbani.

Il quadro normativo per la simbiosi industriale

Ad oggi non esistono ancora molte norme tecniche che trattano in maniera diretta il tema della simbiosi industriale. Tuttavia, la materia è già in parte integrata nel corpus normativo sull'economia circolare, in particolare attraverso gli standard che ne definiscono principi, terminologia, modelli di business e indicatori di performance.

Gli standard della serie ISO 59000 forniscono il quadro di riferimento generale dell'economia circolare. In particolare, la ISO 59010 approfondisce i modelli di business e gli approcci collaborativi, inclusa la simbiosi industriale. Questi documenti riconoscono la simbiosi come uno dei principali modelli di transizione, accanto alla servitizzazione e ad altri paradigmi innovativi.

In ambito nazionale, l'Italia ha assunto un ruolo di apripista con due documenti fondamentali: la UNI/TR 11821, rapporto tecnico che raccoglie 41 buone pratiche di economia circolare, di cui 3 dedicate alla simbiosi industriale, e fornisce un framework metodologico per la loro documentazione e valutazione; e la UNI/TS 11820, specifica tecnica che introduce 68 indicatori di misurazione della circolarità, 9 dei quali specificamente riferiti agli scambi simbiotici di materiali, sottoprodotti, acqua, energia e servizi, consentendo così una valutazione quantitativa delle performance di simbiosi industriale.

A livello europeo, il documento CWA 17354 "Industrial Symbiosis: Core Elements and Implementation Approaches" rappresenta il primo riferimento tecnico dedicato interamente alla simbiosi. Pubblicato nel 2018, esso definisce i principi fondamentali, i fattori abilitanti, i modelli di implementazione e le condizioni favorevoli alla diffusione della simbiosi industriale, sottolineandone il contributo alla competitività, all'innovazione e allo sviluppo regionale.

Considerata la sua rilevanza e l'evoluzione del contesto tecnologico e politico, il CEN/TC 465 "Sustainable Cities and Communities" ha istituito nel 2025 un nuovo gruppo di lavoro (il Working Group 5) con il mandato di trasformare il CWA 17354 in una norma europea. Questo passo segna l'avvio del primo percorso formale di normazione specificamente dedicato alla simbiosi industriale, con l'obiettivo di garantire coerenza metodologica, tracciabilità dei dati e replicabilità delle pratiche.

Conclusioni

La normazione rappresenta un fattore chiave per l'evoluzione della simbiosi industriale da approccio sperimentale a pratica sistemica e scalabile. La definizione di standard condivisi consente di creare un linguaggio comune tra imprese, enti pubblici e comunità scientifica, favorendo la misurabilità dei risultati e la fiducia tra gli attori coinvolti.

Attraverso i progetti europei e i lavori tecnici in corso presso UNI e gli organismi di normazione europei e internazionali, si sta costruendo una base solida per supportare la transizione verso modelli produttivi pienamente circolari, in cui la simbiosi industriale non è solo un'opportunità ambientale, ma anche un motore di innovazione, competitività e coesione territoriale.

CALL FOR PAPERS PRESENTATIONS

Advancing circular construction through innovative bio-based materials and digital product passport

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Abstract

This research addresses the dual ecological and digital transition challenges in the construction sector by exploring industrial symbiosis as a systemic lever for innovation and resource efficiency. The project targets structural barriers to circularity, such as excessive raw material consumption and limited traceability, through two combined technological solutions: developing a local, bio-based building block and implementing a Digital Product Passport (DPP) platform. The bio-block, composed of lime, hemp, and local agro-wastes, shows improved performance, achieving a 30% increase in thermal insulation and a 10% gain in mechanical strength over conventional bio-based materials. Simultaneously, the DPP platform centralizes product lifecycle data to enable traceability and regulatory alignment. By integrating material innovation with digital infrastructure, this study demonstrates how industrial symbiosis operationalizes circular business models. The findings underscore that scaling these solutions requires standardized data protocols, cross-sector collaboration, and targeted education to foster a resilient industrial ecosystem.

Keywords: Bio-based construction; Digital Product Passport; Twin Transition; Innovation; Circular Economy.

Introduction

The European Union's "Twin Transition" seeks to establish a greener, more circular, and digital economy [1]. The construction sector is a strategic domain for this transition due to its substantial environmental impact, accounting for approximately 50% of all raw material extraction, nearly 40% of EU waste generation, and 5-12% of national greenhouse gas (GHG) emissions. The Circular Economy Action Plan [2] advocates for integrating bio-based materials through industrial symbiosis to reduce the carbon intensity of construction inputs and mitigate Construction and Demolition (C&D) waste generation [3]. Enhancing material efficiency in this sector could potentially reduce GHG emissions by up to 80% [4].

Furthermore, increasing the rate of preparation for reuse and high-quality recycling of C&D waste to the technologically achievable threshold of 83% across the EU would result in annual savings of 33 million tonnes of CO2 equivalent [5]. Despite these established benefits, the market penetration of bio-based products is constrained by barriers such as a fragmented supply chain, process inefficiencies, and low industry adoption [6, 7]. Within this context, supply chain traceability emerges as a pivotal enabler for circular value chains, supporting material certification and quality assurance [8]. To address these limitations, the Regulation on Ecodesign for Sustainable Products has designated the Digital Product Passport (DPP) as a foundational tool for the Circular Economy transition in construction [9]. The DPP enables stakeholders to access key lifecycle data, such as material composition, supply chain details, and guidelines for reuse and disassembly. The EU-funded DIGI4BIOMAT project is investigating the opportunities and challenges of the Twin Transition through a case study focused on developing a high-performance hemp-based bio-block supported by an integrated DPP. This study aims to achieve a set of objectives designed to drive both technological and circular business innovation within the construction industry, specifically:

- To develop an innovative bio-based building block using 100% natural materials;
- to clarify the information flows required to characterize a bio-based construction product;
- to design a DPP platform that centralizes product life cycle data.

Methods

The case study centers on a bio-based materials manufacturer in Apulia, Southern Italy, focused on developing sustainable construction products. The company's research initiative was driven by the imperative to minimize dependence on conventional mineral aggregates and reduce the substantial carbon footprint associated with imported hemp. Consequently, the project was structured around the formulation of a high-performance bio-based block designed to meet stringent structural and thermal performance criteria while achieving optimal environmental mitigation. To enhance regional sustainability, the project investigated the substitution of traditional aggregates with locally sourced agro-industrial by-products, specifically olive stones and almond shells. These materials were selected based on their regional availability and promising mechanical and ecological characteristics, enabling a reduction in the required hemp volume and thus improving the overall product sustainability profile.

The methodological framework for this development was executed across four distinct phases:

1. Materials characterization: the bio-composite (lime, hemp, agro-industrial waste) was analyzed using EN standards to define its physico-mechanical properties (e.g., granulometry, strength), validating the suitability of the agro-waste aggregates for construction.
2. Process and stakeholder mapping: workflow documentation identified critical decision points and information flows, essential for DPP development and defining the circular business model.
3. Platform development: the digital traceability platform was iteratively built using user-centered design methodology, integrating material and process data to generate a regulatory-compliant DPP.
4. End-user validation: Relevance and usability were confirmed through participatory design (interviews, testing) with stakeholders, and feedback was aligned with the User Acceptance Test (UAT) framework.

Findings

The DIGI4BIOMAT project achieved substantial progress in the development of bio-based building block, designed to meet both environmental and performance criteria. The final formulation, which incorporated locally sourced agro-industrial by-products such as olive stones and almond shells, demonstrated a 30% improvement in thermal insulation and a 10% increase in compressive strength compared to conventional hemp-lime blocks. These results were validated through standardized laboratory testing and confirmed during industrial-scale prototyping, indicating the successful scalability of the material and its compatibility with existing production technologies (Figure 1).

Figure 1. Bio-block prototype produced and test (courtesy of PEDONE Srl).

In addition to improved technical performance, the use of regional waste materials contributed to a significant reduction in the environmental footprint of the product. Preliminary estimates suggest the potential to divert up to 500,000 tons of organic waste annually from landfills in the Apulia region, thereby supporting local CE strategies and reducing dependency on imported hemp, which is associated with considerable transport-related emissions.

However, the most transformative result of the project lies in the development and role of the DPP platform (Figure 2). The DPP platform enables bio-block manufacturers to consolidate and manage all relevant product-related information in a single, structured, and safety data environment. This includes information on raw material sourcing, supply chain composition, product declaration and conformity, technical specifications, product and process certification, and guidelines for correct transportation, installation, use, maintenance, and end-of-life treatment. By centralizing this information, the DPP platform facilitates the creation of a complete and verifiable digital identity for each product batch, which can be accessed and updated throughout its life cycle.

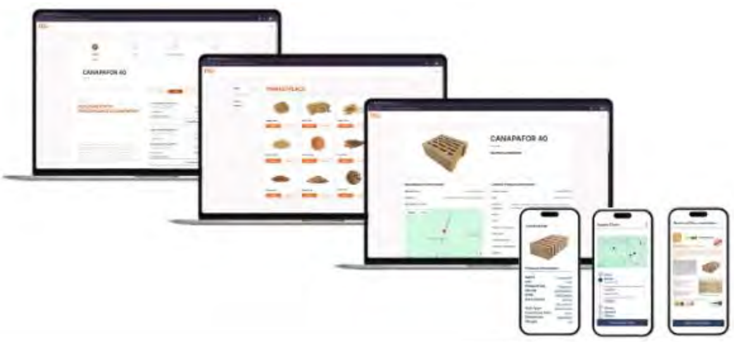

Figure 2. DPP platform (DeePPy platform developed by Levery)

DPP platform functionality supports dynamic configuration of product batch, enabling producers to optimize sustainability outcomes by selecting the most appropriate supply chain components. To enhance accessibility and usability, the platform incorporates guided data entry modules that assist users in the manual input of information. These modules are designed to reduce errors, improve data consistency, inform users about regulations, and lower the technical barrier for adoption, particularly among small and medium-sized enterprises. Additionally, the platform supports the generation of QR codes linked to individual products, which can be physically applied to each product batch produced. The key benefits are:

- Enhanced traceability and certification readiness: centralized documentation of product attributes and supply chain data streamlines the certification process and improves quality control. The availability of detailed lifecycle data also facilitates rapid LCA report generation, supporting compliance and accurate environmental impact quantification.
- Operational efficiency and error reduction: digitizing documentation workflows minimizes the time and errors associated with manual data management. This improves efficiency in regulatory and certification procedures and reduces administrative burdens across the stakeholder value chain.
- Transparent communication of product performance: the platform enables clear dissemination of material specifications and performance metrics to architects, designers, and end-users. This transparency promotes informed decision-making and accelerates the adoption of bio-based materials.
- Configurable sustainability through supplier selection: the platform allows producers to register and compare suppliers, enabling the configuration of supply

chains to minimize environmental impact. This capability supports the development of an adaptive circular business model.

Discussion/Conclusion

The DIGI4BIOMAT project establishes a robust and replicable framework for advancing the Twin Transition in the construction sector by successfully developing a high-performance bio-based building block from locally sourced agricultural residues. This material innovation enhances circularity and reduces the carbon footprint associated with conventional and imported resources (like hemp). Crucially, this physical innovation is integrated with a web-based Digital Product Passport (DPP) platform. The DPP acts as a central repository for comprehensive product lifecycle data accessible via digital interfaces like QR codes. This digital infrastructure enables traceable, transparent, and data-driven circular practices, allowing manufacturers to configure supply chains based on environmental impact and facilitating regulatory compliance and stakeholder communication. The project demonstrates that the convergence of material innovation and digital traceability is essential to operationalize circular business models focused on material recovery and life extension. However, the research highlights persistent barriers to widespread adoption, including the limited standardization of data protocols and a low cultural readiness for systemic change. Future scaling of the DIGI4BIOMAT model is contingent on sustained collaboration across industry and policy, with necessary investments in digital infrastructure, stakeholder education, and the harmonization of data standards to support a resilient and sustainable construction ecosystem.

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The new Science-policy panel on chemicals, waste and pollution: establishment process and future perspectives

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Abstract

The Intergovernmental Science-Policy Panel on Chemicals, Waste and Pollution (ISP-CWP) was formally established on 20 June 2025 in Punta del Este (Uruguay), following UNEA resolution 5/8 (2022). This panel represents the first intergovernmental body dedicated to strengthening the science-policy interface on chemicals, waste, and pollution. It adopts an integrated, solution-oriented approach, aiming to ensure policy relevance and scientific independence. The ISP-CWP incorporates diverse knowledge systems, including Indigenous and local perspectives, and implements Proposed mechanisms for conflict-of-interest management and sensitive data protection. This contribution outlines the institutional framework, operational principles, and governance structure of the panel, highlighting key challenges for its effective implementation and future perspectives in global environmental governance.

Keywords: Science.policy interface; chemicals; waste; pollution; governance.

Introduction

The planet is currently facing a "triple planetary crisis" characterized by interconnected climate change, biodiversity loss, and pollution [1]. While the first two challenges have been addressed by dedicated bodies like the IPCC and IPBES [2,3], the third component has suffered from a fragmented approach [4]. Pollution prevention and sustainable management of chemicals and waste are critical priorities for protecting human health and the environment [5]. Current data indicate rapidly growing industrial chemical production, projected to double by 2030 compared to 2017 levels [6]. Similarly, municipal solid waste generation is expected to rise from 2.1 billion tonnes in 2023 to 3.8 billion by 2050, with global management costs amounting to 252 billion USD in 2020 [7]. Air pollution alone is linked to approximately 6.5 million deaths annually, with a 66% increase in deaths related to modern forms of pollution over the last two decades [6]. To address these challenges, a transition from a "cradle-to-grave" to a "cradle-to-cradle" model is proposed, promoting the circular economy. In this context, the United Nations Environment Assembly (UNEA), through Resolution 5/8, recognized the need to establish a science-policy panel (SPP) [8]. The complex relationship between these elements and the need for a dedicated interface is illustrated in Figure 1.

The Intergovernmental Science-Policy Panel on Chemicals, Waste and Pollution (ISP-CWP, hereafter the Panel") proposes a strategy based on strengthening the scientific knowledge base and promoting policies informed by the best evidence, aiming to ensure relevance without being prescriptive.

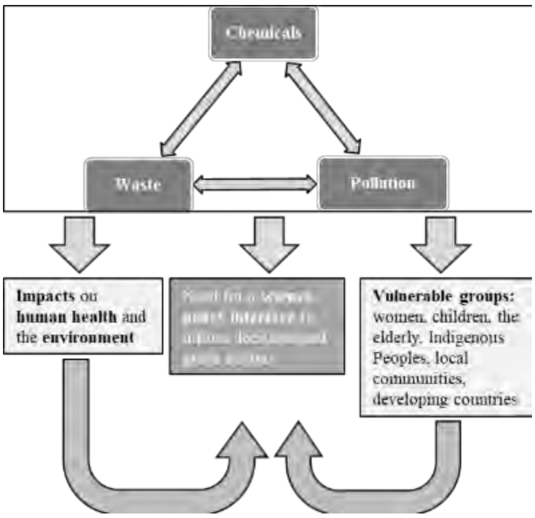

Figure 1. Relationships between chemicals, waste and pollution: impacts and need for a science-policy interface.

Methods and findings

The methodology adopted for this work is based on the analysis of the negotiation process and the foundational documents developed through the work of the ad hoc Open-Ended Working Group (OEWG). The process was mandated by UNEA Resolution 5/8 [9] and involved a series of five meetings conducted in three sessions, convened by the UNEP Executive Director. As shown in the timeline in Figure 2, the OEWG met starting in 2022 to prepare proposals for the Panel's establishment [10].

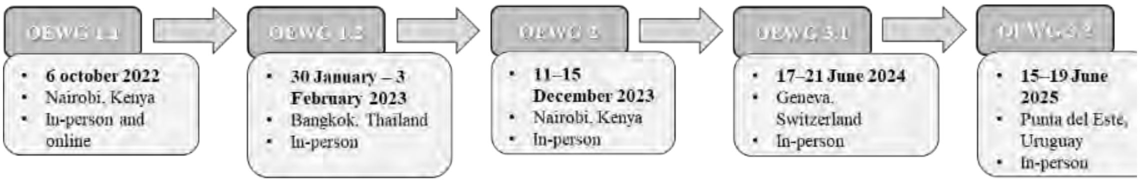

Figure 2. Timeline of OEWG meetings, following UNEA resolution 5/8 of 2022.

The analysis focused on the package of texts finalized by the OEWG, which included the foundatinal document [11], recommendations for the first session [12], and arrangements for the interim period [13]. These documents were adopted by the Intergovernmental Meeting, culminating in the formal establishment of the Panel in Punta del Este in June 2025 [14,15].

Institutional Structure and Principles

The ISP-CWP is established as an independent intergovernmental body. Its governance structure includes:

- Plenary: the decision-making body open to UN Member States, responsible for adopting the work program and budget.
- Bureau: composed of two members from each of the five UN regional groups, providing advisory support and monitoring procedures.
- Interdisciplinary Expert Committee (IEC): composed of experts nominated by regions and elected by the Plenary to provide scientific and technical advice, ensuring interdisciplinarity.
- Trust Fund: a voluntary trust fund will be established to receive contributions without conditionality that could bias the Panel's work.

Innovative Aspects

Unlike existing bodies, the ISP-CWP adopts a holistic and integrated approach to chemicals, waste, and pollution [2,16]. The Panel emphasizes solution-oriented assessments [17] and utilizes a risk-based conceptual framework for prioritizing issues [18]. A new key function is "horizon scanning" for the early identification of emerging issues and potential threats, often referred to as "green swans" [19]. This proactive approach allows for the timely identification of risks relevant to policymakers.

Negotiation Dynamics and Unresolved Issues

The establishment process was complex, characterized by diverse positions on decision-making modalities and observer participation. During the drafting of the foundational documents, unanimous consensus was not reached on specific issues, particularly regarding gender parity and the rights of Indigenous peoples. Consequently, some passages in the adopted text remain in brackets, indicating points still subject to discussion. However, these elements did not preclude the adoption of the package as a whole. Another critical aspect is the "Conflict of Interest" (COI) policy, which is essential for the Panel's credibility but not yet fully finalized [20]. The proposed policy includes mandatory declarations of interest and potentially an independent reviewer to ensure impartiality in data use, addressing historical concerns about industry influence.

Digitalization and Capacity Building

Capacity building for developing countries is a core function of the Panel, encompassing technical support and technology transfer [21]. A significant open question concerns the use of digital transformation to make data and knowledge open, accessible, and transparent, in line with FAIR (Findability, Accessibility, Interoperability, Reusability) principles. These elements are still under discussion but are considered fundamental to ensuring global equity in access to scientific evidence and strengthening decision-making capacity worldwide.

Conclusions

The establishment of the ISP-CWP represents a historic milestone in multilateral environmental cooperation. By operating alongside the well-established IPCC (Intergovernmental Panel on Climate Change) and IPBES (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services), the new Panel completes the "triple crown" of UN scientific bodies, offering strategic support to manage the third planetary crisis. While the foundational documents have been approved, challenges remain regarding the full operationalization of the Panel. The bracketed text in the adopted documents highlights persistent divergences on social equity issues. Future success will depend on the Panel's ability to overcome these issues, maintain scientific independence, and ensure that its findings translate into concrete policy actions at national and international levels.

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System dynamics for modeling eco-industrial systems: an overview

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Abstract

This study aims to provide an overview about the use of System Dynamics (SD) in the development of Eco-Industrial Systems. The results highlight how, in Industrial Ecology studies, SD is used to model and simulate closed-loop scenarios in multiple sectors and at various levels of scale, considering the economic, environmental, and social dimensions of systems and including different types of variables. However, the review reveals that only a minority of studies develop comprehensive models accompanied by a final validation process, which is crucial to ensure robustness and credibility. In this regard, the integration of advanced tools - such as machine learning - appears particularly promising for enhancing model accuracy and strengthening the predictive capacity of circular transition analyses.

Keywords: Industrial Ecology; Circular Economy; Decision-making; Modeling and Simulation; Scenario Analysis.

Introduction

In recent years, the circular transition has emerged as a paradigm for moving from linear to regenerative production and consumption systems, which are recognized as complex socio-technical contexts involving multiple actors, divergent goals, and evolving non-linear dynamics [1]. Industrial Ecology (IE) [2] provides a solid framework for supporting an efficient (re)design according to Circular Economy (CE) principles [3]. Eco-industrial systems [4] exemplify this approach by integrating synergistic solutions for material, energy, and by-product flows to enhance economic and environmental sustainability. CE and IE offer complementary perspectives - combining transformative aims with systemic analysis - but traditional assessments remain largely static and one-dimensional, limiting their ability to capture dynamic interdependencies, time delays, feedback loops, and qualitative variables [5]. System Dynamics (SD) [6] helps address these gaps by modelling and simulating economic, environmental, and social implications of circular transition across different scales. Through a literature review, this study outlines how SD has been applied to model and simulate circular scenarios from an eco-industrial perspective. The results are presented in two sections: an overview of publication trends over time, key keywords, and the thematic structure of the field, followed by a content analysis examining the modelling and simulation approaches discussed in the literature.

Methods

The literature search was conducted in the Scopus database [7] using the query: ("industrial ecology" OR "industrial symbiosis") AND "system dynamics", applied to Title, Abstract, and Keywords, and including only English-language, peer-reviewed articles published in scientific journals. The search returned to 41 publications, which were examined for the bibliometric analysis [8]. Data were processed using Biblioshiny [9], a web interface based on the Bibliometrix package in RStudio, which supports bibliometric evaluation through visualizations such as Collaboration Network, Word Cloud, and Thematic Map. For the content analysis, more restrictive criteria were applied, selecting only articles that explicitly report a quantitative model structured through a stock-and-flow diagram, including scenario analysis, and providing a model validation phase (10 articles analyzed).

Findings

Trends, most relevant scientific journals, and most frequent words

The trend in publications is irregular (Fig. 1), but with a clear overall upward trend. Although there are fluctuations, the annual production level since 2018 is higher than in previous years, which often recorded zero or very low production. The data also show that the Journal of Industrial Ecology, with 16 articles out of 41, is the reference journal for scholars working on IE and SD.

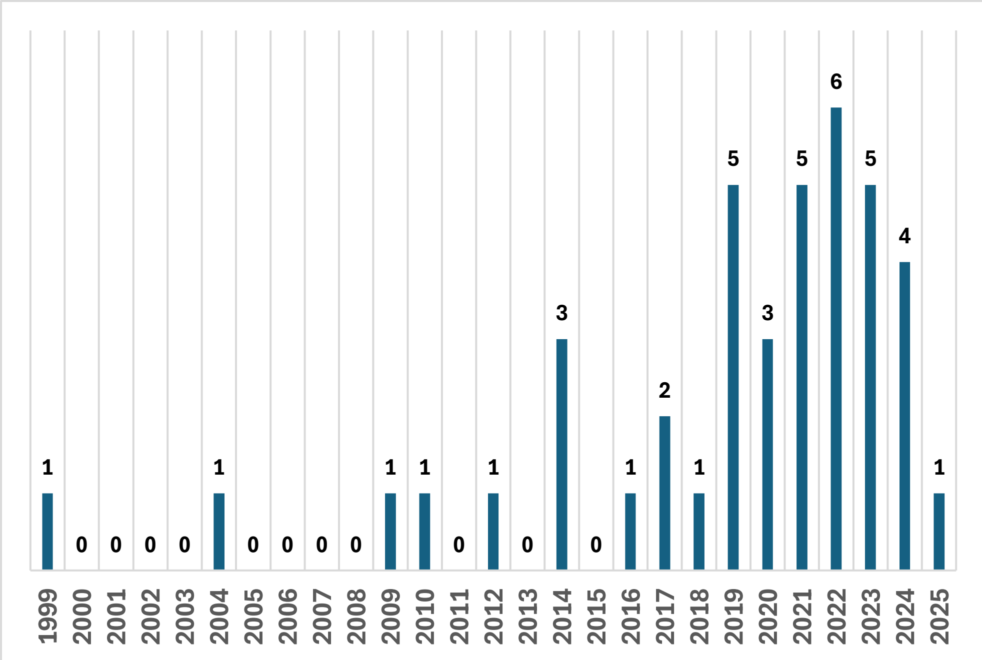

Figure 1. Annual scientific output. Source: authors' elaboration based on Biblioshiny data.

In analyzing the most relevant keywords, the ten most frequent terms among those appearing six times or more were considered. Terms such as industrial ecology, industrial symbiosis, and system dynamics were excluded because they were part of the search criteria, while similar terms (e.g., life cycle assessment and life cycle assessment (LCA)) were consolidated as synonyms. Fig. 2 highlights Life Cycle Assessment (LCA), Sustainability, and Material Flow Analysis (MFA) as the most prominent keywords. Their prevalence indicates that the field is strongly anchored in quantitative and impact-assessment methodologies aimed at analyzing material flows and supporting sustainability goals. Other relevant concepts - System Theory, Circular Economy, Decision Making and Agent-Based Modelling (ABM) - suggest that research extends beyond assessment toward the use of systemic and advanced modelling approaches to inform decision-making for CE strategies.

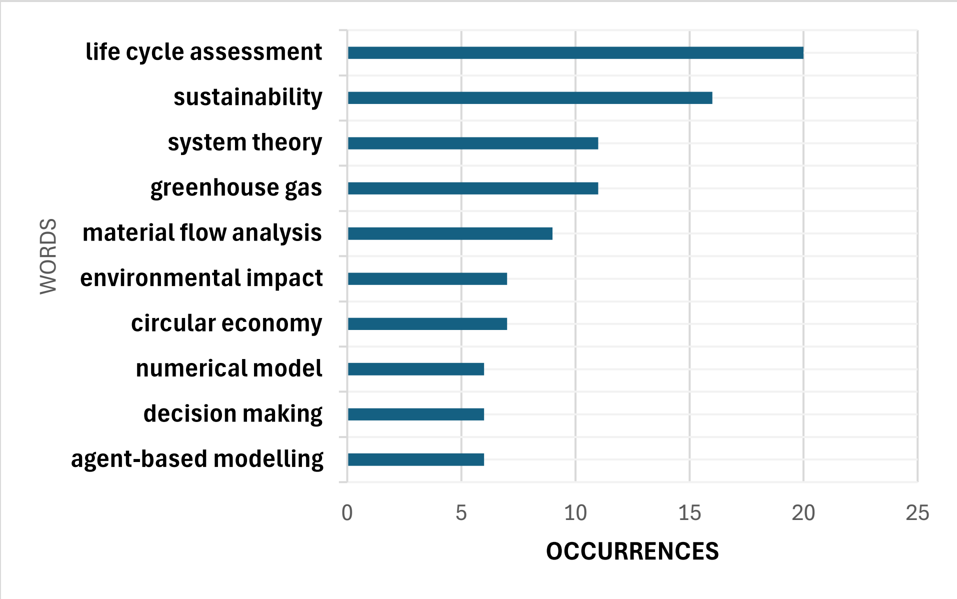

Figure 2. Relevant keywords.Source: authors' elaboration based on Biblioshiny data

The Thematic Map (Fig.3), generated using the Walktrap algorithm, highlights the following clusters: 'Sustainability', 'Decision Making', and 'Greenhouse Gas' as Motor Themes (central and well developed); 'Material Flow Analysis' as a Basic Theme (a consolidated yet less explored methodology); 'Metabolism' as a Niche Theme (specialized within specific domains); 'Conceptual Framework' as a bridge connecting different thematic areas; and 'Sensitivity Analysis' and 'Efficiency' as Emerging/Declining Themes (peripheral themes with potential for future development).

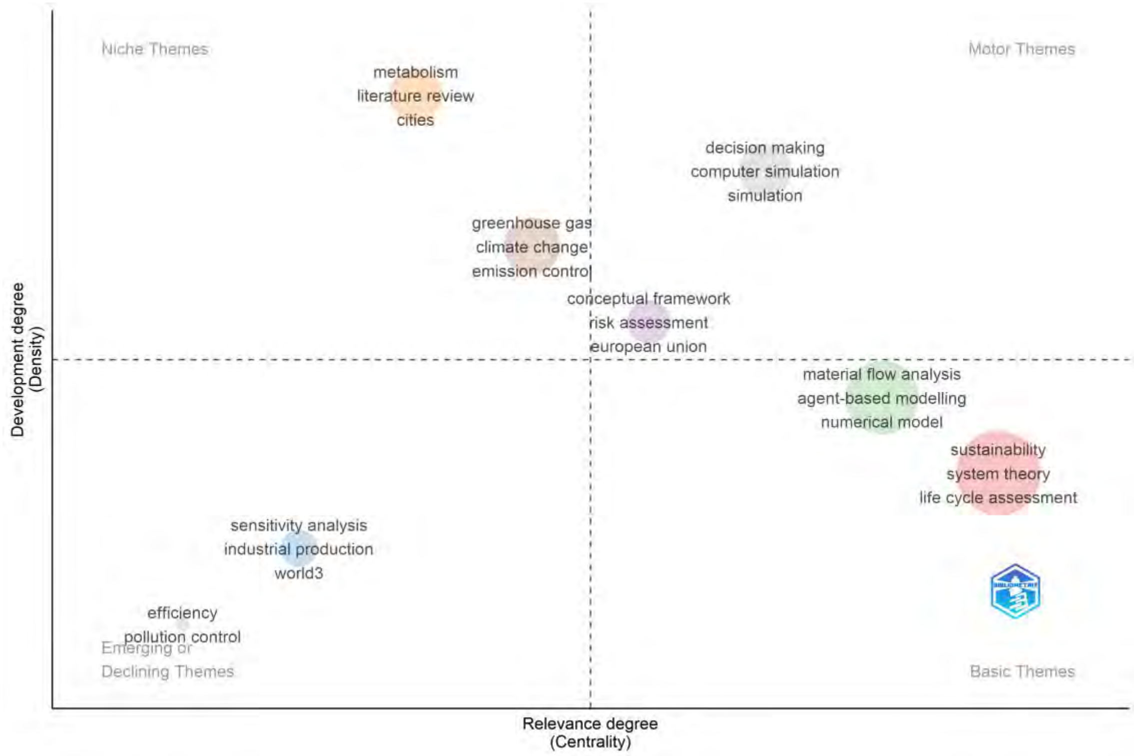

Figure 3. Relevant keywords – Thematic map.Source: Biblioshiny

Content Analysis

The content analysis first highlights the wide diversity of sectors in which SD has been applied, as well as the scales of analysis (Fig. 4), which focus mainly on meso- and macro-level systems (industrial networks and urban systems) demonstrating SD's ability to analyze complex interactions among multiple entities and support strategic decision-making.

Figure 4. Content analysis: sector-specific applications and scale of analysis. Source: authors' elaboration based on [10].

The analysis further shows that, in addressing the complexity of eco-industrial contexts, SD is often combined with complementary methods to develop more accurate and reliable models. Methods typical of IE, such as LCA and MFA, help map material and energy flows and quantify environmental impacts, while ABM integrates SD's macro-level perspective with micro-level decision processes, overcoming methodological limits and providing a more comprehensive system view. The reviewed models employ multidimensional indicators that extend beyond economic metrics to include environmental and social aspects, reflecting a holistic sustainability perspective. Findings also show that model structures extend beyond physical flows, incorporating conceptual and behavioral variables that influence system evolution [10]. This makes it possible to represent dynamics determined not only by the physics of the system, but also by human and organizational decision-making.

Discussion/Conclusion

The first phase of the analysis shows growing interest in using SD to study eco-industrial systems and support circular strategies. Publications have increased markedly since 2018, especially in journals like the Journal of Industrial Ecology. Keyword analysis highlights Sustainability, LCA, MFA, and Decision Making as core topics, reflecting an interdisciplinary approach that integrates multiple methods, including ABM, and quantitative tools. The

Thematic map shows centrally established concepts surrounded by emerging themes, indicating a blend of theoretical and applied research to advance the CE. Content analysis confirms that SD, often combined with IE methods and ABM, models complex industrial systems across meso- and macro-scales, including economic, environmental, and social variables. However, only 10 of 41 studies present complete SD models with scenario analysis and validation; many report only qualitative diagrams or unvalidated quantitative models. Validation remains critical, often limited by data availability, suggesting the potential for machine learning to enhance model reliability. Overall, multi-method approaches and advanced modeling methods and tools show great promise in guiding industrial systems toward greater circularity and sustainability.

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Industrial Symbiosis for Efficient Resource Use: Terminology, Analytical Tools, and Legal-Administrative Mechanisms

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Abstract
Within the agreement between the Ministry of Environment and Energy Security (MASE) and ENEA and the related SIMBIOSI program, a set of methodological and analytical activities has been undertaken to foster industrial symbiosis (IS) in Italy. This article presents methods and findings of the research on three interrelated areas: the operational definition of "resource" in IS, the development of a Resource Audit 2.0 method for non-energy physical resources, and the analysis of legal and administrative tools enabling resource sharing. The definition of resource is based on 115 real-world IS cases, technical documents, and national and European regulatory frameworks and validated by a pubblic consultation. The Resource Audit 2.0 provides a replicable method to assess resource streams, internalpotential of resource efficiecy, inter-firm synergies, and, as a whole, the resource efficiency potential. Legal and administrative rules and procedures are discussed to highlight enablers and constraints for resource sharing. Overall, the work provides a clear definition of resources as physical or intangible assets that can be sustainably utilized or shared among organizations, demonstrates how the Resource Audit 2.0 supports both internal optimization and inter-firm collaboration, and highlights legal and administrative enablers and constraints, offering a practical framework to promote circular, collaborative industrial symbiosis.

Keywords: Industrial symbiosis; Resource Efficiency; Circular Economy; Resource audit; Legal and Administration Mechanisms.

Introduction

Industrial symbiosis (IS) is increasingly recognized as a key strategy to enhance circularity and sustainability in industrial production systems, allowing enterprises to exchange and utilize resources, optimize use, reduce waste, and generate mutual benefits. Inspired by natural ecosystems, IS links environmental improvement, economic development, and local regeneration, with outputs of one process serving as inputs for another (Frosch &

Gallopoulos, 1989; Ehrenfeld & Gertler, 1996; Chertow, 2000). Numerous definitions emphasize resource exchanges, inter-firm collaboration, and value creation from underutilized resources (Jacobsen, 2006; Lombardi & Laybourn, 2012; European Union, 2018; European Commission, 2020a). Policy frameworks at European and national levels support IS adoption. European initiatives, including the Roadmap to a Resource Efficient Europe (2011) and Circular Economy Action Plans (2015; 2020), encourage the development of IS networks to improve resource efficiency. Italian strategies, such as the Circular Economy Strategy (2017–2022), the Bioeconomy Strategy (2019), and the National Recovery and Resilience Plan (2021), similarly recognize IS as a tool to optimize resources, foster collaboration, and generate environmental, social, and economic benefits. The concept of "resource" is therefore central to IS. Concurrently, methodological and legal tools are needed to facilitate a widespread adoption of IS. Against this background, this paper presents the work to reach three interrelated objectives: (i) establishing an operational definition of resource for IS; (ii) presenting the Resource Audit 2.0 methodology; and (iii) examining national legal and administrative tools that enable resource sharing, providing the governance context to implement IS and collaborative circular business models. Together, these analyses offer a comprehensive framework to enhance resource efficiency, promote circularity, and support sustainable industrial systems.

Methods

This section outlines the methodologies used to achieve the three research objectives.

Definition of resource for Industrial Symbiosis

To define the concept of resource in IS, a combination of literature review, case study analysis, technical standards, and stakeholder consultation was conducted. The scientific and technical literature on industrial ecology and IS was systematically reviewed to identify existing definitions, frameworks, and typologies of material and immaterial resources. Complementary, the analysis of numerous documented IS cases captured how resources are exchanged, shared, or optimized, and to identify resource types, exchange mechanisms, and organizational arrangements. Relevant national and international policy documents and technical standards (ISO and UNI) were also analyzed to integrate regulatory perspectives. A structured stakeholder consultation validated the definition and provided operational insights. This combined approach allowed the construction of a comprehensive framework, considering both technical feasibility and socio-economic context, to deliver an informed definition of resource in IS, encompassing their availability, exchange potential, and contribution to circular and sustainable industrial systems.

Resource Audit 2.0

Starting from the Resource Audit methodology already proposed by ENEA (Cutaia eta al 2020), The Resource Audit 2.0 was developed as a multi-step methodology combining a review of scientific and technical literature, analysis of existing management frameworks, examination of ISO and UNI standards, and insights from operational best practices. The tool supports organizations in assessing, monitoring, and optimizing both physical (non-energy) and organizational resources, focusing on efficiency, sustainability, and circularity. Literature and standards review informed the identification of key components and operational steps, ensuring alignment with recognized best practices and compatibility with reporting frameworks such as GRI and ESRS. The findings were synthesized into a structured methodology that integrates theoretical insights with practical tools to support industrial symbiosis implementation.

Legal and administrative mechanisms

The research investigates both legal and administrative rules, procedures and tools as defined by the Italian law, focusing on definition and sharing of resources within IS networks, in the light of current trajectories of law and research occurring at EU level. The method allowed us to track and distinguish real cases between those dealing with the transfer or sharing of physical resources, such as wastewater, energy waste, and shared infrastructure, and those including intangible resources, as canteen service, training services and welfare. The cases included various types of resource transfer and sharing, other than those regulated under the legal classification of by-products, offering a wider perspective on modalities activated between different organizations. Therefore, the designed method allowed us to embraced various forms of resources, while expressly highlight specificities from technical-operational and legal-administrative perspectives.

Findings

Definition of "resource" in industrial symbiosis

According to review and consultation done, resources are defined as physical and intangible assets that organizations can sustainably utilize or share when underutilized or discarded. Physical resources include materials, energy, water, and land, while intangible resources cover services, logistics, production capacity, skills, and knowledge. Sharing of intangible resources may also extend to tools, facilities, or infrastructure, as integral elements of service provision and collaboration.

Resource Audit 2.0

The Resource Audit 2.0 foresees seven steps: defining objectives, boundaries, resources, and stakeholders; collecting and structuring data; identifying optimization scenarios using circular economy and IS solutions; assessing scenarios via technical, economic, regulatory, and environmental tools (e.g., cost-benefit analysis, LCC, LCA, SWOT); consulting stakeholders to validate scenarios; drafting the audit report; and defining a monitoring plan with KPIs for continuous improvement. This framework supports both internal efficiency and inter-firm collaboration.

3.3 Legal and administrative tools

Implementation of IS synergies relies on a combination of private and public law tools. Network contracts already facilitate resource sharing, while ecological contracts offer a potential evolution for regulating multiple converging interests in environmental protection. A typical contract can provide a common framework for companies' initiatives with competent authorities, contributing to avoid fragmented practices and environmental assessments or underestimate cumulative impacts (falling into an alternative form of "salami slicing", European Commission, 2003; Enríquez-de-Salamanca, 2016).

Discussion/Conclusion

This paper presents the operational definition of "resource" in IS, the development of the Resource Audit 2.0 methodology for non-energy physical resources, and the analysis of legal and administrative tools enabling resource sharing. A validated definition of resource for IS reduces information asymmetry and knowledge gaps, supporting more informed policy processes. The Resource Audit 2.0 methodology allows organizations to optimize internal resource use and identify inter-firm synergies, promoting collaboration within industrial symbiosis networks. Its iterative and flexible design enables continuous improvement and supports the transition to a circular economy. The review of legal and administrative rules and procedures highlights the complexity and heterogeneity of procedures between private and public actors, showing the need for a broad set of tools to facilitate effective resource transfer and sharing.

This work demonstrates the multidimensional nature of IS, integrating methods and tools from diverse disciplines, and confirms that research can help both private and public actors to address the challenges of building more sustainable and circular industrial ecosystems.

Since the research focuses on the Italian case the part of the analysis focusing on rules and procedures is country-focused, even if the Italian legislation operates whitin a broader European legal framework.. Nevertheless, the results provide concrete guidance for improving technical and operative activities to support IS adoption, enhance resource efficiency, and foster circular, collaborative business models.

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Mitigating critical raw material supply risk: a global perspective from automotive suppliers

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Abstract

This study explores how automotive suppliers manage supply risks related to Critical Raw Materials (CRMs) across different regulatory and geographic environments. Using a multiple-case research approach, it examines three global automotive component suppliers in Asia, Europe, and North America, utilising semi-structured interviews and secondary data to investigate their CRM supply risk exposure, mitigation practices, and performance outcomes. The results show that CRM supply risks differ based on supply chain position and institutional environment, requiring customised mitigation practices that include strategic sourcing, financial instruments, circular economy models, and transparency driven by compliance. Successful mitigation depends on coordinating complementary practices rather than adopting isolated solutions. Additionally, compliance and emissions reporting have become proactive tools supporting sustainability, resilience, and cost management. The research offers practical insights for managers by demonstrating that combining context-specific practices can improve supply continuity, sustainability outcomes, and strategic agility in response to increasing CRM scarcity and regulatory pressure.

Keywords: Automotive industry; Critical Raw Materials; Supply Risk Mitigation; Resilience performance; Sustainability performance.

Introduction

Critical Raw Materials (CRMs), such as lithium, cobalt, rare-earth elements (REEs), nickel, and manganese, are now indispensable to the automotive industry. They enable electrification, lightweighting, and digitalisation, cornerstones of the green and digital transition, and underpin key applications such as electric powertrains, batteries, and advanced electronic systems (European Commission, 2023; Ortego et al., 2020). At the same time, they currently expose automotive supply chains to unprecedented levels of supply risk (Schmid, 2020; Ghezzi et al., 2025). Price volatility, geopolitical tensions, regulatory pressure, and sustainability concerns increasingly shape access to these materials and, consequently, firms' operational and financial performance (Løvik et al., 2018; Herrington & Gordon, 2024). Recent policy initiatives, particularly in Europe, have emphasised the strategic importance of securing the supply of CRMs as a prerequisite for industrial competitiveness, innovation, and strategic autonomy over critical resources (Draghi, 2024). However, from a managerial perspective, the global challenge is how automotive supply chains can effectively manage their exposure to CRM-related risks in day-to-day operations, while maintaining cost discipline, compliance, and supply continuity.

While policy documents and academic research often propose solutions such as circular economy (CE), supply diversification, or reshoring (Løvik et al., 2018; European Commission, 2023), managers frequently face practical constraints, including limited availability of secondary materials, immature technologies, supplier lock-ins, capital-intensive transitions, market volatility and rising compliance and disclosure costs (Knoeri et al., 2013). As a result, many firms struggle to identify what practices to adopt, understand how to operationalise them under different regulatory, geographical, and supply chain structures, and assess the performance trade-offs these decisions entail. What remains insufficiently understood, especially from a managerial standpoint, is how automotive suppliers exposed to distinct CRM supply risks deploy mitigation practices within global supply chains and how these practices impact performance. This research addresses this gap by translating insights from an in-depth qualitative study of three global automotive component suppliers operating in Asia, Europe, and North America. By comparing these firms and their distinct CRM risk profiles and regulatory environments, the article provides practitioners with concrete lessons and empirically grounded guidance on how CRM supply risks differ across contexts, which mitigation practices work best in specific contexts, and how these practices jointly support supply chain resilience and sustainability.

Methods

To generate actionable insights into how automotive firms manage supply risks associated with CRMs, this study employs an in-depth, multiple-case research design. This approach is particularly suitable for exploring complex and evolving phenomena, such as CRM supply risks in real operational settings, where standardised solutions rarely apply uniformly across firms or regions (Eisenhardt, 1989; Yin, 2009). The study focuses on three large automotive component suppliers operating at comparable supply chain tiers but embedded in different geographical and regulatory environments: Asia, Europe, and North America. The firms were purposefully selected to ensure comparability in governance structures and supply chain roles, while capturing differences in CRM exposure, regulatory pressure, and market conditions (Eisenhardt, 1989). Each company manufactures CRM-intensive components, such as permanent magnets, transmission systems, or e-mobility solutions and is directly and indirectly exposed to CRM supply risks. Primary data were collected through semi-structured interviews with senior managers responsible for purchasing, supply chain management, and sustainability, ensuring informed perspectives on both risk exposure and mitigation decision-making (Yin, 2009). Interviews were conducted between February and June 2025, lasted approximately one hour, and followed a structured protocol covering three core areas: CRM supply risk exposure, mitigation practices, and performance implications. Interview data were complemented with secondary sources, including annual and sustainability reports, to triangulate evidence and strengthen robustness (Eisenhardt & Graebner, 2007).

Findings

The findings show that CRM supply risks manifest differently across automotive suppliers depending on their supply chain position and geographic location. Direct exposure to CRMs, as in the case of the Asian supplier, leads to a strategic focus on securing long-term access through upstream partnerships, supplier diversification, and in-house preparedness measures such as internal recycling, safety stocks, and scenario planning. This approach ensures material continuity and pricing stability but relies heavily on geographic concentration and long-term policy consistency. In contrast, the European supplier, predominantly exposed to indirect risks, prioritises financial and contractual instruments, including hedging, index-linked agreements, and vendor-managed inventory to absorb volatility without breaking compliance constraints. This is complemented by a global risk management structure that dynamically reallocates sourcing across facilities, and by cascading certification requirements down the supply chain to ensure traceability and alignment with evolving regulations, particularly around carbon emissions and origin disclosure. The North American company focuses on excluding restricted sources, auditing suppliers, and sourcing from producers with low-emission profiles, especially for resource-intensive components. Here, technological investments in transparency tools and scenario analysis for forthcoming regulations are used to anticipate disruptions and proactively reconfigure sourcing portfolios. Across all cases, CE practices emerge as complementary mechanisms that support long-term risk mitigation by reducing exposure to primary CRM markets and embedded emissions, while remaining constrained by technological maturity and material availability. Moreover, emissions disclosure, origin screening, and certification cascades enable firms to identify suppliers that can deliver both compliant and lower-impact materials, thereby expanding the pool of eligible sourcing options. In this vein, compliance shifts from an ex-post reporting obligation to an ex ante operational capability that shapes supplier selection, cost governance, and reconfiguration speed during disruptions. When supported by digital traceability and regulatory alignment, these practices demonstrate to lower embedded emissions, reduce dependence on primary extraction, and improve reputational risk management.

Managerial implications

- CRM risk management requires orchestration, rather than isolated interventions: Effective mitigation arises from the intentional combination of access, coordination, financial, governance, and compliance mechanisms, whose value lies in how they are aligned and sequenced, rather than in the adoption of any single practice.
- Resilience is built on the ability to assess options before disruptions happen: Firms that treat supplier eligibility, origin compliance, and emissions disclosure as proactive choices in supplier selection, expanding their feasible action space in line with current regulations and minimising reconfiguration time during shocks.
- CE practices have a role in managing long-term supply risk exposure: Recycling, secondary sourcing and low-emission material pathways do not replace conventional CRM supply sources, but progressively dampen dependency on primary extraction, lowering systemic exposure to geopolitical, environmental and regulatory volatility.
- Cost stability and sustainability performance are increasingly interconnected: Integrating emissions, origin, and compliance data into sourcing and cost governance reshapes total cost considerations, enabling firms to balance short-term price volatility with long-term resilience and sustainability goals.
- Interdependence across supply chain tiers heightens both risks and solutions: CRM supply risk is rarely manageable at the firm level alone; instead, it relies on cross-tier coordination and shared standards that align suppliers' capabilities, validation processes, and compliance requirements.

Conclusion

Managing supply risks associated with CRMs has become a strategic imperative for firms operating in CRM-intensive industries, such as the automotive industry. This study shows that mitigation is not about selecting the "right" practice in isolation, but about constructing coherent and context-sensitive portfolios of practices that address both short-term operational continuity and long-term regulatory and sustainability expectations. Firms operating in different geographies and at different tiers in the supply chain face structurally distinct risk exposure profiles related to CRM supply. As a result, they adopt different configurations of mitigation practices, ranging from strategic partnerships and hedging mechanisms to digital traceability and circular sourcing pathways. What distinguishes the most advanced approaches is not just which practices are used, but also how they are embedded in sourcing decisions, supplier governance, and regulatory compliance. In this context, compliance is not treated as a burden, but as an enabler of resilience and a filter for supplier selection. While CE practices remain constrained in the short term, they represent a structural lever for gradually reducing exposure to critical dependencies when integrated with procurement and compliance systems. As CRM demand and scrutiny continue to rise globally, those firms that design their supply chains around resilience, transparency, and circularity will be better positioned to navigate volatility and capture long-term value.

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Hydrogen mobility through industrial symbiosis; the SFBM S.p.A. approach

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Abstract

This study examines the integration of industrial symbiosis into sustainable urban mobility through the SFBM S.p.A. case, analysing how hydrogen and hydro biomethane technologies mediate tensions between urban hyper acceleration and qualitative deceleration. Using a multidisciplinary approach, it examines technical, governance, and cultural dimensions of the transport energy transition—responsible for 25% of global CO_2 emissions—through experimental validation, policy analysis, and socio-technical theory. Findings indicate that hydrogen mobility fosters reflexive, decelerated urban paradigms while maintaining technological efficiency (500–600 km autonomy, fossil equivalent refuelling). The SFBM S.p.A. model demonstrates how industrial symbiosis—linking waste derived biomethane with hydrogen blends—operates within multilevel governance and public-private partnerships to advance smart cities. The research contributes to both theory and practice by framing hydrogen mobility as a sociotechnical laboratory where acceleration legacies are reconciled with deceleration imperatives in evolving urban systems.

Keywords: Industrial symbiosis; Hydro biomethane; Hydrogen mobility; Urban transition; Cultural deceleration.

Introduction

The transition toward sustainable urban and industrial models necessitates a profound reconfiguration of traditional productive, logistical, and infrastructural paradigms [1]. Within this context, characterized by interconnected environmental and digital transitions, industrial symbiosis emerges as a pivotal instrument of the European Green Deal, designed to foster a circular economy that synergistically integrates innovation, cooperation, and sustainability. From both theoretical and applied perspectives, industrial symbiosis distinguishes itself as a collaborative practice oriented toward maximizing resource value through efficient exchanges of materials, energy, services, and competencies among firms, thereby promoting closed loop production cycles and mitigating environmental impacts [2]. Far from constituting a mere technical instrument, it functions as a mechanism capable of stimulating collective innovation, bolstering territorial resilience, and catalysing sustainable economic development dynamics. At the national level, the Draghi Report underscores the imperative to adopt innovative and sustainable industrial policies, with particular emphasis on decarbonization and the modernization of productive and mobility infrastructures as cornerstone elements for ensuring competitiveness and balanced development within European and global contexts. The Report further highlights the critical role of digitalization, which redefines productivity boundaries by integrating social inclusion and urban quality of life dimensions. In direct response to these challenges, hydrogen derived from renewable sources constitutes an innovative and strategic solution for abating emissions in the transport sector, as elaborated in the subsequent section.

Methods

This study is based on an in-depth analysis of the SFBM S.p.A. project, adopted as a representative case study of the application of industrial symbiosis to the energy transition in the sustainable mobility sector. The transport sector, responsible for approximately 25% of global CO_2 emissions and characterized in Italy by a 6.7% increase in emissions between 1990 and 2023 [3], requires innovative solutions within a framework where, although electric mobility predominates for passenger vehicles, heavy transport highlights diversified needs in which hydrogen technologies (FCEV and HICEV) are assuming a central role, as recognized by the National Hydrogen Strategy.

The investigation relies on a multidisciplinary approach that integrates three orders of analysis: (i) technical engineering, aimed at understanding the production and use processes of idrobiometano, resulting from the integration of biomethane produced by anaerobic digestion of organic waste, agricultural scraps, and livestock residues, and hydrogen; (ii) systemic, which analyses multilevel governance and public-private partnerships supporting technological innovation and project scalability; (iii) cultural, aimed at interpreting the social and communicative dynamics connected to the transition, particularly the tension between the dominant model of urban hyper-acceleration and the need for a qualitative and shared deceleration of mobility.

The methodology includes the detailed analysis of technical and scientific documents produced by the SFBM project, including experimental tests developed in collaboration with universities and the National Research Council, which have validated the safety and performance of mixtures containing up to 25% hydrogen and confirmed the robustness of high-pressure cylinders for concentrations up to 60% hydrogen. These technical data are integrated with the analysis of national regulatory directives and reports, such as the National Hydrogen Strategy 2024 and the ISPRA Report [1], as well as external quantitative data such as hydrogen demand projections adapted from international literature [4]. The approach adopts the multilevel perspective to interpret interactions between niche innovations, established regimes, and external contexts, with references to the literature on industrial symbiosis and sociological theories on social acceleration and urban space [5,6,7], thus ensuring a holistic understanding of the phenomenon. The most relevant methodological limitations include the focus on a single national case study and the predominant reliance on secondary sources, while future research is planned to extend the investigation with primary data collected through stakeholder interviews and comparative analyses with similar European cases. generate actionable insights into how automotive firms manage supply risks associated with CRMs, this study employs an in-depth, multiple-case research design. This approach is particularly suitable for exploring complex and evolving phenomena, such as CRM supply risks in real operational settings, where standardised solutions rarely apply uniformly across firms or regions (Eisenhardt, 1989; Yin, 2009). The study focuses on three large automotive component suppliers operating at comparable supply chain tiers but embedded in different geographical and regulatory environments: Asia, Europe, and North America. The firms were purposefully selected to ensure comparability in governance structures and supply chain roles, while capturing differences in CRM exposure, regulatory pressure, and market conditions (Eisenhardt, 1989). Each company manufactures CRM-intensive components, such as permanent magnets, transmission systems, or e-mobility solutions and is directly and indirectly exposed to CRM supply risks. Primary data were collected through semi-structured interviews with senior managers responsible for purchasing, supply chain management, and sustainability, ensuring informed perspectives on both risk exposure and mitigation decision-making (Yin, 2009). Interviews were conducted between February and June 2025, lasted approximately one hour, and followed a structured protocol covering three core areas: CRM supply risk exposure, mitigation practices, and performance implications. Interview data were complemented with secondary sources, including annual and sustainability reports, to triangulate evidence and strengthen robustness (Eisenhardt & Graebner, 2007).

Findings

Hydrogen mobility addresses societal demands for qualitative deceleration by integrating technological efficiency, autonomy of 500–600 km and refuelling times equivalent to fossil fuels, with urban quality of life enhancements, extending beyond transport decarbonization, which accounts for 25% of global CO_2 emissions. This paradigm shift promotes sustainable, humane, and reflexive mobility practices that redefine efficiency as a balance of energy transition, territorial liability, and temporal rhythms. Urban culturally, hydrogen technologies renegotiate mobility's time space dynamics, countering hyper-acceleration hegemony with rapid sustainable integration that fosters critical reflection in daily urban practices. SFBM S.p.A. exemplifies this as a mediating model through industrial symbiosis, combining hydro biomethane from waste with CNR validated 60% H_2 cylinders to reorient innovation toward equilibrated mobility. Multilevel governance, public and private partnerships, stakeholder participation, and urban regeneration at SFBM S.p.A. enable smart city advancements that simultaneously achieve efficiency, sustainability, and quality of life improvements. However, hydro biomethane mobility presents significant limitations that must be overcome for full scalability. These include dependence on limited production and distribution infrastructures, with high costs for biomethane purification and hydrogen blending (up to 60% CNR validated), hindering widespread diffusion in smart cities. Variability in organic waste quality for anaerobic digestion leads to fuel performance instability, necessitating advances in stabilization technologies and resilient supply networks. Market immaturity, with hydrogen demand projections rising but refueling infrastructure below 1% of current needs in Italy, requires targeted public-private investments and subsidy policies to compete with electric mobility. These challenges, combined with sociocultural acceptance barriers, outline research trajectories to bridge niche innovations and established regimes, as per the multilevel perspective.

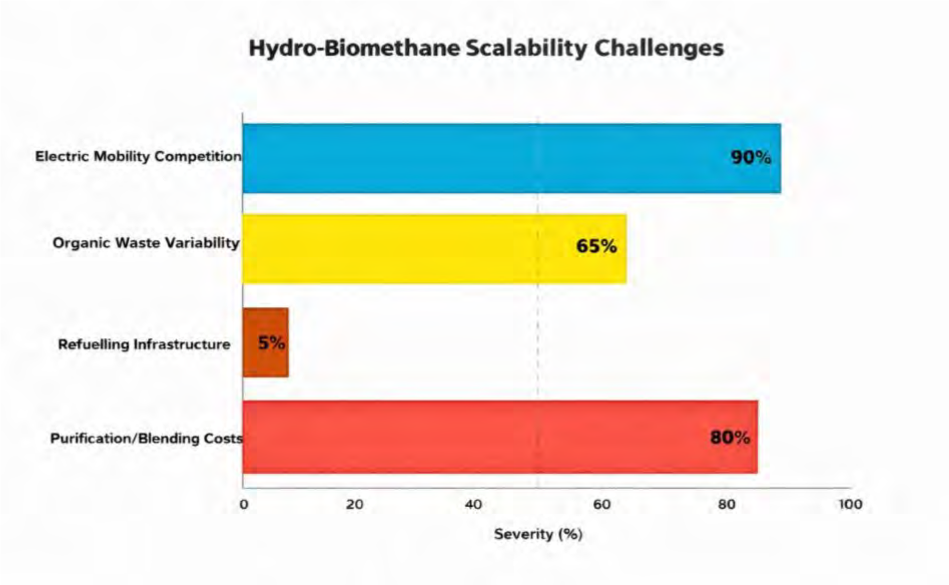

Figure 1. Comparative Barriers To Hydro Biomethane Adoption Vs. Electric Mobility In Italy (Data Adapted From National Hydrogen Strategy 2024 And ISPRA Report 414/2025.

These findings position hydrogen ecosystems as sociotechnical laboratories bridging acceleration legacies and deceleration imperatives in urban evolution.

Conclusion

The introduction of hydro biomethane represents an efficacious intermediate pathway in the decarbonization of transport, enabling significant emission reductions while utilizing extant infrastructural assets. The SFBM S.p.A. model innovatively integrates biomethane derived from anaerobic digestion with hydrogen blends, achieving technical benchmarks such as extended vehicle autonomy (>500 km) and validated safety standards (CNR certification). These findings underscore the viability of hybrid gaseous fuels within existing mobility frameworks, highlighting a paradigm of industrial symbiosis that can be extrapolated to diverse low emission urban industrial contexts. Notwithstanding these advancements, sociocultural acceptance remains a critical barrier. Theoretically, this research contributes to the integration of sociotechnical transition theory with empirical evidence, marrying technical innovation with cultural frameworks that critique urban hyper-acceleration and endorse qualitative deceleration for urban sustainability. Practically, it advances the conceptualization of industrial symbiosis as a nexus for resource optimization and circular economy principles, operationalized through multi stakeholder governance structures that reconcile technological feasibility with social inclusivity and infrastructure scalability. Strategic development should pivot beyond incremental regulatory adjustments towards an anticipatory governance paradigm that incorporates adaptive policy instruments enabling dynamic hydrogen blending thresholds responsive to evolving scientific evidence. Communication strategies must transcend traditional informational campaigns, leveraging discourse analysis and framing techniques to deconstruct acceleration myths and cultivate a sociotechnical imaginary conducive to sustained behavioural change. Moreover, advancing interdisciplinary research through multilayered comparative frameworks will enable differential policy designs reflecting regional cultural and regulatory heterogeneities, thereby enhancing technology transfer efficacy and systemic sustainability transitions.

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From circular economy to regenerative agriculture: the case of pollina PAV

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Abstract

This paper presents the pilot production of POLLINA PAV, an innovative biofertilizer/biostimulant derived from poultry manure via a patented enzymatic biological treatment, as a circular economy practice. The process consists in poultry manure maturation in piles, using a vegetal enzymatic preparation that fosters both aerobic and microaerophilic conditions, resulting in a stabilized product rich in organic matter and essential nutrients, including nitrogen, potassium, and phosphorus predominantly present in struvite form. Characterization of the final pellets revealed an almost neutral pH, reduced salinity, and absence of pathogenic bacteria; characterization showed the presence of phosphatase activity, able to catalyze organic phosphorus mineralization, enhancing soil phosphorus availability for plants, thus reducing P inputs, a critical raw material. The POLLINA PAV biofertilizer offers multifunctionality: nutrient supply, soil organic matter restoration, microbial stimulation, and enhanced phosphorus cycling, consistent with regenerative agriculture objectives of soil health, ecosystem service provision, supporting sustainable crop production systems.

Keywords: Biofertilizer; Enzyme; Phosphatase; Poultry manure; Regenerative agriculture.

Introduction

The need for food and feed increases with population growth, and it is often associated with increase in by-products and waste generation. Poultry manure/litter (PM) represent the main by-product in poultry cycle, both for meat and egg production. In Europe, PM production accounts for 25-30 Mt/y and Polland with 4,5 Mt/y is the main producer [1]. In 2018, the principal poultry producers in the EU-28 were: Poland (16.8%), UK (12.9%), France (11.4%), Spain (10.7%), Germany (10.4%) and Italy (8.5%, with about 2 Mt/y manure) [1]. These by-products need proper collocation and recycling, according to Circular Economy strategy to conserve resources. Their final utilization or disposal is in soil, for agricultural purposes. They are raw materials for energy and/or fertilizer production.

Agriculture is facing important challenges, such as climate change effects, soils degradation, difficult economic sustainability for farmers, with increased cost for energy and fertilizers, and generational turnover. Currently over 60% of soils in Europe are unhealthy, according to the 19 indicators defined by European Soil Observatory [2], in particular SOM (Soil Organic Matter) depletion, erosion, loss of biodiversity. Therefore, the supply of Organic Matter (OM) is crucial for physical and biological fertility, for the maintenance of ecosystem services, and for C sequestration to mitigate climate change (soil as a sink for Carbon).

New business models have been developed for agriculture systems that allow for the maintenance of resources and productivity, as well as income for farmers. Currently, Regenerative Agriculture (RegenAg, RA) is recognized as a tool for soil health and the maintenance of agricultural productivity and natural capital [3]. Pillars of Regenerative Agriculture are the use of organic fertilization for restoring soil fertility leading to broader ecosystem benefits including water quality, biodiversity, and carbon sequestration.

This paper presents the first application of a new biological treatment of poultry manure and litter to obtain biofertilizer/biostimulant POLLINA PAV (Vegetable Active Principles) in the organic supply chain. POLLINA PAV is obtained according to new patent [4], as a further step beyond project LIFE17 ENV/IT/POREM [5]. The goal is to develop flexible and versatile techniques and products that can be applied in conventional agriculture, in the organic sector, and in new scenarios such as Regenerative Agricolture.

Attention was focused on P, recognized as a critical raw material, CRM [6]. The technique was developed to obtain a biofertilizer/biostimulant that provides nutrients but also has the capacity to enhance the availability of nutrients present in the soil. In fact, P is often present in soil, but only a small fraction is available for plants. It was investigated the presence of phosphatase, a group of enzymes that catalyse the hydrolysis of esters and anhydrides of phosphoric acid, releasing inorganic P and phosphate ions, assimilable by plants. This can improve soil P availability, to reduce P input needs. Enhancing the availability of nutrients in the soil or rhizosphere, particularly within the root zone, constitutes a requisite function for biostimulants as per Regulation (EU) 2019/1009.

Methods

Two different raw materials were tested: poultry manure from laying hens (PM1) and poultry litter from broilers (PM2), both from organic farming. Pilot tests were carried out at Agrofertil plant: two piles of about 15 tons each undergone a maturation process for 100 days as described in patent, to obtain an organic fertilizer/biostimulant. It is a simplified and energy saving treatment. Treatment is based on the use of vegetal enzymatic preparation (adaptive complex system) inserted inside pile during its formation, in dose of about 0.5 kg/ton PM and subsequent biostabilization in batch static pile (Figure 1). It is simplified composting, with aeration via natural convection. The "microenvironmental" conditions induced by the process lead to the creation of at least two zones within the pile: a surface layer, in contact with the air, in completely aerobic conditions, and an internal zone, in microaerophilic conditions, i.e., with a reduced O2 concentration, where the processes of intense mineralization are therefore slowed. Final products were pelleted at low temperature.

The temperature trend was automatically monitored on the surface and at a depth of 1 m depth the pile. The measurements were taken using IoT devices (Taua architecture). The data were sent to the server and displayed on the system dashboard.

Substrate evolution during treatment was assessed with matrices sampling (t = 0, t = 75 days maturation and t=100 days, for final pelletized biofertilizer) and subsequent analyses.

Analytical methods

The matrices were subjected to chemical-physical, physical and biological characterization.

pH and CE were measured at a 1:5 solid: liquid ratio and then measured, after centrifuging and filtering through ash-less filter paper (Albet 145 110). Volatile substance/Organic Matter was determined via calcination (550°C for 6 h). TOC (Total Organic C) e Ntot were measured with elemental analyzer LECO C, N, S. Watersoluble fraction of TOC and N (TOCws and Nws: on the same extraction, were quantified with a TOC analyzer (TOC- 5050A, Shimadzu). Macro and Microelements were determined using an inductive optical emission spectrometer (ICP-OES, model ICAP 6500 DUO THERMO).

Biological characterization included respiration and enzymatic activities connected to C, N and P. Phosphatase activity was determined by the method of Tabatabai and Bremer (1969).

Figure 1. Poultry manure: r) manual insertion of vegetal enzymatic preparation (complex adaptative system), during heap formation and l) final heap, in evidence temperature monitoring system

Findings

Characterization of the final pelletized fertilizers showed an almost neutral pH, reduced salinity, and absence of pathogenic bacteria (Table 1). Process monitoring showed a profile of $T > 65$°C required for sanitization, over a few weeks.

Final fertilizers are very rich in Organic Matter in both cases, with all nutrients and micronutrients (data not shown) to prevent deficiencies of elements that can affect production (law of minimum). Organic matter content exceeds 70%, with total organic carbon up to 35%, and approximately 8% humic substances and 8% available, indicating maturity and stability. Nitrogen content is high (>3.5%).

Special features are connected to P: it contains about 2% of P_2O_5, mainly in the struvite form, which has low hydrosolubility but is available for plants, so that to reduce leakage. About 20% in water soluble form. Furthermore, phosphatase enzymatic activity in the biofertilizer reaches 10-15 µmol PNP/g h, useful to interfere with P present in soil to transform P organic compounds into forms available for plants.

Table 1. *Chemical – physical characterization of final pelletized biofertilizer*

Parameter	Measure Unit	PM1 (PELLET)	PM2 (PELLET)
pH		7.50	7.53
CE	mS/cm	3.56	3.52
Humidity	%	16.58	14.43
Organic Matter	% DM	72.34	75.78
TOC	g/100g	33.63	38.78
Cws	g/100g	8.24	8.61
Chumic	g/100g	7.74	8.32
P_2O_5	g/100g	1.99	1.64

Discussion/Conclusion

The final organic fertilizers/biostimulants POLLINA PAV are obtained by a circular economy technique. They are very rich in Organic Matter and Carbon, and contain all the necessary nutrients and micronutrients to prevent deficiencies that could compromise production. The distinctive features concern phosphorus:

- They contain about 2% P2O5, mainly in the form of struvite; Struvite is a slow-release fertilizer for N and P, with low water solubility but availability to plants, reducing losses;
- They present of phosphatase activities, which release inorganic phosphates, available for plants. This improves P availability in the soil, reducing the need for external inputs – a crucial aspect for phosphorus, classified as a Critical Raw Material (CRM) and it is consistent with biostimulant function.

Final organic fertilizers are versatile, applicable in conventional agriculture, organic production, and Regenerative Agriculture. The POLLINA PAV biofertilizer offers multifunctionality: nutrient supply, soil organic matter restoration, microbial stimulation, and enhanced phosphorus cycling, coherent with regenerative agriculture objectives of soil health, enhancement of biodiversity, and reduction of greenhouse gas (GHG) emissions, with CO_2 sequestration in soils.

Further field validation is recommended to quantify nutrient release dynamics and crop responses under diverse agroecosystems, integrating economic and environmental sustainability assessments including carbon credit potential and biodiversity enhancements, also in Regenerative Agriculture business models. New business models can be investigated, in which income from agricultural production can be integrated by revenues from environmental services (credits from CO_2 sequestration and biodiversity enhancement). In fact, soil health is directly linked to competitiveness, a sustainable competitiveness based on economic aspects, but also on environmental respect and the reduction of inputs.

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Green Hydrogen for Sicily's energy transition: technologies and material circularity

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Abstract

The ecological transition is a critical challenge for Europe, especially for regions like Sicily, which combine high renewable energy potential with infrastructural limitations. In this context, green hydrogen emerges as a strategic tool for decarbonization and for enhancing the regional energy system. This study analyzes green hydrogen production in Sicily, focusing on water electrolysis powered by renewables, which enables CO_2-free hydrogen generation for industrial and transport applications. The research also explores the innovative reuse of industrial molybdenum waste, transformed through nanostructuring into electrodes and catalysts, reducing reliance on scarce materials and promoting circular economy practices. By evaluating renewable resource availability, regulatory frameworks, and environmental impacts, the study highlights technology-specific opportunities and challenges. Recommendations are provided to integrate the green hydrogen value chain into Sicily's ecological transition strategy, emphasizing infrastructure development, materials innovation, and supportive policies to maximize sustainability, efficiency, and regional competitiveness.

Keywords: Biofertilizer; Enzyme; Phosphatase; Poultry manure; Regenerative agriculture.

Introduction

The ecological transition represents one of the most urgent and complex challenges of our time, requiring a fundamental restructuring of economic growth, social welfare, and environmental management. In Italy, this challenge is heightened by environmental fragility, exposure to climate-related risks, and the concentration of valuable cultural and natural assets. Policy frameworks such as the Piano per la Transizione Ecologica (PTE) and the 2030 Agenda for Sustainable Development provide guidance for building resilient systems that integrate environmental, social, and economic goals, while climate-induced events like droughts, flooding, and landslides underscore the need for effective mitigation and adaptation strategies.

Sicily holds a strategic position within this context. Its central Mediterranean location and abundant solar and wind resources offer significant renewable energy potential, though infrastructural limitations constrain full exploitation. Green hydrogen, produced via water electrolysis powered solely by renewable electricity, emerges as a key technology to support decarbonization and manage renewable intermittency (Bahman et al., 2024). The process, however, depends on critical materials such as platinum, iridium, and rare earth elements, raising economic and environmental concerns. Innovative approaches, including the reuse of industrial molybdenum waste, offer sustainable alternatives for electrodes and catalysts, with nanostructured residues demonstrating potential to replace scarce elements and promote circular economy practices (Costanzo et al., 2024). Green hydrogen also enhances energy independence by storing surplus renewable electricity (Ponzio et al., 2021).

This study explores Sicily's green hydrogen potential, evaluating local renewable resources, technological options, regulatory frameworks, and material considerations, and proposes strategies to integrate hydrogen into the island's sustainable energy transition.

Methods

The analysis is grounded in an assessment of Sicily's renewable endowment, hydrogen production technologies, materials availability, and regulatory environment. Sicily's environmental and climatic characteristics make it one of the Italian regions with the greatest capacity to generate solar and wind energy, and consequently one of the most suitable for hydrogen production through renewable-powered electrolysis. Hydrogen in this setting acts as an energy vector capable of absorbing otherwise unused renewable electricity and supplying sectors that are difficult to electrify, such as heavy industry, long-distance transport, and maritime mobility.

The study examines the principal electrolysis technologies currently available. Although all systems share the same fundamental physico-chemical principle—splitting water into hydrogen and oxygen using electricity from renewable sources—they differ significantly in efficiency, operational conditions, material requirements, and technological maturity (Matarazzo et al., 2024). Alkaline electrolyzers, the most established and widely used technology, rely on potassium or sodium hydroxide solutions. They offer robust and cost-effective operation at moderate temperatures, but their slower response to variations in electrical load limits their compatibility with highly intermittent renewable sources.

Proton Exchange Membrane (PEM) electrolyzers use solid polymer membranes that allow proton conduction while separating gases. Their ability to operate at high current densities and rapidly adapt to changes in power input makes them particularly suited to fluctuating renewable generation. However, their heavy dependence on noble metals such as platinum and iridium significantly increases costs and raises concerns relating to supply security and environmental impact. Current research increasingly focuses on replacing these critical materials with more abundant and accessible alternatives, such as catalysts derived from recycled industrial molybdenum waste.

Solid Oxide Electrolysis Cells (SOEC) represent a third major category. Operating at temperatures between 650 and 850 °C and using ceramic electrolytes that conduct oxygen ions, SOEC systems can achieve very high efficiencies, especially when their heat demand is met by industrial waste heat, geothermal energy, or concentrated solar power (Flis, 2023). Their high-temperature operation requires advanced and durable materials, which increases costs and limits their current deployment.

The analysis also considers emerging hybrid solutions such as Anion Exchange Membrane (AEM) systems, which combine some advantages of both alkaline and PEM technologies, and innovative approaches like direct seawater electrolysis, which remains at an early research stage but could represent a promising pathway for coastal regions with abundant renewable resources but limited access to freshwater.

Findings

The comparative evaluation of alkaline, PEM, and SOEC electrolyzer technologies highlights that each presents unique advantages and constraints depending on the operational and environmental context. Alkaline electrolyzers currently offer a balanced solution in terms of cost, durability, and limited reliance on critical raw materials. Their use of abundant and widely available metals, such as nickel and steel, reduces both economic and ecological risks, although their slower response to fluctuating renewable electricity represents a significant limitation when integrating with variable solar and wind generation (McKenzie et al., 2024). By contrast, PEM electrolyzers excel in operational flexibility, enabling rapid adjustments to intermittent renewable output and thus maximizing the utilization of certified clean electricity. However, the dependence of PEM systems on noble metals such as platinum and iridium increases both upfront costs and life-cycle environmental impacts. Research into partial substitution with industrial molybdenum residues offers a promising pathway to enhance sustainability while reducing overall material criticality.

SOEC technology, operating at high temperatures and using ceramic electrolytes, provides the highest conversion efficiencies, particularly when combined with renewable or low-cost heat sources. In such configurations, the environmental benefits are significant because electricity demand can be partially offset by thermal integration. Nevertheless, technological immaturity, high costs, and sensitivity to thermal stress continue to restrict large-scale deployment. The regulatory environment strongly shapes the competitiveness of these technologies. DL 144/2022, which requires temporal matching between renewable electricity generation and electrolysis, inherently favors PEM systems capable of rapid load-following, while alkaline electrolyzers require stable renewable sources or supplementary storage to comply, and SOEC systems remain less adaptable to variable electricity profiles.

MASE Reform 3.2 further influences technology selection by providing financial and procedural incentives, which favor different approaches depending on project design. Continuous industrial operations paired with dedicated renewable plants benefit from the low capital costs and long operational life of alkaline systems, whereas SOECs achieve efficiency gains where renewable heat sources, such as concentrated solar power or geothermal energy, are available. In scenarios dominated by highly variable renewable supply without extensive storage, PEM electrolyzers remain the most suitable choice due to their operational flexibility.

To quantify dependence on scarce materials, the study introduces the Critical Raw Material Substitution Index (CRM-SI), ranging from 0 (full dependence) to 1 (full substitution).

Table 1. CRM-SI calculated

ELECTROLYSIS TECHNOLOGY	KEY MATERIALS	CRITICAL RAW MATERIALS INVOLVED	CRM – SI (0-1)
AEL (AlkalineElectrolysis)	Nickel, steel	Low dependence on CRMs	0,8
PEM (Proton Exchange Membrane)	Pt, Ir, PolymerMembrane	Platinum and Iridium(highly critical)	0,1
PEM with recycled Mo-based catalysts	Recycled Mo + reducedshare of Pt/Ir	Partial substitution of nobl e metals	0,6
SOEX (Solid OxideElectrolysis C ells)	Rare earth elements, a dvanced ceramics	Rare earth elements(mode rate criticality)	0,4

Alkaline electrolyzers score high due to minimal use of noble metals, PEM systems score low under conventional configurations but improve significantly with molybdenum-based catalysts, and SOECs occupy an intermediate range due to reliance on ceramic and rare-earth components. Analysis of the 2024 molybdenum market shows a 6 percent global supply increase, driven by China, Chile, Peru, the United States, and Mexico, while European

prices remained high between €21,000 and €30,000 per ton, underscoring the material's strategic importance. Italy's role as an importer and processor reflects both dependence on global markets and an opportunity to valorize industrial molybdenum waste within a circular economy.

Sicily's abundant renewable resources, competitive electricity generation costs, strategic location near maritime trade routes, and industrial clusters with high energy consumption create favorable conditions for green hydrogen production and export. Coupled with circular economy strategies, material recycling, and process optimization, these factors enable significant reductions in environmental impacts and position the island as a potentially leading hub for sustainable hydrogen development.

Discussion/Conclusion

The analysis illustrates that Sicily is uniquely positioned within the European and Mediterranean energy landscape. Its combination of natural resources, industrial capabilities, and strategic geography provides a solid foundation for developing a robust and sustainable green hydrogen sector. The role of hydrogen extends beyond being a technological alternative: it becomes a structural connector linking renewable energy generation, industrial processes, infrastructure development, and circular economy strategies.

The results demonstrate that no single electrolysis technology can address all operational and environmental requirements. Instead, a differentiated and site-specific combination of alkaline, PEM, and SOEC systems emerges as the most effective approach for maximizing renewable integration, minimizing costs, and ensuring alignment with regulatory frameworks. The reuse of industrial molybdenum waste, (Costanzo et al. 2024), strengthens the sustainability and resilience of the hydrogen value chain by reducing dependence on critical raw materials while simultaneously promoting circularity.

If supported by stable policy measures, appropriate transmission infrastructure, and targeted public and private investments, green hydrogen production in Sicily has the potential to evolve from a regional initiative into an internationally relevant project. In such a scenario, the island could supply decarbonized hydrogen to energy-intensive industries, support maritime and heavy-duty mobility, and export hydrogen-based products to Mediterranean and European markets. This would not only contribute to Italy's ecological transition but also position Sicily as a strategic energy hub capable of fostering innovation, industrial competitiveness, and environmental sustainability on a wider scale.

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H2 ERA Green Valley

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Abstract

A revolutionary impact: regenerating a brownfield site by converting it into a sustainable circular infrastructure. H2-Era Green Valley transforms the former Bekaert industrial area into a multifunctional hub for green hydrogen production and the promotion of a circular economy. Sustainable innovation: where the sun creates energy, we cultivate the future.

Keywords: Circular economy; Green hydrogen; Industrial regeneration; Renewable energy systems; Sustainable innovation

Introduction

H2-Era Green Valley is an ambitious and concrete example of how innovation can transform environmental challenges into sustainable opportunities.

The project reimagines a former industrial and mining site, converting it into a fully integrated, zero-impact circular industrial ecosystem. At the heart of the complex lies solar energy. Built on 80 hectares of reclaimed land, the photovoltaic power plant will be the largest self-consumption solar facility in Italy. Using bifacial panels with solar tracking, it will generate approximately 140 million kWh per year, supplying nearly the entire energy demand of the site with clean, renewable power.

This energy drives the production of green hydrogen through modular electrolyzers located in a dedicated Hydrogen Valley. With an initial capacity of over 1,400 tonnes per year and the possibility to scale further, hydrogen becomes both an energy vector and a strategic enabler of industrial decarbonisation. Water and electricity — the two essential inputs — are sourced directly on site, ensuring efficiency and autonomy. The project extends innovation beyond energy production into sustainable mobility. A strategically located Mobility Green hub along the Autostrada del Sole will support hydrogen and electric vehicles, serving heavy transport and private mobility with zero emissions, and acting as a key node in the future of clean transport infrastructure.

Circularity is fully expressed in the integration of food production systems. The oxygen generated as a by-product of electrolysis is reused in a high-efficiency fish farm based on recirculating aquaculture systems, drastically reducing water consumption while maintaining environmental balance. At the same time, the recovered heat from the electrolyzers powers Italy's largest vertical farm, where indoor crops achieve productivity levels equivalent to ten times that of traditional greenhouses, using 95% less water. To ensure energy continuity, a large-scale battery storage system guarantees round-the-clock self-sufficiency, stabilising operations throughout the year and reinforcing the resilience of the entire ecosystem.

H2-Era Green Valley is not simply an industrial project. It is a replicable model of ethical and technological innovation, where energy, food, mobility and storage are interconnected in a closed-loop system in which nothing is wasted. By regenerating land, reducing emissions, producing clean energy and healthy food, the project demonstrates how industry can become a positive force for both the environment and society.

Figure 1. Plant Ex-Bekaert

Figure 2. Regenerated Ex-Bekaert site

Figure 3. The ESG principles fulfilled by the H2-Era Green Valley project

Findings

- **Successful regeneration of a brownfield industrial site**

  The project demonstrates that a former industrial and mining area can be fully regenerated into a productive, sustainable, and zero-impact industrial ecosystem, without additional land consumption.

- **Energy self-sufficiency through renewable sources**

  The integrated photovoltaic plant, combined with large-scale battery storage, enables near-total energy self-consumption, significantly reducing dependence on external energy supply and fossil fuels.

- **Scalable green hydrogen production model**

The deployment of modular electrolyzers allows flexible and expandable green hydrogen production, exceeding 1,400 tonnes per year, with on-site availability of both renewable electricity and water resources.

- **Effective circular use of industrial by-products**

  By reusing oxygen and waste heat from electrolysis processes in aquaculture and vertical farming, the project achieves a closed-loop system where no material or energy stream is wasted.

- **Significant reduction in water consumption**

  The integration of RAS-based aquaculture and vertical farming technologies results in up to a 95% reduction in water usage compared to conventional agricultural and aquaculture systems.

- **Zero-emission mobility infrastructure**

  The Mobility Green hub supports both hydrogen and electric vehicles, enabling zero-emission transport for heavy-duty and light vehicles and reinforcing the decarbonisation of logistics and mobility corridors.

- **Continuous operational stability (24/7)**

  The 90 MWh battery energy storage system ensures uninterrupted operation of all industrial processes, guaranteeing reliability, resilience, and energy continuity throughout the year.

- **Positive environmental balance**

  The system produces more oxygen than CO_2 emissions across the integrated processes, contributing to improved local air quality and a net-positive environmental impact.

- **High productivity with reduced environmental footprint**

  The vertical farming system achieves productivity equivalent to ten times that of traditional greenhouses while drastically lowering land and resource use.

- **Replicable and transferable innovation model**

  The project validates a scalable and replicable framework for sustainable industrial reconversion, applicable to other brownfield sites and industrial regions.

Discussion/Conclusion

The H2-Era Green Valley project demonstrates that industrial regeneration can be effectively achieved through an integrated circular economy approach, where energy, production systems, and infrastructure operate as a single interconnected ecosystem. The results confirm that brownfield sites, often considered environmental and economic liabilities, can be transformed into high-value, zero-impact industrial assets without additional land consumption.

From the findings, several general principles can be inferred. First, renewable energy self-consumption combined with energy storage is a key enabler of industrial resilience and autonomy. Second, green hydrogen can act not only as an energy carrier, but also as a central connector between energy production, mobility, and industrial processes. Third, the circular reuse of by-products such as oxygen and waste heat significantly enhances overall system efficiency and environmental performance.

Some limitations and challenges remain. The initial investment required for large-scale integrated infrastructures is substantial, and project implementation depends on regulatory alignment, grid integration frameworks, and permitting timelines. In addition, the scalability of similar models may vary depending on local water availability, land characteristics, and policy incentives.

Despite these constraints, the practical implications of the project are highly relevant. H2-Era Green Valley provides a concrete, operational model for decarbonising energy-intensive sectors, promoting sustainable mobility, and integrating food production within industrial environments. The project also contributes to ESG objectives by addressing environmental sustainability, supporting local economic development, and introducing a governance model based on transparency, efficiency, and long-term value creation.

In conclusion, H2-Era Green Valley represents a replicable and forward-looking model of sustainable industrial reconversion. The project shows that technological innovation, when guided by circular principles and ethical responsibility, can generate positive environmental, social, and economic impacts. It is therefore recommended that similar integrated approaches be considered in future industrial redevelopment strategies, particularly in regions affected by deindustrialisation and environmental degradation.

Human-Centric digital transition in urban waste management: the experience of Alia Servizi Ambientali

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Abstract

Alia Servizi Ambientali S.p.A., the main environmental services provider in Tuscany, has initiated a broad digital transformation programme to improve operational efficiency, transparency and citizen participation in urban waste management. A central component of this evolution is Genius 5.0, a new generation of intelligent waste containers equipped with sensing technologies, user identification systems and IoT-GIS connectivity. The introduction of this technological infrastructure has been accompanied by a deliberate human-centric strategy aimed at strengthening internal competencies, fostering citizen engagement and supporting behavioural change. This paper describes the implementation pathway and the socio-technical approach adopted by Alia, illustrating how technology, organisational learning and participatory processes have been combined to advance circular economy goals and industrial symbiosis. The results obtained demonstrate how a digital transition becomes effective only when aligned with human values, institutional collaboration and an inclusive vision of environmental responsibility.

Keywords: Digital Waste Management; Human-Centric Innovation; Smart Waste Systems; Urban Circular Economy; Industrial Symbiosis.

Introduction

Alia Servizi Ambientali manages integrated waste collection and recycling services for more than 1.5 million inhabitants across the Metropolitan Area of Florence and neighbouring municipalities. In recent years, the company has undertaken a comprehensive transformation of its operational and organisational model, pursuing the dual objective of increasing resource efficiency while strengthening accountability towards both citizens and public institutions. This transition reflects a broader reconfiguration of organisational structures and governance arrangements enabled by digital technologies, particularly within public service contexts where innovation is increasingly driven by environmental, social and institutional objectives rather than purely economic considerations [1,2]. Comparable initiatives across Europe indicate that the Alia experience is not an isolated case, but part of a wider evolution in smart waste management practices. Studies and applied experiences in cities such as Barcelona, Stockholm and Amsterdam demonstrate how the combined adoption of digital technologies and citizen engagement models can effectively support the transition towards circular economy objectives [3,4,5,6]. In parallel, private operators including Enevo in Finland and FCC Environment in Spain have deployed IoT-based collection systems and predictive analytics to enhance operational efficiency and service accountability. Situating the Italian case within this dual landscape of public-sector transformation and private-sector innovation highlights how digital dynamics differ across organisational contexts, reinforcing the need for analytical frameworks capable of capturing such diversity without oversimplification [7].

Within this strategic framework, Genius 5.0 represents a significant technological development. The system introduces intelligent waste containers capable of monitoring fill levels, identifying users and transmitting operational data in near real time through IoT-enabled communication networks. These functionalities enable data-driven collection strategies, support advanced pay-as-you-throw schemes and improve transparency in service provision.

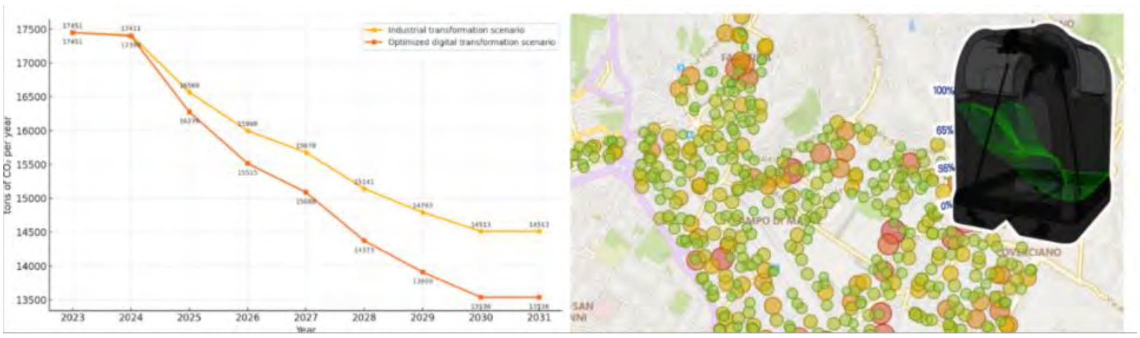

Figure 1. On the left are the annual CO_2 emissions of the collection services; on the right is a rendering of the Genius 5.0 data.

However, the transformation undertaken by Alia was not conceived as a purely technological upgrade. From the early stages, the company acknowledged that the effectiveness of digital tools and processes would largely depend on the people interacting with them, including field operators, technical staff and citizens whose participation is essential for circular economy initiatives. As a result, the digital transition was designed as a socio-technical process that integrates technological innovation with organisational learning and participatory engagement, in line with public-sector digitalisation trajectories shaped by governance, regulatory and societal considerations.

Despite its potential, the integration of circular economy principles through digital innovation raises organisational and governance challenges. Utility companies are required not only to adopt new technologies, but also to reorganise internal workflows, respond to evolving regulatory requirements and actively involve citizens as stakeholders in sustainability-oriented services [8,9]. In this sense, the Alia approach aligns with the broader objectives of industrial symbiosis and the green and digital transition, emphasising governance, replicability and shared responsibility.

Methods

The roll-out of Genius 5.0 required the development of a coherent digital ecosystem capable of supporting both technological and organisational change. On the technological side, the system is based on a network of intelligent containers equipped with volumetric sensors, electronic locks, near-real-time communication modules and user identification devices. The data generated by these components are integrated into an IoT-GIS platform that enables geospatial analysis, optimisation of collection routes, detection of anomalies and certification of operational events through blockchain-based mechanisms.

Figure 2. Data flow.

While this infrastructure provides the technological foundation for a modern waste management system, Alia placed equal emphasis on internal capacity-building. The introduction of digital workflows demanded new competencies among field operators, technicians and administrative personnel. Training programmes were therefore developed to ensure familiarity with data-driven processes, digital diagnostics, remote monitoring tools and updated operational procedures. This investment in human capital contributed to a broader cultural evolution, fostering greater confidence in digital tools and promoting collaboration across organisational units. In parallel with internal preparation, Alia implemented a structured programme of citizen engagement.

Since waste management requires active participation from communities, it was essential to ensure that users understood the functioning and benefits of smart containers. Public communication campaigns, meetings with residents, participatory design sessions and digital interfaces providing feedback on individual contributions were introduced at different stages of the pilot projects. The company also began exploring incentive-based approaches to encourage proper sorting and more sustainable behaviours. Through these actions, Alia positioned the digital transition as a shared process rather than a purely technological imposition.

Findings

The implementation of Genius 5.0, supported by organisational training and structured citizen engagement, produced a set of converging findings that demonstrate the value of a human-centric approach to digital transformation in waste management. The availability of real-time operational data enabled Alia to reorganise several aspects of service delivery. Collection routes were progressively optimised based on actual fill-level conditions, which reduced unnecessary vehicle movements and improved intervention timing, especially in areas characterised by variable waste generation patterns. Remote diagnostics and event logging also facilitated more timely maintenance actions, contributing to a smoother operational workflow and a more efficient allocation of technical resources.

The project also generated important improvements in transparency and accountability. The certification of access events and container status through blockchain mechanisms strengthened the reliability of reported data, supporting emerging pay-as-you-throw schemes and reinforcing trust between the company, municipalities and citizens. This data integrity framework has proven essential in contexts where public authorities require verifiable evidence of service quality and compliance with local regulations. Citizen participation increased in the areas where the system was introduced. Users showed higher engagement with separate collection, better sorting performance and greater willingness to interact with digital interfaces when accompanied by coherent communication initiatives. The feedback collected during pilot phases confirmed that user understanding and inclusion are pivotal for the acceptance of digitally mediated waste systems.

At an organisational level, the initiative stimulated a measurable consolidation of digital competencies. Cross-departmental collaboration intensified, particularly between operational units, ICT functions and customer-facing teams. Staff reported a clearer perception of how data can support operational decisions, indicating a gradual cultural shift towards evidence-based service delivery. Together, these findings illustrate how the combination of technology, organisational learning and community involvement shapes the effectiveness and sustainability of digital transitions in environmental services.

Discussion/Conclusion

The experience conducted by Alia demonstrates that the effectiveness of digital transformation in waste management depends on the integration of technological systems with human competencies, organisational readiness and sustained citizen engagement. Consistent with existing studies on digital transformation in public services, the findings confirm that data-driven tools such as smart containers and IoT-GIS platforms generate tangible benefits only when embedded within organisational structures capable of supporting new workflows, learning processes and collaborative practices [1,2]. In this sense, the results reinforce the principle that digital infrastructures act primarily as enablers rather than autonomous drivers of change, with their value materialising through the behaviours, decisions and interactions of the people involved [7].

Despite these positive outcomes, several limitations should be acknowledged. The implementation was carried out in selected pilot areas, which may not fully capture the heterogeneity of operational, social and institutional conditions across the entire service territory. Citizen behavioural responses were influenced by targeted communication and engagement activities and may evolve differently in contexts characterised by lower digital literacy or reduced institutional trust, as highlighted in previous research on circular economy governance [8,9]. Furthermore, the integration of blockchain-based certification mechanisms is still at an early stage and requires further consolidation to ensure scalability, long-term interoperability and alignment with external regulatory and reporting systems. These limitations do not undermine the relevance of the findings but underline the importance of contextual adaptation, incremental implementation and continuous monitoring.

From a theoretical perspective, this work contributes to the growing body of literature emphasising the socio-technical nature of digital transformation in public utilities. The Alia case supports the view that organisational and behavioural dimensions are as critical as technological innovation in shaping the outcomes of digital transitions, particularly in sectors where public value, accountability and trust are central. From a practical standpoint, the experience provides evidence that early and sustained involvement of staff and citizens enhances acceptance, improves service performance and strengthens institutional accountability. The results also suggest that transparent and certified data streams can play a key role in facilitating policy integration and enabling circular economy models based on differentiated charging schemes and resource optimisation.

In conclusion, the initiative undertaken by Alia illustrates a replicable pathway for organisations seeking to modernise waste management systems within the framework of the green and digital transition. The experience confirms that effective digital transformation requires a balanced combination of technological investment, organisational capacity-building, participatory practices and governance mechanisms that ensure data integrity and social inclusiveness. It is recommended that future deployments expand the scope of pilot testing, strengthen long-term monitoring of citizen behaviour and further develop interoperability frameworks for certified data. These actions will support system scalability and reinforce the role of human-centric digital innovation in advancing circular economy and industrial symbiosis objectives.

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Industrial symbiosis in the textile equipment industrial laundry and linen-hire services

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Abstract

In the procurement process for the low environmental impact industrial laundry and linen-hire services, competing companies that have systematically adopted measures to maximize garment reuse were given priority. The two winning companies presented several industrial symbiosis projects, such as the reuse of linens no longer usable by healthcare providers by non-profit organizations and their sale to startups for repurposing (such as transforming them into bags, backpacks, or blankets). These projects demonstrate how it is possible to optimize resource use and reduce waste by adopting circular economy models. In the procurement process for the low-impact laundry rental service, competing companies that have systematically adopted measures to maximize garment reuse were given priority. The two winning companies presented several industrial symbiosis projects, such as the reuse of linens no longer usable by healthcare providers by non-profit organizations and their sale to startups for repurposing (such as transforming them into bags, backpacks, or blankets).

Keywords: Industrial symbiosis; textiles; Healthcare; Circular Economy; Reuse.

Introduction

Intercent-ER, the Agency for the development of electronic markets of the Emilia-Romagna Region, operates as a central purchasing body and regional aggregator. In addition to streamlining spending by local governments, the Agency aims to contribute to the goals of the 2030 Agenda by promoting efficiency, transparency, innovation, and environmental and social sustainability in public procurement. It also pursues these goals by integrating Green Public Procurement (GPP) practices into its tenders to reduce the environmental impact of public activities.

At the end of 2023, it announced the second edition of the tender "Integrated industrial laundry and linen-hire services with low environmental impact for the Bologna Local Health Authority" for a total of €55,028,400. The tender highlights the "Measures aimed at maximizing garment reuse" defined in paragraph D) point 5 of the CAM (Procurement of the industrial laundry service and rental of textiles and mattresses).

In particular, the ways of maximizing the life extension of garments fall within the process of industrial symbiosis, which means the exchange of resources between two or more dissimilar industries, considering as "resources" not only materials (by-products or waste), but also energy waste, services, expertise [1]. Industrial symbiosis is an important element of environmental sustainability, as defined by Chertow: "Industrial symbiosis engages traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and/or by-products. The keys to industrial symbiosis are collaboration and the synergistic possibilities offered by geographic proximity." [2] and by Neves, et al. "Industrial symbiosis, which allows entities and companies that traditionally be separated, to cooperate among them in the sharing of resources, contributes to the increase of sustainability with environmental, economic and social benefits."

Methods

The initiative is aimed at meeting the needs expressed by the local health authorities. To understand the number of items circulating within a healthcare facility, Table 1 shows some data relating to flat linen and packaged linen in the surgical room:

Table 1. Quantity of flat linen and packaged linen for surgical room operators expressed in pieces per year

Typology	AUSL Bologna	IOR Bologna	IOR Bagherìa	I.R. Montecatone
Flat linen from the department	3.902.502	593.504	81.820	333.200
Packaged linen for the operating room	503.269	144.008	23.435	---------------

The number of employees in uniform is 14,674, the average number of uniform items is 58, and the average number of uniforms provided is 4 for employee, for a total of 3,404,368 items per year.

The GPP assumes a strategical role, becoming a fundamental leverage for innovation policies implementation and contributing to the sustainability of the system, not only from an economic but also environmental and social perspective. The tender used a significant percentage of environmental sustainability criteria were included, then the application of CAM was chosen not only as a technical requirement, but also as a reward, to promote more sustainable supply models that focus on reuse and circularity. Furthermore, to ensure complete monitoring of service performance, the Supplier is required to produce a report on the quantity of garments disposed of at the end of their life because they are no longer usable within the service (for example, if the maximum number of washes required to ensure the preservation of their characteristics has been exceeded and/or the garment is no longer suitable), also indicating the methods for their recovery. This monitoring represents an innovative element compared to previous editions of the tender, offering a useful tool for verifying the environmental sustainability aspects of the service provided.

Findings

The companies that were awarded the service proposed the industrial symbiosis projects illustrated below.

Servizi Ospedalieri SpA

Servizi Ospedalieri SpA, the successful contractor for the Bologna Local Health Authority, is pursuing several initiatives aimed at minimizing waste disposal by extending the life cycle of garments. Some items no longer usable in contracts or discarded from the production process are sent to Fody SB Srl, an innovative socially responsible startup working for a more inclusive and sustainable world.

By integrating innovation, the circular economy, and social inclusion, Fody promotes a positive business model to solve multiple problems simultaneously: reusing leftover production, avoiding waste with a negative impact on the environment, and offering training and employment opportunities to disadvantaged people. At Fody, every resource, both material and human, becomes an opportunity for valorization and growth by using Servizi Ospedalieri SpA's textile waste in new products, such as bags, backpacks, and gadgets in general, or to make blankets that are donated to social initiatives.

For example, Fody used wool blankets and cotton bedspreads from Servizi Ospedalieri SpA, which were earmarked for disposal, for the "The Only Way is Home" initiative, an awareness-raising flashmob held in Piazza della Scala in Milan, which actively involved 250 people. For this purpose, Servizi Ospedalieri donated 3,820 blankets to two organizations (Fondazione Progetto Arca Onlus and the Italian Red Cross) dedicated to protecting the homeless and migrants.

With this new process, the life cycle of Servizi Ospedalieri S.p.a. products changes: at their end of life, instead of being disposed of, products are reintroduced into the community, thus extending the product's lifespan by approximately 2 years and minimizing its environmental impact. Fig. 1 summarizes the results of the Foody project:

Figure 1. The results of the Fody project by Servizi Ospedalieri.

Servizi Italia SpA

Servizi Italia, the company awarded the same laundry rental service, has implemented an advanced lifecycle management system for hospital textiles, aimed at extending their useful life and maximizing material recovery at the end of their service life. Materials no longer useable in healthcare facilities are collected and sent to the laundry in Lastra a Signa, where a virtuous textile recovery and transformation project, the Santa Gemma project, is active.

Here, discarded linen is processed by staff with cognitive disabilities and neurodivergence, creating a process that integrates social inclusion, professional training, and environmental sustainability (Fig. 2). The Santa Gemma project represents a concrete example of a circular economy with a positive social impact, in which environmental care is combined with the valorization of vulnerable groups and the development of new skills for people often excluded from the workforce.

Figure 2. Santa Gemma project by Servizi Italia.

Throughout 2024, Servizi Italia constantly monitored recovery activities, ensuring annual reporting of the results achieved: out of over 680 tons of textile waste (flat and packaged linen), nearly 50 tons were recovered and processed as part of the Santa Gemma project.

The material that could not be repaired or transformed was used to produce rags and other items. Of this, 60 tons were returned to the same hospitals from which they originated, following a closed-loop supply chain logic, while the remaining 570 tons were transformed by third-party companies and put back on the market.

This project demonstrates that it is possible to combine innovation in healthcare services, environmental respect, and social inclusion, generating a positive systemic impact on the local community. A replicable circular economy model that values every stage of the production cycle and every person involved.

The value of the network

"The networks for industrial symbiosis are cognitive/relational tools that aim to enabling the meeting of supply and demand of resources between interlocutors who, due to their economic and social activities, would not otherwise have the opportunity to meet.", as A. Neves states in a recent contribution [3].

In this context, it's important to note that both companies are members of the Retex Green consortium, the leading national consortium of producers for the management of clothing, home textiles, footwear, and leather goods waste, promoted by Confindustria Moda and the Fondazione del Tessile Italiano. The consortium's goal is to make textile (and other) waste circulars, as advocated by all its member companies. Through its network, Retex Green offers support in the recovery and recycling of garments at all stages. The consortium's primary objective is to help companies improve their production processes to minimize waste. At the same time, it aims to train companies, through circular economy projects, in eco-design to create durable and more easily recyclable products.

Retex Green also supported Servizi Ospedalieri SpA and Servizi Italia SpA with pre-consumer services, namely the collection of unsold products and products from expired contracts, often with attractive quality characteristics and suitable for high-quality reuse.

The reuse of Servizi Ospedalieri SpA unsold products sold to the Retex Green Consortium has so far resulted in saving approximately 150,000 kg of CO_2 emissions and 105,000,000 liters of water consumption. The collaboration between Servizi Italia and the Retex Consortium has enabled the recovery of over 32,000 kg of textiles that would otherwise be incinerated by 2024.

Discussion/Conclusion

Intercent-ER's growing sensitivity to the application of rewarding criteria aimed at valorizing industrial symbiosis projects has gone hand in hand with a market increasingly receptive to the adoption of circular economy measures. The industrial symbiosis projects presented by competing companies demonstrate how this method of garments reuse is now extremely widespread, so much so that it allows for the configuration networks that connect different interlocutors, sharing data on the availability of output resources and the demand for raw materials as input [1]. Market maturity could act as a stimulus to find new and broader ways to extend the product life cycle, expanding the product categories beyond textiles and the quantities of recovered products.

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From Firm – Level practices to policy design: empirical evidence on industrial symbiosis adoption

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Abstract

Industrial symbiosis is driving the ecological transition of production systems. However, its adoption is still hindered by several barriers, and targeted incentive policies are required. This study investigates the current diffusion of industrial symbiosis practices, as well as the perceived barriers and drivers, with the aim of providing policy-relevant insights. The paper presents the findings of a survey of 61 companies from seven key industrial sectors in North-West Italy. A cross-sectoral approach was adopted to enhance understanding of sector-specific dynamics and strengthen policy implications. The results reveal significant variations in geographical break-even points for symbiotic exchanges depending on the material involved, as well as marked differences in perceived drivers and barriers across sectors. Six critical areas that affect the implementation of industrial symbiosis are identified. Based on these findings, the study proposes tailored policy recommendations to promote the development and expansion of industrial symbiosis initiatives.

Keywords: Industrial symbiosis; Cross-sectorial analysis; Economic incentives; Technological barriers.

Introduction

Industrial symbiosis (IS) is recognised as a key strategy for achieving green growth by promoting the ecological transition of production systems. Exchanging unused resources optimises the consumption and recirculation of resources. Furthermore, IS is often described as a win-win strategy that combines environmental and economic benefits [1]. Companies can reduce their environmental impact and production costs by avoiding waste disposal and/or using alternative raw materials. Nonetheless, technological, normative, organisational and informative factors affect the feasibility of adopting IS [2].

The present study aims to advance the knowledge in the field of IS in order to inform future policymaking processes that will promote IS within the territory. To this end, a survey was conducted with the objective of analysing current symbiotic practices and to understand perceived barriers and drivers for companies. onmental impact of public activities.

Methods

The present study analysed IS within 7 production chains: agrifood, constructions, petrochemical, textile, energy, chemical, and waste services. The survey was limited to the North-West Region of Italy, which comprises Aosta Valley, Piedmont, and the bordening provinces of Pavia, Varese and Como.

The analysis focused only on symbiotic material flows, i.e. the exchange of waste, by-products and end-of-waste, collectively referred to as production residues [3]. Furthermore, IS practices were investigated according to the binary synergy approach [4], which models IS transactions as a flow between a producer and a utiliser of production residues. Main drivers and barriers identified in IS literature were evaluates through the use of a 5-point Likert scale. The survey was conducted using an online questionnaire supported by LimeSurvey. Filtering criteria were applied during data cleansing to ensure a robust and coherent dataset. The final sample consisted of 61 companies. Data analysis relied on descriptive statistics and cross-sectoral comparisons.

Findings

Current IS practices

72% of the respondents declared that they were implementing circular strategies in terms of input procurement and/or residue management. In particular, 47.5% of them have already adopted IS as a production strategy. Most of these companies engage in symbiotic networks as producers of residues (62%), while only 10% act as utilisers. The remaining 28% are companies that adopt IS for both input sourcing and residue management. Textile, petrochemical and agrifood companies were found to be the most engaged in symbiotic activities.

The geography of the current symbiotic exchanges has been investigated considering the material commodity typology. Textile residues are those that are exchanged over longer distances, with an average travelled km of 656 km. Chemical and plastic residues are exchanged especially at the national level, whilst organic and mineral residues at the province and district level. All symbiotic exchanges are conducted through road transport, with the exception of two cases related to textile residues, which are internationally exchanged through maritime transport.

From a technological standpoint, the valorisation methods employed are predominantly of low technological intensity. For example, plastic and textile residues are primarily recycled mechanically, while mineral residues are used as filler materials. Only organic residues undergo a variety of valorisation processes, such as energy recovery and biocomponent extraction.

Perceived drivers and barriers of IS

74% of respondents considered IS to be a viable strategy in their sectors. However, cross-sectoral comparisons revealed differences. Particularly the construction industry resulted the most confident, whilst 66% of companies in the waste services sector did not consider IS to be a viable practice.

Economic convenience resulted the most important factor driving to adoption of IS. Conversely, technology-related factors such as technology costs and the absence of appropriate valorisation technologies were considered the most significant barriers to IS adoption, followed by a lack of economic incentives, overly restrictive rules, and the high cost of residue valorisation.

Nonetheless, the cross-sectoral approach revealed some divergences. For instance, agrifood companies considered the imagine gain to be the most important factor, whereas environmental policies were considered particularly relevant by the chemical, petrochemical and energy industries. Waste service companies considered a lack of economic incentives and the high cost of technology and valorisation treatment to be the most significant obstacles. The energy and chemical industries considered over-restrictive laws and the high cost of valorisation to be the most relevant barriers.

Discussion

The survey demonstrated that IS practices are already in place within the territory. However, the current level of valorisation technologies employed is low, indicating room for improvement in symbiotic performance through the adoption of innovative technologies. The analysis of current symbiotic practices revealed the geographic break-even point varies for different commodity residues. This may be due to the intrinsic characteristics of the residues and their economic value. For example, the perishability of organic residues may necessitate trading them over shorter distances. Conversely, plastics and textiles, even in the form of residues, have a high monetary value as materials, enabling them to be profitably exchanged over longer distances. It should be noted that road transport was the most common method for conducting symbiotic exchanges. This may undermine the environmental benefits of symbiotic transactions.

The survey highlighted that most sectors view IS as a viable strategy for achieving green growth. Considering the perceived barriers and incentives, economic and technological factors resulted the most relevant. On the one hand, economic convenience is considered the main driver for adopting IS. Conversely, companies request greater economic incentives to make technologies more affordable. It is interesting to note the dual role played by normative factors. While it is a driving factor, compelling companies to adopt a more sustainable production approach due to strict environmental legislation, it also acts as a barrier due to the high operational and bureaucratic costs it imposes.

The cross-sectoral analysis highlights the scepticism in the waste service sector related to IS. As waste companies are able to act as intermediaries between producers and utilisers by transforming waste into End-of-Waste materials, it is crucial to raise their awareness and address their perceived barriers.

The findings of the present survey provide a basis for orienting future policies towards fostering IS adoption. On the one hand, the environmental profile of current IS practices could be enhanced by promoting innovative valorisation technologies and alternative transport methods. Furthermore, since there is no preferential scale for closing the resource loop and that different residues have different geographical break-even points, symbiotic networks should be planned at various scales that take the regional economy into account.

On the other hands, incentive measures should be introduced to help companies overcome the main IS barriers. For instance, economic incentives could be introduced to make technologies more affordable, thereby reducing the cost of residue valorisation. Other economic incentives could encourage IS adoption among companies and reward virtuous production models. The normative framework for by-products and end-of-waste should be clarified to provide greater legal certainty for companies regarding the reuse of production residues. Finally, programmes to raise awareness of the viability of IS should be promoted, especially within the waste service sector.

In summary, the study identified six critical areas affecting the implementation of IS and proposed tailored policy recommendations. Table 1 summarises the main findings and their associated policy implications.

Table 1. Main findings and related policy implications.

Main Findings	Policy Implications
Low technological intensity of valorisation processes	Promoting the dissemination of innovative technologies, both in terms of knowledge transfer and of affordability.
Difference in geographical break-even point based on the commodity of residues	Promotion symbiotic practices on a local basis, considering the predominant sectors in the area.
Road transport as the predominant mode of transport	Promoting alternative transport systems or fuels, e.g., modular transport, transport by train, transport by road with electric vehicles, transport by road with biofuel-powered vehicles.
Lack of awareness in the waste service sector	Raising awareness of waste companies through engagement in IS facilitation programmes and by clarifying regulations in the field of IS.
Economic and technological factors as the most relevant incentives and barriers	Providing financial incentives for the purchase of new technologies. Establishing compensation models for companies that implement virtuous practices.
Normative as both barrier and driver	Increasing stringent environmental legislation. Clarifying regulations in the field of IS (e.g. institutional definition, inclusion of EoW). Simplifying administrative processes.

Conclusions

This study examined the current practices of IS and the perceived barriers and drivers among firms. The cross-sectoral analysis revealed that geographical break-even points for symbiotic exchanges differ depending on the type of resource involved. It also highlighted that technological, economic and regulatory factors affect the adoption of IS in different ways across sectors. Beyond mapping existing practices, the analysis sheds light on the structural and contextual conditions that enable or hinder the development of IS. Examining the findings through a policy-oriented lens highlights implications for both strengthening existing IS initiatives and fostering the establishment of new symbiotic relationships. In this respect, the results suggest the need for differentiated, targeted policy interventions capable of addressing sector-specific barriers and leveraging context-dependent drivers, in order to effectively support the diffusion and scaling up of IS.

Nonetheless, the study has some limitations. Firstly, its limited geographical scope which may undermine its representativeness. Similar considerations applied to the limited number of sectors included in the research. Therefore, future research should extend the geographical scope and include a wider range of sectors to validate and refine the policy implications identified in this study.

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Measuring circularity in food donation networks

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Abstract

This study quantifies the economic impact of surplus food donations from companies to the Banco Alimentare of Catania and examines how these donations reduce operational costs and promote the development of a circular economy model within the agribusiness sector. Food waste generates substantial financial losses for companies due to product depreciation, logistical inefficiencies, storage and disposal costs. Donating surplus food transforms a cost center into an economic opportunity through fiscal incentives that improve financial sustainability. The research aims to quantify circular economy indicators according to the UNI/TS 11820:2022 standard applying them to the case of the Banco Alimentare of Eastern Sicily. The analysis is based on a comparative examination of the organization's 2023 and 2024 Social Report to assess circularity and socio-economic impact. Supply chain analysis highlights improvements in logistics but also gaps in territorial coordination. The model is scalable and adaptable to heterogeneous urban contexts.

Keywords: Circularity Indicators; Food donation; Food waste reduction; Third sector organizations; UNI TS/11822.

Introduction

Food waste represents a major global challenge, with more than one-third of food production lost annually (UNEP, 2024), while nearly 800 million people remain food insecure and about 200 million suffer micronutrient deficiencies (Sassi, 2018). Academic literature stresses the urgency to shift toward sustainable food systems based on agroecology, circular and solidarity economies, knowledge co-creation, and transparent governance (Wezel et al., 2020; Illich, 1973). According to FAO (2011), food losses occur during production and processing, and food waste during distribution and consumption; together they form food wastage (FAO, 2013). In Italy, the economic cost of food waste exceeds €15 billion (Waste Watcher, 2025), due to inefficiencies in logistics, storage, and planning.

Food banks play a key role in converting surplus food into consumption-worthy resources, reducing environmental and economic burdens. The Italian Gadda Law 166/2016 simplifies food donations and provides tax incentives for companies, fostering collaboration between businesses and nonprofits (Maino et al., 2020). Yet, gaps remain in territorial coordination, shared digital tools, and information flows, hindering efficient surplus management (Berti et al., 2023). This study examines Banco Alimentare of Eastern Sicily's contributions to circular food systems aligned with SDG 12.3. The paper is structured around three core components. It introduces the issue of food waste by outlining its economic, social, and environmental implications and linking these challenges to circular economy principles. It then describes the methodology used to measure circularity, focusing on the UNI/TS 11820:2022 framework and its system of specific and optional indicators for evaluating organizational performance (Amicarelli et al., 2023; Matarazzo et al., 2024). Finally, it presents the case study of the Banco Alimentare of Catania and the economic advantages of surplus food donations, concluding with reflections on scalability and digital tools.

Methods

The circularity assessment is based on the UNI/TS 11820:2022 standard, which comprises 71 indicators across six categories: material resources, energy and water, waste and emissions, logistics, products and services, and human resources and sustainability policies (UNI, 2022). Although updated in 2024, the 2022 version was adopted due to its methodological stability and wider academic application (Amicarelli et al., 2023). Data were collected from SAP ERP traceability systems, organizational monitoring documents, Social Reports (2023–2024), and interviews with company managers, volunteers, and third-sector operators. Continuous participant observation was carried out at the MAAS food hub in Catania. All core indicators were measured, more than half of the specific indicators were included, and rewarding indicators were used when available. Each indicator was normalized on a 0–1 scale and aggregated to calculate the organization's Circularity Level. A qualitative assessment was conducted to interpret technological, logistical, and territorial dynamics, following the analytical frameworks proposed by ISO 59004 and recent works on circularity measurement (Fantin et al., 2024).

Case study

The indicators derived from UNI/TS 11820:2022 summarize the performance of Banco Alimentare across six categories. The material indicators show that 100% of the managed flow is reclaimed and redistributed, both in percentage terms and total kilograms. Energy indicators report that renewable sources cover an estimated 5–10% of consumption. Waste and emissions indicators highlight a reduction of 7.300 tons of CO_2 and 512.5 kg emitted from logistics. Logistics indicators include 10% electric vehicles and full digital traceability through SAP ERP. Product and service indicators record an average permanence of one day in distribution and 401.185 kg of reclaimed fruit and vegetables (+39.6%). Human resources and policy indicators show full compliance regarding volunteering, partnerships, control systems, educational programs, and local recovery projects, with the model classified as replicable (Caglioti 2022). The application of UNI/TS 11820:2022 determines a Circularity Level (LC) of 70.31% for 2024. Circularity reaches 100% for materials, waste and emissions, and human resources; 10% for energy and water; 55% for logistics; and 89.60% for products and services. Figure 1 presents a radar chart that visually displays the score of each indicator category, providing an integrated representation of Banco Alimentare's circularity performance.

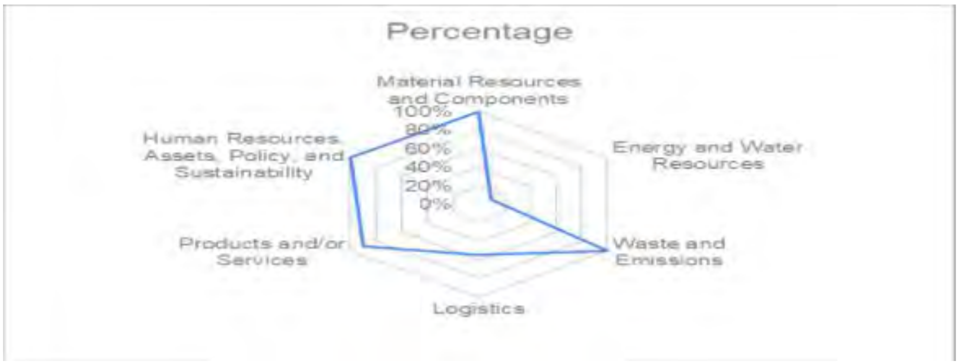

Figure 1. Radar chart or each indicators' category from UNI/TS 11820:2022 (Authors' elaboration).

Findings

In 2024 the Banco Alimentare of Eastern Sicily managed 7.922.763 kg of food, a 25.1% reduction from 2023 without decreasing operational effectiveness or compromising the quality of recovery activities. FEAD and national supplies reached 4.211.339 kg (–44%), while donations from agri-food companies amounted to 1.335.510 kg (–14.85%). Through the Siticibo Program, 820.712 kg of fresh and cooked food were recovered, and fruit and vegetable donations reached 401.185 kg (+39.58%) due to stronger partnerships with the MAAS wholesale market and local producers. SAP ERP ensures full traceability, compliance with HACCP regulations, and redistribution of products past their Best Before Date under Law 166/2016.

Environmental performance remains relevant: about 7.300 tons of CO_2 were avoided through recovery activities, while logistics produced only 512.5 kg of emissions in total. The organization collaborates with over 350 partners and integrates corporate volunteering worth €30.030 (1.155 hours). Education programs, photovoltaic installations, and electric vehicles further support long-term sustainability and operational efficiency.

Circularity indicators based on UNI/TS 11820:2022 show strong alignment with circular economy principles. The organization achieved 100% in materials, waste and emissions, and human resources; 89.6% in products and services; 55% in logistics; and 10% in energy and water. These results correspond to the values illustrated in Figure 1 through the radar chart.

Discussion/Conclusion

The study highlights the strategic role of third-sector organizations in promoting circular economy practices in the agri-food sector. The Banco Alimentare of Eastern Sicily achieves a high level of circularity according to UNI/TS 11820:2022, supported by efficient recovery systems, strong territorial partnerships, transparent governance, and measurable environmental benefits. Despite these results, challenges remain in logistics integration, renewable energy adoption, and coordination among territorial actors. A key opportunity emerges in the development of a digital territorial platform capable of managing real-time surplus flows, improving matching between supply and demand, and strengthening collaboration between companies, institutions, and non-profit actors. Integrating carbon footprint monitoring and circularity indicators into a unified digital reporting system would further support transparency, operational efficiency, and resilience. The model presented is scalable and adaptable, offering a valuable contribution to sustainable food systems and to European strategies aimed at reducing food waste and supporting social inclusion.

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Industrial symbiosis and SNEC within a sustainability framework: process optimization and fundraising strategies for the digital and green transitions

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Abstract

Industrial Symbiosis (IS) represents a strategic pillar within the Italian National Strategy for Circular Economy (SNEC), supporting both the digital and green transitions. This work explores how process optimisation and collaborative resource management can enhance industrial efficiency, reduce waste, and strengthen environmental sustainability. The study examines IS as an operational model where by-products, excess energy and materials from one company are transformed into resources for another, generating economic and environmental benefits. A reference case is surely the Kalundborg industrial ecosystem, demonstrating the impact of integrated industrial networks on energy recovery and resource efficiency. The paper also highlights the role of Industry 5.0, where human-centric innovation, Artificial Intelligence and data intelligence enable predictive analysis, energy optimisation and adaptive production systems. Finally, the study outlines the main public and private funding instruments supporting these transitions, including national incentives, EU Innovation Fund mechanisms, and sustainable finance tools. Together, these elements shape an integrated pathway toward resilient, efficient and sustainable production models.

Keywords: Industrial symbiosis; Circular Economy; Industry 5.0; Process Optimization; Sustainable Finance.

Introduction

Industrial Symbiosis (IS) plays a central role within the Italian National Strategy for Circular Economy (SNEC), supporting the transition toward more efficient, integrated and sustainable production systems. The increasing pressure on companies to reduce waste, optimise resource use and minimise environmental impacts makes process optimisation and circular models essential levers for competitiveness.

In this context, the digital and green transitions represent two interconnected dimensions. Process optimisation enables companies to streamline operations, reduce inefficiencies, and manage energy and materials more effectively. At the same time, Industrial Symbiosis offers an innovative collaborative approach in which the waste, by-products or excess energy of one company become resources for another. This integration not only reduces costs and consumption of raw materials but also supports environmental and economic sustainability.

A well-known example is the Kalundborg industrial park in Denmark, where energy and thermal by-products are exchanged among factories and reused for district heating. This model demonstrates how cooperation, efficiency and technology can generate shared value.

The transition toward Industry 5.0 further strengthens this vision. Unlike Industry 4.0 — mainly focused on automation— Industry 5.0 promotes a human-centric, resilient and environmentally conscious approach. Smart technologies such as Artificial Intelligence and data intelligence assist human decision-making, enabling predictive maintenance, energy optimisation and adaptive production systems. These technologies create a more sustainable industrial ecosystem, enhancing efficiency while supporting environmental and social objectives.

Methods

The methodological approach integrates three complementary analytical perspectives:

Process Optimization Assessment

The study examines optimisation levers within production systems, focusing on time–cost trade-offs, energy efficiency measures and resource utilisation strategies. Particular attention is given to how process integration and the reduction of inefficiencies contribute to the implementation of Industrial Symbiosis.

Industrial Symbiosis Analysis

The research reviews established IS models, with a focus on the Kalundborg industrial park as a benchmark case. The case illustrates how waste heat, steam, water, by-products and excess energy can be redistributed within an industrial network to reduce primary resource consumption, emissions and operational expenditure.

Funding and Policy Framework Examination

The study maps and synthesises public and private funding instruments that support the green and digital transitions. These include national incentives (PNRR Mission 1 and Mission 2, Transition 5.0 tax credits), European funds (FESR, FSE+ 2021–2027, EU Innovation Fund), and sustainable finance tools (green bonds, social bonds, ESG-aligned banking instruments, venture capital and crowdfunding models). This combined methodology provides a comprehensive perspective linking technological, organisational and financial dimensions of sustainable industrial transformation.

Findings

The analysis reveals that process optimisation and Industrial Symbiosis generate significant benefits for companies and territories. Optimised production systems reduce waste, lower energy consumption and improve operational efficiency. When extended to symbiotic networks, these improvements enable circular exchanges that drastically reduce the need for virgin raw materials, while simultaneously cutting emissions and logistics costs.

The Kalundborg case demonstrates the technical and economic feasibility of large-scale symbiosis. Exchanges of thermal energy, steam and by-products enhance efficiency and create shared economic value, confirming the relevance of IS as a replicable model also in Italy.

Moreover, the principles of Industry 5.0—particularly artificial intelligence, predictive analytics and data intelligence—emerge as key enablers of resource optimisation, fault prediction, process adaptation and human-machine collaboration.

Finally, the study highlights a wide availability of financial support instruments. National schemes (PNRR, Transition 5.0), regional funds (FESR, FSE+) and EU programs, combined with private sustainable finance (green bonds, ESG funds, impact investing), create a comprehensive ecosystem capable of supporting industrial transformation at scale.

Conclusion

The results indicate that Industrial Symbiosis, supported by process optimisation and advanced digital technologies, represents a strategic pathway for achieving environmental, economic and social sustainability. IS enables significant reductions in resource consumption and emissions, while improving industrial competitiveness and fostering collaborative value creation among companies.

The transition toward Industry 5.0 reinforces this potential by emphasising human-centric innovation, intelligent technologies and resilient production systems. Artificial intelligence and data intelligence allow real-time monitoring, predictive maintenance and optimisation of energy and material flows, contributing to more sustainable and adaptive operations. However, successful implementation depends on adequate policy support, investment capacity and coordinated governance across public and private actors. In this context, funding instruments—such as PNRR measures, EU Innovation Fund initiatives and sustainable finance tools—play a pivotal role in enabling both individual and systemic projects. Overall, integrating Industrial Symbiosis, process optimisation and strategic financing creates a robust framework for guiding industries toward greener, smarter and more resilient production models, aligned with national and European sustainability priorities.

Circularity assessment in the construction sector

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Abstract

Circular economy plays a key role in sustainability strategies by reducing the use of non-renewable resources, waste generation, and environmental impacts. In the construction sector—characterized by high energy and material consumption—it is essential to adopt operational tools to assess project circularity. This study presents an applied case using the UNI/TS 11820:2024 standard, recently updated with indicators tailored to construction. Two Sicilian companies were analyzed: one using traditional methods and one specialized in green building and timber structures. Using energy audits, direct observations, financial statements, and ESG questionnaires, the study evaluates their circularity level (CL). Results show increasing attention to energy efficiency, waste management, and responsible water use. The findings suggest that circularity provides not only environmental benefits but also competitive and strategic opportunities for innovation in the construction sector.

Keywords: Circular Economy; Energy impacts; Level of circularity; Sustainable construction; UNI/TS 11820:2024.

Introduction

The circular economy is now one of the main strategic pillars for guiding sustainability policies and transforming production models, especially in sectors with high environmental impact. Its principles aim to reduce the use of non-renewable resources, limit waste generation, and extend the lifespan of materials and products, generating environmental, economic, and social benefits. In the construction sector, which has a significant impact on energy consumption, emissions, and waste production, practices such as reuse, recycling, modular design, and efficient resource management can greatly improve performance throughout the entire life cycle of buildings and infrastructure. Despite growing interest in more sustainable construction models, the literature highlights a lack of operational and standardized metrics for measuring circularity in this field. The UNI/TS 11820:2024 technical specification addresses this gap by providing a methodological framework composed of 71 indicators (core, specific, and rewarding) to assess the Circularity Level (CL) of organizations and products.

This study presents a comparative analysis of two construction companies in Sicily, differing in production approach and degree of sustainability integration. A selected set of indicators from UNI/TS 11820:2024, adapted to the construction context, is applied to measure and compare their environmental, social, and governance circularity performance.

Methods

The analysis followed three methodological phases: defining study boundaries and selecting indicators; collecting and validating data; calculating and presenting the circularity level. In the first phase, UNI/TS 11820:2024 was used as the reference framework. The 71 indicators of the standard, grouped into six macro-categories (materials, energy and water, waste and emissions, logistics, product and service, human resources and governance), were filtered based on data availability and relevance to the construction sector. All core indicators were included, along with at least 50% of specific indicators per category, as required by the standard. Rewarding indicators were considered only when supported by verifiable evidence. The second phase involved gathering primary data through energy audits, site observations, staff interviews, and ESG questionnaires, and secondary data from company documents such as financial statements, procurement records, waste reports, and environmental certifications. A mass balance approach was applied to quantify material flows, integrating direct measurements with documented estimates. In the third phase, the Circularity Level (CL) was calculated using the UNI/TS 11820:2024 formula, combining weighted scores from core, specific, and rewarding indicators. Results were produced both by macro-category and as an overall circularity score, and presented through comparative tables and radar charts to provide a clear overview of performance. This approach ensured methodological rigor while accommodating the operational characteristics of the construction sector.

Case Study: Comparison between two companies in the Construction sector

The case study examines two construction companies in Sicily that represent contrasting production models: ALFA, focused on green building and certified natural materials, and BETA, operating in traditional construction with standard materials and contract-oriented management. ALFA specializes in timber buildings, modular and prefabricated systems, and processes aimed at energy efficiency, while BETA relies mainly on reinforced concrete and brick construction, with limited attention to resource traceability and environmental certification.

These differences influence the applicability of the UNI/TS 11820:2024 indicators. The standard includes 71 indicators (core, specific, and rewarding), but not all can be calculated for both companies. Some apply only to ALFA, while for BETA they must be considered unmet, highlighting the standard's ability to distinguish between more and less advanced circular practices. For ALFA, indicators within "Material Resources and Components" are particularly relevant because of the use of certified wood, eco-materials, and modular, disassemblable solutions. Indicators such as the share of recycled or secondary materials, certified materials, and modularity closely reflect the company's circular approach. BETA, lacking comparable data and certifications, was assessed mainly through core indicators—energy consumption, waste management, and CO_2 emissions—which offer a realistic basis for evaluating potential improvements in a traditional firm. Both companies provided data for energy and water indicators, though with different outcomes: ALFA benefits from renewable energy systems and water-saving solutions, while BETA shows limited renewable energy use and lower monitoring detail.

Waste and emissions data were also available for both, but ALFA's formalized systems enable more accurate measurement and higher recovery rates, whereas BETA follows compliant but less detailed procedures. Further differences emerge in logistics, product, and governance indicators. ALFA benefits from local supply chains and multiple certifications (ISO 9001, ISO 14001, CasaClima), while BETA focuses mainly on site operations and safety training, without environmental certifications. Indicator selection therefore combined mandatory core indicators with specific and rewarding indicators wherever applicable, allowing recognition of best practices without disproportionately penalizing less advanced companies. The following section presents the comparative results, illustrating how the two production models translate into measurable circularity performance.

Results and Discussion

The application of UNI/TS 11820:2024 enabled the creation of a comparative indicator matrix to measure circularity performance in the two companies. The selection included all core indicators, over half of the specific indicators per category, and a set of rewarding indicators chosen according to relevance and data availability, ensuring full compliance with the standard while adapting it to the construction context.

Results were expressed on a 0–1 normalized scale, where 1 indicates full compliance and 0 indicates non-application. Intermediate values were assigned based on the degree of implementation. This normalization process, aligned with UNI/TS 11820, allowed qualitative and quantitative information to be converted into comparable scores. ALFA achieved high values, receiving full scores for indicators related to certified or secondary materials, and slightly lower values (0.8–0.9) for energy performance due to incomplete self-sufficiency. BETA obtained mid-range scores (0.5–0.7) for regulatory-compliant but unsophisticated energy and waste management, while minimal or purely formal practices were scored between 0.1 and 0.3. Indicators with no evidence—such as certified materials, modular design, or renewable energy in BETA—received a score of 0.

This structured scoring ensured an objective comparison. ALFA satisfies most core and specific indicators and performs strongly in rewarding indicators due to its green building approach. BETA, in contrast, shows weaknesses particularly in material management and governance, though some progress is visible in energy monitoring and staff training. Based on the assigned scores, ALFA achieved approximately 94.1% (16/17 indicators), while BETA reached 27.1% (4.6/17).

This large performance gap reflects the difference between an advanced circular model and a more traditional production structure. ALFA's strengths lie in material choices, modularity, and certifications, demonstrating a comprehensive circular strategy. BETA's lower results are mainly due to the reliance on conventional materials, the absence of environmental certifications, and the lack of structured ESG policies. However, the gap represents an opportunity: UNI/TS 11820 clearly highlights areas where traditional companies can improve, offering guidance for future investments and innovation.

Conclusion

The application of UNI/TS 11820:2024 enabled an effective comparison of circularity performance between two construction companies with contrasting production models: ALFA, oriented toward green building, and BETA, operating in traditional construction. The results revealed a marked difference, with circularity levels of 94.1% for ALFA and 27.1% for BETA. This confirms the importance of design choices, material management, and environmental certifications in improving sustainability performance. ALFA's high score reflects its systematic use of certified materials, modular components, renewable energy, and integrated management systems. BETA's lower performance is mainly due to limited ESG integration, reliance on conventional materials, and the absence of certifications.

Nonetheless, the analysis also highlights clear opportunities for improvement: adopting secondary materials, implementing process certifications, and formalizing ESG strategies could significantly raise BETA's circularity level. For ALFA, future progress lies in extending circular practices across the entire value chain, including industrial symbiosis and post-sale services that promote maintenance and reuse.

More broadly, the study demonstrates that UNI/TS 11820:2024 is a practical and reliable tool for the construction sector, allowing quantitative and comparable assessments despite the sector's complexity. The Circularity Level (CL) indicator provides useful support for companies and decision-makers, helping guide policies, incentives, and investments. Integrating UNI/TS 11820 with European regulatory frameworks and minimum environmental criteria would further strengthen its role, supporting alignment with the European Green Deal and long-term decarbonization goals. Overall, the comparison shows that transitioning to more sustainable construction models represents not only an environmental requirement but also an opportunity for innovation and competitiveness, with UNI/TS 11820:2024 serving as a valuable tool to support this transition.

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Transformation for sustainable investments AR2 investment be change and ESG strategies

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Abstract

AR2 Investment Be Change SRL pioneers sustainable investment by guiding companies through ESG (Environmental, Social, Governance) transformation. The company integrates financial performance with measurable environmental and social impact, creating long-term value for stakeholders. This paper outlines the methodology and results of AR2's program for energy-intensive companies, focusing on energy audits, renewable integration, and continuous monitoring. Findings demonstrate average energy savings of 40–60%, reduced emissions, and improved corporate responsibility. The initiative highlights how ESG strategies can drive both profitability and sustainability, positioning AR2 as a leader in the transition towards a fully sustainable economy.

Keywords: Sustainable Investment; Energy transition; Measurable Impact; Corporate transformation.

Introduction

Sustainable investment is increasingly recognized as a strategic priority for addressing climate change and resource scarcity. AR2 Investment Be Change SRL combines financial expertise with environmental and social responsibility to create replicable models of corporate transformation. The company allocates over 75% of its porYolio to projects with measurable positive impact, demonstrating that sustainability is not only an ethical imperative but also a winning strategy for long-term value creation.

Methods

Preliminary Analysis

A complete energy audit of the target company is conducted, mapping consumption and identifying priority areas for intervention. The potential for transformation is assessed, along with estimated economic and environmental benefits.

Solution Design

A customized transformation plan integrates renewable technologies, energy efficiency systems, and process optimization. Timelines and investment budgets are defined to ensure feasibility and scalability.

Implementation

The project is executed under continuous technical supervision. Sustainable technologies are installed, and company staff are trained in sustainable practices. Real-time monitoring ensures performance during the transition phase.

Continuous Monitoring

A permanent control system tracks energy and environmental performance. Periodic reports are shared with investors, ensuring transparency and continuous optimization of implemented processes.

Results

Environmental Impact

- Average reduction in energy consumption: 40–60%
- Implementation of renewable energy systems
- Optimizazion of production processes
- Reduction of emissions through smart technologies

Social and Governance Impact

- Training programs for employees on sustainable practices
- Transparent reporting of results to stakeholders
- Strengthened corporate responsibility and reputation

Economic Value

The portfolio of investments has generated an average annual return of 12% while maintaining high sustainability standards.

Table 1. Key Performance Indicators

Indicatore	Azienda Convenzionale	Azienda Trasformata	Miglioramento (%)
Consumo Energetico	100	55	-45
Emissioni di CO_2	100	50	-50
Efficienza Operativa	100	160	+60

Discussion/Conclusion

The AR2 Investment Be Change methodology demonstrates the effectiveness of integrated ESG strategies in transforming energy-intensive companies. Results confirm that sustainability can coexist with profitability, delivering measurable environmental, social, and economic benefits. Future work will focus on expanding partnerships, refining technological solutions, and accelerating the transition towards a fully sustainable economy.

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Red dress: fashion, sustainability, and solidarity. A Circular Economy Project

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Abstract

The Red Dress project represents an innovative initiative that transforms high-quality tex3le waste into elegant dresses, epitomizing the excellence of Made in Italy craftsmanship. Introduced at the SUN Conference 2025, the project stands at the intersection of fashion innovation, sustainability, and social solidarity. By adopting a circular economy model, Red Dress reduces environmental impact, supports ar3san communities, and fosters cultural appreciation for sustainable fashion. The project demonstrates how creativity and responsibility can drive both social change and industry transformation, making it a beacon for fashion professionals and sustainability advocates worldwide.

Keywords: Circular Economy; Fashion; Sustainability; Solidarity, Textile waste.

Introduction

The SUN Conference 2025 provides an international plaQorm for showcasing innovations that address pressing social and environmental challenges. Within this framework, the Red Dress project is presented as a flagship example of how the fashion sector can embrace circular practices to achieve economic, ecological, and social goals. By transforming tex3le waste into luxury garments, the project underscores the synergy between Italian design tradi3on and modern sustainability values.

Methods

Circular Economy Approach

- Material Recovery: Textile waste collected from regional partners.
- Redesign and Upcycling: Fabrics processed using environmentally responsible methods.
- Artesan Collaboration: Skilled Italian artesans and designers convert materials into elegant dresses.
- Closed-loop System: Minimizes waste, extends material lifecycles, reduces reliance on virgin resources.

Results

Environmental Impact

- Significant reduction in textile waste diverted from landfills.
- Decreased use of water, chemicals, and energy compared to conventional textile production.
- Lower carbon footprint across the supply chain.

Social Impact

- Creation of fair employment opportunities for local artisans, particularly women and marginalized groups.
- Empowerment through skill development and community engagement.
- Promotion of ethical labor practices and fair wages.

Cultural Impact

- Revitalization of Italian fashion heritage and ar3sanal craBsmanship.
- Awareness campaigns highligh3ng the importance of sustainable fashion.
- Inspiration for designers and consumers to embrace responsible fashion choices.

Conclusion

The Red Dress project exemplifies how the fashion industry can serve as a catalyst for environmental stewardship, social responsibility, and cultural enrichment. Through its circular economy framework, the project not only diverts waste and reduces emissions but also empowers communities and preserves heritage skills. Its success at the SUN Conference 2025 highlights the poten3al for replicability and scaling, offering a model for other sectors and regions. Ul3mately, Red Dress demonstrates that sustainability and solidarity are achievable realities through innova3on, collabora3on, and commitment to positive change.

SYMBA: advancing industrial symbiosis for a sustainable, circular and bio-based Europe

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Abstract

SYMBA aims to reduce environmental pressures on soil, water and air by deploying industrial symbiosis practices that enhance local supply chains and resource efficiency in bioeconomy value chains. The project co-creates a SYMBA Methodology with industries, regional hubs and policymakers, integrating AI-based tools to anticipate environmental, social and economic impacts. Building on life cycle assessment frameworks, the methodology optimizes resource flows, valorizes waste and supports circular bioeconomy aligned with EU policies. Multi-criteria decision analysis is used to rank and select industrial symbiosis options against multiple readiness dimensions, making trade-offs explicit and supporting evidence-based decisions. Four demonstration regions test and refine the approach, generating data on sustainability outcomes and regulatory barriers. Findings indicate that IS practices can reduce emissions and costs while reinforcing supply-chain circularity, innovation capacity and resilience. SYMBA also develops circular business model elements and a Policy Roadmap to enable systemic uptake of industrial symbiosis in the European bioeconomy.

Keywords: Industrial symbiosis; Multi-criteria decision analysis (MCDA); Co-Creation Decision Method (CCDM); Resource efficiency; Life cycle assessment; Circular economy.

Introduction

European industry constitutes a fundamental driver of economic development while continuing to generate significant environmental pressures through emissions, resource extraction and waste production. In this context, circular economy approaches, and industrial symbiosis (IS) have gained recognition as key levers for decoupling growth from resource consumption. IS promotes ecosystems in which energy and material flows are optimized and by-products are reused as inputs in other processes, thereby reducing waste and creating additional value [1,2].

Despite growing interest and numerous local initiatives, IS often remains difficult to replicate on a large scale. Barriers include regulatory uncertainty on the distinction between waste and by-products, limited information on available secondary resources and business models, and the lack of robust tools to evaluate environmental, economic and social impacts of symbiotic networks [2,3].

SYMBA addresses these challenges with an integrated framework that combines methodological innovation, stakeholder engagement and real-world experimentation. The project co-creates a decision method and Multi-Criteria Decision Analysis (MCDA) framework to identify and prioritize IS solutions, develops guidelines for applying Life Cycle Assessment (LCA), Life Cycle Costing (LCC) and Social Life Cycle Assessment (S-LCA) to IS systems, maps and evaluates existing IS solutions across Europe, and tests the methodology in four demonstration regions with strong bio-based potential. The overall objective is to provide evidence-based operational tools and governance models that facilitate deployment, scalability and transferability of IS in diverse European industrial contexts.

Methods

Co-Creation Decision Method and MCDA

SYMBA adopts a Co-Creation Decision Method (CCDM) to systematically involve key stakeholders, industry, public authorities, research organizations and civil society, in the design and assessment of IS options [4]. The CCDM structures workshops and surveys to elicit expectations, constraints and preferences, and to jointly define evaluation criteria.

On this basis, a weighted-sum MCDA is implemented to compare alternative IS solutions. The criteria set is aligned with life cycle sustainability assessment (LCSA) and includes Symbiosis Readiness Level (SymRL), Environmental Readiness Level (ERL), Legal & Ethical Readiness Level (LRL), Organizational Readiness Level (ORL) and Societal Readiness Level (SRL). Two rounds of internal and external weighting are conducted. The final weights give highest importance to SymRL (28%) and ERL (22%), followed by LRL and ORL (18% each) and SRL (14%), reflecting a shared view that technical feasibility and environmental performance are essential preconditions, while governance and social aspects act as enabling factors [5].

Mapping of IS solutions and regional selection

To understand the existing IS landscape and support region selection, SYMBA compiles a database of more than 150 IS-related solutions across Europe, including platforms, approaches and methodologies. These are classified by sector (e.g. wastewater, agri-food, textiles, packaging, waste valorization), functional focus and governance model [2,6].

In parallel, a multi-stage procedure identifies high-potential demonstration regions. An open call for expressions of interest is circulated through partner networks, and candidate regions are screened using four criteria: bio-based potential and availability of suitable by-product streams; geographic diversity across EU macro-regions; potential for local value chain development and existing cluster structures; and commitment from regional stakeholders to engage in SYMBA activities.

The final selection includes the Metropolitan City of Milan (Italy), Region of Murcia (Spain), Flanders (Belgium) and Bornholm (Denmark). For each region, geographic information systems (GIS) are used to map industrial clusters, resource flows and possible symbiotic linkages, providing a spatial basis for subsequent MCDA and case study work.

SYMBA guidelines for LCA, LCC and S-LCA

A core methodological task is the development of guidelines for applying LCA, LCC and S-LCA to IS networks. A targeted literature review of seminal and recent IS assessments identifies recurring challenges and promising practices [7-11]. Key issues include the definition of reference scenarios that compare IS solutions with realistic counterfactuals, the treatment of multifunctionality arising from multiple products and services, the selection of system boundaries that capture upstream and downstream effects, and the integration of environmental and economic assessments.

The guidelines also address how to include social impacts, distributional aspects and value chain transparency in S-LCA. Preliminary versions are co-developed with demonstration regions through feedback rounds to ensure that methodological recommendations are both scientifically robust and operationally feasible. They are then refined and validated through selected case studies, which serve as “living laboratories” for real-world application.

Business model and governance framework

Building on the taxonomy of sustainable business models [3] and on governance typologies for IS networks [5], SYMBA designs a modular business model canvas tailored to IS. The canvas focuses on key partners, activities and resources; value propositions and stakeholder segments; innovation services and circular innovation portfolios; impact and sustainability metrics; and cost structure and revenue mechanisms. The model integrates different governance options, ranging from consortium-based arrangements and dedicated facilitation entities to coalitions of large industrial actors. This modularity supports both scalability within value chains and transferability to new regions and sectors and provides a practical template for emerging IS initiatives.

Results

TPolicy landscape and regulatory barriers

Analysis of European and national frameworks shows that industrial symbiosis is only partially embedded in current legislation. While the EU Waste Framework Directive provides core definitions and outlines end-of-waste criteria, it does not offer a dedicated pathway for inter-firm material exchanges. As a result, many potentially reusable flows remain legally classified as waste, creating additional permitting requirements and transaction costs for companies [6,7].

Comparative evidence across countries highlights strong variation in enforcement practices, economic incentives and permitting procedures. Complex and fragmented regulations, especially for cross-border movements of secondary materials, are a major barrier to scaling IS [2]. At the same time, few policy documents explicitly refer to industrial symbiosis, leading to weak alignment between regional development objectives and IS initiatives.

Methodological insights for life cycle sustainability assessment

The literature review confirms that LCA is widely used to quantify environmental benefits of IS, but results are sensitive to methodological choices [7,9]. Typical reference systems compare symbiotic networks with stand-alone production or sector averages, yet inconsistencies in the ambition and definition of these counterfactuals limit comparability and may over- or underestimate benefits. Multifunctionality remains a central challenge due to multiple outputs and shared infrastructure; while system expansion is often recommended, data limitations frequently require allocation based on mass, energy or economic value.

Integrated environmental-economic assessments are still relatively rare. Existing studies often focus on direct investment and operational costs, neglecting avoided costs and the distribution of benefits among actors. Recent advances, such as combinations of Material Flow Cost Accounting with Cost-Benefit Analysis, show promise in addressing these gaps [10]. Preliminary review of S-LCA applications reveals a narrow focus on a small set of indicators (e.g. employment, occupational health, community well-being). SYMBA's guidelines therefore emphasize coherent indicator selection across LCA, LCC and S-LCA, data hierarchies and stakeholder involvement to improve social impact assessment [11,12].

Industrial Symbiosis solutions mapping and MCDA results

The mapping exercise confirms a heterogeneous but dynamic landscape of IS initiatives in Europe. Most identified solutions are in Northern and Western Europe, particularly in Denmark, Sweden, Finland, Germany, the Netherlands and Northern Italy, with emerging clusters in Spain and France. Self-organized networks are prevalent in Nordic countries, while EU-funded methodologies and digital platforms dominate at the continental scale [2,6].

Applying the MCDA framework to prioritized solutions in the demonstration regions shows that Symbiosis and Environmental Readiness are perceived as the most critical dimensions for decision-making, followed by legal/ethical and organizational aspects. Societal readiness, while weighted lower, often acts as a decisive factor in early-stage contexts, where community acceptance and local capacity can accelerate or block implementation. The combination of CCDM and MCDA proves effective in making trade-offs explicit, facilitating dialogue among stakeholders and identifying "low regret" options with robust performance across criteria. It also highlights where targeted policy or investment interventions could unlock higher impact, but currently constrained, opportunities.

Conclusion

SYMBA demonstrates that advancing industrial symbiosis requires enabling policy frameworks, robust analytical tools and context-sensitive governance and business models. The project provides an integrated methodology that connects co-creation processes, MCDA and LCSA with spatial mapping and case study implementation.

The results underline priority actions: clarifying the distinction between waste and by-products and expanding end-of-waste criteria; creating economic incentives for verified symbiotic exchanges; investing in information systems that ease matchmaking; embedding IS in regional development strategies; and strengthening guidance and capacities for combined LCA, LCC and S-LCA.

By pairing methodological innovation with real-world testing in four European regions, SYMBA offers a scalable pathway for implementing IS in key industrial and agri-food value chains, supporting policymakers, facilitators and companies in designing and evaluating initiatives that enhance resource efficiency, competitiveness and sustainability.

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Analyzing territoriality and circularity in local systems: insights from the sheep supply chain

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Abstract

Local systems can be conceived as complex entities in which the features of a geographically bounded area, including its history, culture, and social and environmental structures, can shape the activities and, consequently, the prospects for their economic development. The role of such contexts in fostering economic development, particularly in certain countries, has been widely examined in the literature and, after a period of relative decline in interest, is once again gaining attention as they are increasingly viewed as privileged contexts for implementing Circular Economy tools and practices. This article aims to investigate the contribution of local systems to the transition toward the Circular Economy paradigm. The study presents the preliminary results of the research project named "MAX-SHEEP: Modelling and assessment of circular scenarios in local contexts. Applications in the sheep supply chain", which focuses on the sheep supply chain, as a context of analysis, considering both the breeding phase and the subsequent processing of its main products: meat, milk, and wool.

Keywords: Circular Economy; Industrial Ecology; Sheep Supply Chain; Local Contexts.

Introduction

In recent years, the concept of Circular Economy (CE) has gained prominence at the international level, as it can give rise to an effective model for addressing the environmental challenges caused by human activities. It aims to use raw materials more efficiently, reduce environmental impact, and rethink supply chains, consumption patterns, and production processes from the outset in a regenerative way [1]. The transition toward a more CE requires a systemic approach that considers the interdependencies among productive sectors, institutions, and local actors. Multi-level integrated strategies and public-private cooperation are needed to ensure coherent, efficient, and scalable actions. In the CE debate, attention often focuses on the global scale, but this level of analysis often reveals critical issues such as the operational complexity, territorial inequalities, difficulties in tracking supply chains, and the environmental impacts of transportation, which can hinder the implementation of fully sustainable solutions [2]. In this view, local systems offer strong potential for experimenting with truly circular practices, thanks to a more efficient and traceable resource management and a better integration between production and consumption activities. This also helps reduce environmental impacts and contribute to global challenges such as climate change and biodiversity loss. In fact, local systems can be described as territorial agglomerations involving various types of economic, social, and institutional actors that are closely interconnected and characterized by a high degree of cooperation and interdependence. Spatial proximity and the sharing of the same territory also facilitate the exchange of knowledge, resources, and skills and promote the activation of processes of innovation, productive specialization, and social cohesion within a defined geographical context [3]. These aspects are particularly relevant when such contexts are called upon to face processes of change, such as those stimulated by the circular transition. Although the circular transition is often framed as a global process, the potential and effectiveness of implementation at the local level are undeniable. This premise, grounded also in principles typical of disciplines such as Industrial Ecology [4], is supported by at least three main arguments: (i) local systems often possess the essential elements required to trigger cyclical mechanisms, particularly the diversity and complementarity of actors and production chains; (ii) they offer social conditions that generally foster innovation, including knowledge sharing and trust; (iii) their geographically limited boundaries enable high levels of economic and environmental efficiency in the management of material and energy flows. From this perspective, circular initiative, key to achieving global sustainability goals, must be context-specific, as they are strongly shaped by the characteristics of the territories in which they are implemented.

The present study shows the preliminary results of the research project "MAX-SHEEP: Modelling and Assessment of Circular Scenarios in Local Contexts. Applications in the Sheep Supply Chain, analyzing the role of local systems in the transition towards the CE, with particular reference to the sheep supply chain (SSC). The main characteristics of this supply chain, recognized in the three regions of the Project, namely Abruzzo, Apulia and Sardinia, will be described, highlighting how contextual factors and territorial specificities, significantly influence the characteristics of these supply chains and, consequently, the role they can play in facilitating or hindering the circular transition process.

Methods

The description of the sheep supply chain in the three local systems of the MAX-SHEEP project

The sheep industry plays a crucial role in agricultural and livestock systems by providing meat and milk, while also supporting socio-economic and environmental sustainability in marginal rural areas where intensive cultivation and farming are often not viable. Despite its historically important role, the SSC is currently experiencing a structural crisis in particular linked to low profitability, declining consumption, foreign competition, and the progressive abandonment of inland areas. These factors compromise its economic and social sustainability, with negative repercussions on the territory, such as the abandonment of pastures and the loss of biodiversity [5]. The need to preserve this supply chain and, at the same time, define prospects for its effective relaunch can be effectively supported through the adoption of tools and solutions inspired by the CE model. To better understand its role in the transition process, the main features characterizing it in the three regional areas involved in the MAX-SHEEP project are described and analyzed below.

The Abruzzo region accounts for 3.97% of the total number of sheep in Italy and 0.24% of the total number in Europe [6]. There has been a 17% decrease compared to 2020. The 58.57% of the raised sheep are mixed-purpose (milk and meat or wool), while the 28.26% are raised only for meat production; exclusive milk or wool production is instead marginal (2.43% and 0.02% respectively). Most farms are very small: 67% of the total have between 1 and 20 animals, and only 10% have between 21 and 50 animals. Therefore, it is a sector made up mostly of small entrepreneurs and small businesses. This distribution is consistent with the prevailing farming method, which is outdoor or extensive farming (42% of farms and 81% of animals), followed by stabled or intensive farming, which accounts for 20% of total farms (with 8% of animals). The most common breed is the crossbred - Meticcia – with the 63% of animals.

Apulia's sheep population accounts for the 3.15% of Italy's total sheep population (Table 1) and the 0.32% of Europe's total sheep population [7], recording a sharp decline of more than 10% compared to 2020. From a production point of view, the sheep sector shows limited specialization, confined to the production of meat and/or meat and milk. The Apulian sheep sector is also characterized by the prevalence of extensive farms, which account for

72% of the total, while the most common breed is the crossbred - Meticcia – with an amount of 122,606 f animals.

Sardinia's sheep population consists of just under 3 million head, representing approximately 50% of the Italian sheep population and the 5% of the European one [6]. In recent years, there has been a marked reduction in the number of farms (over 20%), which is broadly in line with the national trend, and in the number of animals raised (approximately 10%). The production is focused almost exclusively on dairy products: milk production stands at around 310,000 tons per year [7], accounting for over 13% of total European production [6]. Approximately the 90% of farms are involved in this type of production, making Sardinia the leading European region for sheep milk production. There are also mixed milk and meat farms and, to a much lesser extent, farms dedicated to wool production. Sheep farming in Sardinia currently accounts for around 25% of the region's agricultural income. Most farms are semi-extensive, with the predominant use of natural and semi-natural pastures. As regards the most commonly bred sheep breed, the 99% of the animals are Sardinian.

From the analysis conducted, significant structural differences are also highlighted; they influence the territorial context and the possibilities of transition towards circular models. Sardinia, for example, stands out for its larger production scale and greater stability in volumes, with a strong specialization in the dairy sector and the almost exclusive breeding of the Sardinian breed, which affects characteristics such as feed requirements, meat yield, and fleece quality. Abruzzo and Apulia have smaller, mixed supply chains, with crossbred breeds and differences in sheep meat consumption (sheep and lamb in the former, lamb only in the latter). Extensive farming prevails in all three regions, which is positive for animal welfare and environmental benefits, but less efficient in terms of manure recovery, limiting the reuse of manure as fertilizer and, therefore, the closure of the nutrient cycle at the local level.

A recognition of circular solutions for the sheep supply chain

The sheep sector, like other sectors of agriculture and animal husbandry, is associated with multiple environmental impacts, the extent and nature of which vary depending on the specific stages of the production chain. During the farming phase, the main effects concern greenhouse gas emissions, particularly methane and nitrous oxide, soil degradation due to overgrazing, consumption and pollution of water resources, and the possible loss of biodiversity due to the conversion of natural habitats into grazing areas.

In meat production, the environmental impact is mainly concentrated on the high carbon footprint per unit of product, intensive use of land and water, and the management of waste and by-products. Milk production involves constant methane emissions, high water and energy consumption for milking and refrigeration, and the production of plastic waste and dairy waste. Finally, wool production is mainly associated with the use of chemicals in washing and treatment processes, significant water consumption, and the risk of wastewater pollution if not properly treated [5].

Despite these significant environmental pressures, the sector also shows considerable potential for adopting practices based on CE principles and, more generally, environmental sustainability. Table 1 summarizes the main ones, derived from an analysis conducted as part of the MAX-SHEEP project, and based on the scientific literature [8].

Table 1. Main circular solutions applicable to the various stages/sub-systems of the sheep supply chain.

	Circular solutions	**Destination sector (by-product-waste-secondary raw material)**
LIVESTOCK	- Recovery and valorization of livestock manure through anaerobic digestion and composting; - Use of crop residues and agro-industrial by-products as ingredients in animal feed.	- Energy sector (biogas production); - Agriculture (organic fertilizers and compost); - Feed industry (formulation of sustainable diets).
MEAT	- Separation and valorization of slaughter by-products (bones, blood, fat) for the extraction of useful compounds; - Production of gelatin and collagen from residual connective tissue.	- Pharmaceutical, food, cosmetics, animal feed (pet food), and energy (biodiesel) industries; - Nutraceutical, cosmetics, and biomedical sectors.
DAIRY	- Recovery of whey using concentration and bioconversion technologies; - Treatment of dairy waste and residues through composting or anaerobic digestion.	- Food industry (high-protein formulations), animal husbandry, bioenergy; - Agriculture (organic fertilizers), energy sector (biogas).
WOOL	- Use of raw wool waste to produce insulating materials or biodegradable mulching systems; - Regeneration and transformation of wool into technical fibers for composite materials or textile products.	- Green building and sustainable agriculture sectors; - Circular textile industry, advanced materials (automotive, furniture, sustainable construction).

Discussion and Conclusion

The sheep sector has significant potential in terms of CE transition, of which the forms of intersectoral integration described above can be considered practical examples. However, as noted, solutions proposed in the technical-scientific literature require context-specific application, as territorial, socio-economic, and infrastructural factors affect their replicability and effectiveness. Within the MAX-SHEEP project, it has gradually emerged that the three regions analyzed have different vocations and farming methods.

For example, one of the most significant environmental issues is related to the disposal of greasy wool, which is considered as waste in all contexts and treated as such. The high degree of specialization of the Sardinia region in dairy production, as well as the prevailing mixed milk-meat vocation found in Abruzzo and Apulia, have progressively marginalized the wool industry, to the point of compromising, in many cases, any form of material and economic value. However, while considering the potential application of circular solutions to this waste, it is clear that the quality of the wool is intrinsically linked to the breed of sheep raised, which in turn depends on the vocation of the farms. The breed affects the characteristics of the fleece, which is much longer and thicker for Sardinian sheep and thinner and shorter for crossbred breeds. The type of wool also affects its workability and, therefore, the finished products that can be obtained. This means that circular solutions linked to the noble valorization of wool in the textile sector must be carefully considered in terms of the technical and commercial properties that are desired. This aspect means that, in addition to textiles, other possible uses that are technically more feasible and economically more advantageous must also be evaluated, such as green building (e.g., the production of insulating panels) and agriculture (e.g., the production of organic fertilizers). This type of cross-sector interaction is one of the most significant objectives and outcomes of eco-industrial approaches that can drive the application of CE at the local level, where closing cycles becomes a driver for activation-reactivation and, therefore, for the development of other supply chains, benefiting the sustainable development of the entire local system.

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Models and strategies for environmental emergency response in a Seveso framework

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Abstract

The management of environmental emergencies in industrial settings is essential to protect human health, ecosystems, and operational continuity. The Seveso III Directive (2012/18/EU), implemented in Italy through the Legislative Decree 105/2015, provides the core regulatory framework for preventing and controlling major accident hazards (MAH). Its structure follows the four phases of emergency management: prevention, preparedness, response, and recovery. Prevention requires operators to identify hazards, assess risks, and implement technical and organizational safety measures. Preparedness focuses on Internal and External Emergency Plans, supported by inter-institutional coordination and regular drills. Effective response depends on clear procedures, training, rapid decision-making, and real-time data. Recovery includes environmental restoration, damage evaluation, and corrective actions. Growing attention is given to NaTech events, which are increasingly relevant due to climate change. The Seveso model promotes resilience, adaptive risk assessment, innovative monitoring tools, transparent communication, and strong safety culture, reinforcing its role as a cornerstone of industrial and environmental protection.

Keywords: Seveso III Directive; Major Accident Hazards (MAH); Emergency Management; NaTech Events; Industrial Resilience.

Introduction

The contemporary industrial landscape is undergoing a profound transformation driven by the dual ecological and digital transition, which is reshaping production models, regulatory frameworks, and competitiveness at European and global scales. In this context, industrial symbiosis has emerged as a strategic approach that integrates resource efficiency, decarbonization, and technological innovation. European and national policy initiatives—including the Green Deal, the National Strategy for the Circular Economy (SNEC), and the

Clean Industrial Deal—promote the creation of interconnected industrial ecosystems that share energy, materials, information, and technological infrastructures to enhance productivity and reduce environmental impacts.

However, the shift toward more integrated and circular production systems also introduces new vulnerabilities. Industrial symbiosis relies on tightly coupled infrastructures, supply chains, and digital platforms, which can amplify technological and environmental risks if not properly safeguarded. Robust management of environmental and technological emergencies thus becomes essential to ensure health protection, ecosystem preservation, and industrial continuity—core elements of long-term resilience.

The Seveso III Directive [1], transposed in Italy through the Legislative Decree 105/2015 [2], remains the primary regulatory framework for preventing and controlling major accident hazards (MAH). Its structured approach—covering prevention, preparedness, response, and recovery—provides an integrated risk governance model suited to the complexities of the digital and green transition. Increasing process automation, real-time data flows, and interconnected safety systems require advanced methodologies for hazard identification, quantitative risk assessment, and safety-barrier management. Emerging challenges such as NaTech events (Natural Hazards Triggering Technological Disasters), intensified by climate change [3–5], further call for resilience-oriented strategies based on multi-hazard analysis and adaptive planning.

As industrial symbiosis networks expand, Seveso-based emergency planning becomes increasingly important. Real-time monitoring systems, SCADA (Supervisory Control And Data Acquisition) and ICS (Industrial Control Systems) infrastructures, GIS-supported situational awareness, and predictive modelling tools enhance decision-making and inter-agency coordination, while a strong safety culture ensures active engagement in prevention and preparedness. Integrating industrial symbiosis with advanced emergency management frameworks is therefore essential for developing safer, more efficient, and resilient industrial systems. This work examines how the Seveso Directive can reinforce the resilience of industrial sites and symbiotic networks, supporting Europe's broader ecological and digital transition.

Methods

The methodological approach adopted in this study is grounded in a dual analytical framework combining the Emergency Management Cycle (Figure 1) with a multi-hazard NaTech assessment paradigm (Figure 2). This integrated structure enables a systematic evaluation of industrial risk governance under the Seveso III Directive [1], supported by national operational guidelines [4] and international NaTech-oriented methodologies [3, 5], with particular emphasis on climate-induced stressors and the increasing interdependence of industrial systems within symbiotic networks.

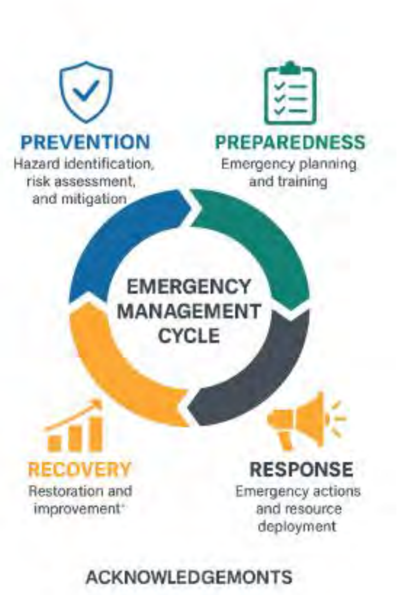

Figure 1. The emergency Management Cycle (Prevention, Preparedness, Response and Recovery).

Figure 2. NaTech Events and Climate Resilience.

The four canonical phases—Prevention, Preparedness, Response, and Recovery—were operationalized as analytical dimensions to assess the robustness of current emergency governance mechanisms in alignment with Seveso III regulatory requirements [1, 2] and ISPRA guidance [4]. Prevention was examined through a detailed review of hazard identification procedures, quantitative risk assessments, and the architecture of technical and organizational safety barriers. Special attention was given to real-time monitoring infrastructures, early-warning thresholds, and the integration of digital control systems (SCADA/ICS), consistent with recommendations for advanced safety-barrier management. Preparedness involved the critical evaluation of Internal and External Emergency Plans (IEP/EEP), their coherence with multi-hazard and NaTech scenarios, and the maturity of inter-institutional coordination mechanisms, in line with national and international best practices [3, 4]. Response capabilities were assessed by modelling activation criteria, the operational efficiency of emergency actions, resource deployment strategies, and the availability of decision-support tools enabling rapid situational awareness (e.g., GIS platforms and predictive dispersion models). Recovery was investigated through post-event restoration methodologies, environmental remediation processes, and the presence of iterative feedback mechanisms enabling continuous improvement of emergency systems, consistent with resilience-oriented frameworks recommended by OECD [5]. This cyclical structure provided a normative and operational lens for benchmarking Seveso-compliant emergency management against evolving industrial and environmental conditions. The NaTech framework (Figure 2) was used to characterize the propagation of disruptions originating from climate-driven natural events, following established methodologies from the European Commission [3] and OECD [5]. Natural hazards were quantified using regional hazard atlases, hydrological datasets, and climate projection models, focusing on flood, heatwave, and seismic stressors. Industrial system vulnerabilities were assessed through structural and functional analyses of critical units, evaluating susceptibility to loss of containment, cascading failures, and impairment of safety-instrumented systems. Accident scenarios were modelled using validated consequence-analysis tools to simulate releases, explosions, and fires triggered or exacerbated by natural events. Consequences were evaluated by integrating exposure models, population and environmental vulnerability data, and emergency response capacity assessments.

The two methodological pillars were synthesized to examine how Seveso III risk governance can be aligned with the requirements of the green and digital transitions. This synthesis drew upon regulatory sources [1, 2] and technical guidelines on NaTech and emergency planning [3–5], focusing on: (a) the incorporation of digital monitoring infrastructures and early-warning systems into Seveso emergency planning; (b) the translation of climate scenarios into probabilistic multi-hazard risk assessments; (c) the adaptation of emergency plans to interdependent industrial networks typical of industrial symbiosis systems; (d) the identification of systemic vulnerabilities that may compromise collective resilience. Through this integrated methodological approach, the study provides a scientifically grounded evaluation of how Seveso-based emergency management frameworks must evolve to remain effective under emerging environmental and industrial conditions.

Results

The application of the Emergency Management Cycle as an analytical framework revealed marked variability in the maturity and robustness of current risk governance practices across industrial sites. Prevention measures generally appeared well structured, particularly in facilities equipped with advanced process control systems and real-time monitoring technologies. Quantitative Risk Assessments demonstrated compliance with Seveso III requirements; however, they only partially accounted for climate-related hazard evolution, indicating a limited integration of long-term environmental dynamics into traditional safety analyses. Preparedness efforts showed greater inconsistency. Internal Emergency Plans were typically comprehensive and technically detailed, whereas External Emergency Plans often lacked alignment with multi-hazard scenarios and did not fully capture the escalation pathways associated with NaTech events. Coordination between operators, emergency services, and local authorities displayed variable levels of interoperability, and exercises or drills seldom addressed compound or climate-exacerbated incidents. The Response phase benefited from the presence of digital infrastructures such as SCADA systems, GIS platforms, and automated alarm networks, which enhanced situational awareness and accelerated decision-making.

Nevertheless, real-time data sharing across agencies remained fragmented, limiting the overall effectiveness of coordinated response operations during high-complexity events. Recovery processes were generally reactive and focused on immediate restoration rather than long-term adaptation. Few facilities incorporated resilience-oriented methodologies into post-event evaluations, and feedback loops to update risk assessments or emergency plans were often underdeveloped. The NaTech analysis further evidenced the amplifying effect of climate-driven natural hazards on technological vulnerabilities. Floods emerged as the most significant trigger, particularly in industrial areas with inadequate hydrological protection, while heatwaves and seismic events also increased the likelihood of equipment malfunction and cascading process failures.

NaTech-induced accidents tended to produce wider off-site consequences due to the concurrent disruption of critical services and communication infrastructures. Finally, the digitalization of industrial operations contributed positively to early detection and response readiness, but also introduced new systemic dependencies. In industrial symbiosis contexts, the interconnectedness of utilities, resource flows, and digital platforms increased the potential for cascading disruptions, especially when emergency plans lacked integration with shared monitoring systems. Overall, the results indicate that the effectiveness of Seveso III governance increasingly depends on the harmonization of technological innovation, multi-hazard preparedness, and climate resilience strategies.

Conclusion

This study shows that the digital, circular, and increasingly interconnected evolution of industrial systems requires a significant reinforcement of risk governance. While the Seveso III Directive offers a solid foundation for managing major accident hazards, its effective implementation must integrate climate-informed hazard assessment, multi-hazard preparedness, and digital emergency coordination. The Emergency Management Cycle revealed uneven maturity across phases, with notable gaps in Preparedness and Recovery, while the NaTech analysis confirmed that natural hazards amplify technological vulnerabilities, especially within industrial symbiosis networks. These findings highlight the need for adaptive, resilience-oriented risk governance that transcends mere regulatory compliance. Enhancing digital monitoring, inter-agency coordination, and climate resilience will be essential to ensure effective emergency response and long-term recovery. Ultimately, aligning industrial symbiosis with advanced emergency management and Seveso-based governance offers a strategic pathway to strengthen competitiveness while protecting ecosystems and communities from increasingly complex risks.

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Mapping industrial symbiosis in the textile sector: a data driven network analysis using GEPHI and R

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Abstract

This study applies a data-driven network analysis to explore industrial symbiosis opportunities in the textile sector of Lombardy, Italy. Using Gephi and R software tools, the work maps and analyses relationships among firms representing different phases of the textile production process, from initial fiber processing to downstream finishing. Data were gathered from public sources, including MUD declarations and sustainability reports, capturing material flows, waste production, and interest in resource-sharing. The mass flow analysis identified packaging and process waste as the main outputs, with packaging accounting for 30–50% of spinning flows and significant landfilling of process waste. Flow mapping and network analysis highlighted existing and potential industrial symbiosis options, distinguishing solutions linked to specialized sub-groups and to the network core. Network-based approaches can therefore support more targeted and scalable strategies to advance circularity in the textile sector.

Keywords: Network analysis; Circular Economy; Textiles; Machine learning.

Introduction

The textile sector is one of the largest industries globally, with a significant environmental footprint, particularly in terms of resource consumption and waste generation. It is estimated that the textile and fashion industry accounts for approximately 10% of global carbon emissions, primarily from energy-intensive processes such as dyeing, finishing, and textile production [1]. Additionally, textile production is responsible for massive water consumption (consuming 93 billion water cubic meters), and wastewater discharge, often containing toxic chemicals [2]. Only 15–20% of total waste is collected for reuse and recycling, while over 80% of clothing waste is sent to landfills or incineration, resulting in higher carbon emissions and losses of energy and raw materials [3]. Despite ongoing efforts to improve sustainability, challenges persist in reducing these environmental impacts while maintaining economic viability. One promising strategy for addressing these issues is industrial symbiosis, which involves the collaborative exchange of materials, energy, and waste between industries to optimize resource use and reduce environmental harm. This study explores the potential of industrial symbiosis within the textile sector, focusing on how data-driven network analysis can identify opportunities for more efficient resource flows and waste reduction. By leveraging the interconnected nature of industrial ecosystems, the study aims to uncover pathways toward a circular economy in textile production, promoting both environmental and economic sustainability.

Methods

The study employed a multi-step methodology to assess the potential for industrial symbiosis in the textile sector in Lombardy. Initially, a comprehensive literature review was conducted to map existing industrial symbiosis scenarios in the textile industry. Publicly available data on waste management within the region provided a foundational framework for the study. In the second step, the focus shifted to analyzing textile companies with recognized sustainability practices in Lombardy. These companies were selected based on their alignment with three specific subcategories under ATECO group 13—spinning, weaving, and finishing—representing the more linear stages of the textile production process. A total of 28 companies were included in the final sample, distributed across six provinces (i.e., Bergamo, Brescia, Como, Lecco, Mantua, and Varese), ensuring both territorial representation and sufficient homogeneity for the analysis (Table 1).

Table 1. Classification of selected sample based on the companies' economic activities.

Activities	ATECO* codes	n. companies
Preparation and spinning of textile fibres	13.1	4
Weaving of textiles	13.2	14
Finishing of textiles	13.3*	10

**Note: one of the companies is involved both in 13.2 and 13.3 ATECO codes*

The third step involved network analysis and mass flow analysis to uncover and characterize Industrial Symbiosis potentials for the textile sector at the regional level (Figure 1). Using Gephi software, network analysis was performed to explore potential synergies among these companies, specifically focusing on waste flows [4].

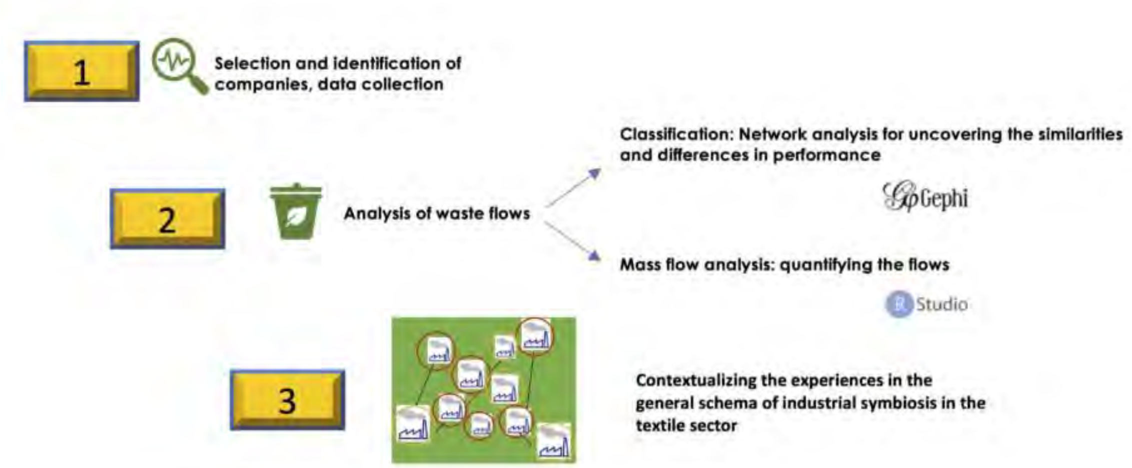

Figure 1. Framework developed to uncover and characterize Industrial Symbiosis potentials for the textile sector at the regional level.

Companies were categorized based on co-ownership (shared waste generation) and kinship relationships (waste originating from the same producer). In this phase, we distinguished between "core" waste—typical of production processes—and more marginal waste, with a focus on quantities and distribution across companies.

Finally, a modularity analysis was applied to identify groups of companies with similar waste profiles, revealing relationships and affinity clusters not immediately apparent through ATECO code categorization. Moreover, company- and sector-level input and output material flows were analyzed using a mass flow analysis. The flow mapping, developed through an algorithm in R (and RStudio), provides a detailed visualization of material distribution across the system [5,6]. The results were analyzed to highlight potential industrial symbiosis opportunities that could enhance waste recycling and circularity within the Lombardy textile sector.

Results

The mass flow analysis identified two dominant output fractions, packaging and process waste, with packaging accounting for 30–50% of spinning outputs and a substantial share of process waste still being landfilled. For each waste subcategory, dedicated flow diagrams were constructed, integrating existing industrial symbiosis and recycling practices as well as the presence of relevant authorizations, which are crucial for assessing practical feasibility. By positioning these cases within the broader literature and combining them with network analysis results, industrial symbiosis experiences were found to align with different network modules, some specific to specialized sub-groups and others linked to the network core. This approach enabled the identification of solutions with higher replication potential at the regional level and supports the development of tailored symbiosis pathways for companies based on their activity affinities.

Discussion/Conclusion

This study highlights that the textile sector offers substantial yet underexplored opportunities for circularity and industrial symbiosis, spanning from fiber recovery to waste valorization. Despite this potential, the existing literature and empirical evidence indicate a limited engagement of the textile sector in industrial symbiosis initiatives, particularly when compared to more extensively studied sectors such as metallurgy. This research identified several critical points within the linear production model where circular strategies could be effectively implemented, consistently with findings reported in the literature. Future research should therefore focus on leveraging network analysis as a foundation for advanced, data-driven tools, including machine learning and big data approaches, to anticipate new symbiotic connections and support strategic decision-making for the circular transition of the textile sector.

Acknowledgement

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Green mobile home experience a new horizon for sustainable building

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Abstract

The Green Mobile Home Experience introduces an innovative approach to sustainable housing through circular economy principles. By recovering waste materials and integrating advanced technologies, the project achieves zero environmental impact while offering educational and social value. This paper outlines objectives, methodology, and findings from pilot initiatives in schools, enterprises, and public institutions. Results demonstrate significant reductions in energy and water consumption, improved awareness of sustainability, and tangible economic benefits for stakeholders.

Keywords: Circular Economy; Sustainable housing; Education; Zero impact; Innovation.

Introduction

Sustainable building is increasingly recognized as a priority in addressing climate change and resource scarcity. The Green Mobile Home Experience, developed by AR2 Investment Be Change SRL, combines eco-compatible materials, smart technologies, and educational programs to create replicable models of sustainable living. This initiative aims to maximize material reuse, foster environmental awareness, and establish strategic partnerships between public and private actors.

Methods

Materials and Technologies

- Recovered materials: construction waste, recycled composites, bio-compatible elements.
- Integrated systems: smart waste compactors, advanced energy monitoring, home automation.

Educational Programs

Interactive workshops and training modules were designed for schools and communities, focusing on circular economy principles and sustainable practices.

Pilot Contexts

- Schools: demonstration units for student engagement.
- Enterprises: workplace solutions with zero impact.
- Public institutions: replicable community infrastructures.
- Associations: event spaces for sustainability promotion.

Results and Discussion

Environmental Impact

- Energy consumption reduced by 40% compared to conventional mobile units.
- Water savings of 35% through smart monitoring.
- CO_2 emissions cut by 50% using recycled materials.

Educational Outcomes

Surveys of participating schools showed a 70% increase in student awareness of sustainability concepts.

Economic Value

Stakeholders reported measurable savings in operational costs and enhanced reputational value.

Table 1. Key Performance Indicators

Indicator	Conventional	Indicator	Unit Green Mobile Home improvement (%)
Energy Consumption	100	60	-40
Water Usage	100	65	-35
CO_2 Emissions	100	50	-50

Conclusion

The Green Mobile Home Experience demonstrates that circular economy principles can be effectively applied to housing solutions, yielding environmental, educational, and economic benefits. Future work will focus on expanding partnerships, refining educational modules, and integrating renewable energy sources.

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Industrial Symbiosis and Circular Economy In Italy: the Circular Eco-District Model

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Abstract

This paper presents a proposal for defining the Circular Eco-Districts (CEDs) model within the framework of Italian National Strategy for Circular Economy. This work was developed through collaboration between MASE and ENEA, creating an integrated national system of tools to support industrial symbiosis and circular economy and to assist industrial areas towards the progressive improvement of their system performance. An extensive analysis was performed on industrial symbiosis principles and applications to industrial clusters, referencing international and European models such as Eco-Industrial Parks, Sustainable Industrial Areas and Italian Environmental Equipped Production Areas. In particular, UNIDO–World Bank–GIZ EIP model was adopted as theoretical reference and it was applied to different Italian industrial areas, with its validation across eight pilot areas. The proposed model implements a rating system, structured on a progressive level system, comprising requirements across management, environmental, economic and social dimensions, supporting the progressive improvement of the area beginning from a baseline level.

Keywords: Industrial Symbiosis; National Strategy for the Circular Economy; Circular Eco-District; Eco-Industrial Parks.

Introduction

In Italy, the sustainable management of industrial areas is a relatively recent question due to the lack of both a regulatory framework and a cultural environment capable of embracing this new concept until about thirty years ago with the so called Bassanini Law (L 112/1998), on APEA (Environmental Equipped Industrial Areas). Based on experiences abroad and regulatory adaptation, the Italian context is evolving toward the application of industrial ecology principles and industrial areas play a significant role in environmental protection, territorial enhancement and business competitiveness. A participatory model is required whose implementation is based on three key actors: organizations, industrial area manager and Local Authorities. In this context, this paper presents a proposal for defining the Circular Eco-Districts (CEDs) in Italy to promote sustainable development models inspired by industrial symbiosis and circular economy, whit a particular focus on regeneration of brownfield sites to convert them into productive areas or into zones that actively contribute to the socio-economic context in which they are situated. This initiative is the result of a collaboration between the Italian Ministry of the Environment and Energy Security (MASE) and the Sustainability Department of Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA) in the framework of the Italian National Strategy for the Circular Economy. ENEA's involvement builds on its experience in the evolution of industrial ecology and industrial symbiosis concepts applied to industrial processes, as tools to ensure efficient resource use, trigger conditions of territorial and economic competitiveness and to promote collaboration among organizations, as well as synergies with Local Authorities and stakeholders, in line with current EU policy framework as European Green Deal, national policy programmes as National Recovery and Resilience Plans (NRRPs) and strategies as Green Economy and Circular Economy.

The work done within the collaboration between ENEA and MASE, is aimed, among the others, at the definition and the implementation of a Circular Eco-District model or, with other words, a model for the definition and assessment of sustainable and circular industrial areas, based on the general framework of eco-industrial parks, but tailored on the Italian industrial system The application of the model of can help industrial areas in their progressive improvement of sustainability and circular performances. Industrial symbiosis, one of the requirements foreseen by the model, generates economic benefits (e.g., reduction of costs for raw materials, energy, and waste disposal; creation of business networks), environmental benefits (e.g., optimization of resource use and reduction of environmental pressure and emissions) and social benefits (e.g., job creation) [1]. The concept of waste disappears since "materials exchanged are not waste at any point in their lifecycle, but rather economic goods" [2]. In general CED foresees several requirements on management, environmental, social and economic performances of industrial areas that all together drive them towards an industrial system where, e.g., collaboration, maintaining resources value, sharing of resources, minimizing environmental impacts both internally and within the territory are key actions together with the business focus [3].

Methods

Methodology for the development of Italian Circular Eco-District model

The proposed CED model was developed by ENEA following an extensive analysis concerning the evolution of the concepts of industrial ecology and industrial symbiosis applied to industrial clusters, investigating several applications implemented at international and European level, such as Eco-Industrial Parks (EIPs), Sustainable Industrial Areas (SIAs) as well as the Italian Environmental Equipped Production Areas (EEPAs) [4] developed by some Italian Regions, on behalf of the Bassanini Law (L 112/98). Other organizational forms of industrial areas, whether established by law (ex-lege) or in practice (de facto), were also analyzed at the national level, including the examination of their legal framework.

The analysis was conducted through a combination of an in-depth literature review and an examination of the most significant case studies. This enabled a survey of existing technical and scientific models and characteristics of different industrial clusters, as well as an examination of the regulatory frameworks, organizational models and direct and indirect economic measures for their management. Besides, the development of the model was further informed by the outcomes of some European projects in which ENEA was involved, including Life SIAM, Sustainable Industrial Area Model [5], and Med MEID, Mediterranean Eco-Industrial Development [6], aimed at defining sustainable industrial area models through the integration of sustainability principles into the planning, development, and management of industrial areas. Following the comprehensive analysis described, the EIP model developed by United Nations Industrial Development Organization (UNIDO), World Bank Group and Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH [7] was selected as the reference framework for the development of ENEA's CED model as this partnership represents a leading international authority in the field of EIPs and the model constitutes a recognized benchmark for EIPs. The model defines performance requirements for EIPs across management, environmental, social, and economic key areas:

- management covers the responsibilities of the area manager and the provision of integrated shared infrastructures and services;

- environmental requirements address the mitigation of potential impacts, low- or zero-carbon energy generation and resource-efficient production, with a focus on pollution prevention, cleaner production, industrial symbiosis and water, waste and energy management;
- social requirements ensure the adoption of good practices in social management;
- economic requirements support the financial sustainability of the area, meeting market demands and future development needs, while enhancing industrial competitiveness.

The model was applied to several Italian industrial aggregations such as Industrial Development Consortia, Industrial Districts, Industrial Development Areas, Special Economic, Areas of Regional Interest, EEPAs and tested through a desk research in eight pilot areas across northern, central, and southern Italy to verify the degree of application of the requirements in Italy (Table 1).

Table 1. Eight Italian industrial organizations analyzed by ENEA to select the requirements of CED model

Organizational types of selected industrial areas in Italy	Northern Italy	Central Italy	Southern Italy
Industrial Development Area (in Italian, Aree di Sviluppo Industriale)	Consortium for Economic Development of Friuli (COSEF) (UD)	n.a.	Provincial Industrial Consortium of Oristano (CIPOR) (OR)
Environmental Equipped Production Areas	Ponterosso Industrial Area in San Vito al Tagliamento (PN)	Environmental Equipped Production Area (EEPA) -Civita Castellana Industrial District (VT)	Environmental and Landscape Equipped Production Area (ELEPA) -Bitonto (BA)
Industrial Districts	Mechanical District of Alto Vicentino (VI)	Industrial District of Santa Croce sull'Arno (PI)	District of Agrumi di Sicilia (CT)

Source: authors 'elaboration.

Results

The analysis of the eight areas, together with the review of regulatory frameworks and Regional Guidelines for EEPAs, enabled the adjustment of requirements to the Italian context. This process accounted for the specific characteristics of national industrial areas, the nature of the organizations, the technical and economic feasibility of the proposed solutions, resulting in EDC model. The model was further integrated by incorporating Best Environmental Management Practices (BEMPs) from EMAS Sectoral Reference Documents and mechanisms for addressing potential external conflicts. Although Italian regulations don't explicitly define EIP requirements, except for EEPAs that – in general – are more addressed to common environmental services more than the application of the EIP principles according to industrial ecology theory, several UNIDO requirements were found to have already been implemented in practice.

Summarising, starting from the general framework of requirements listed by EIPs models (such as UNIDO, e.g.) a short list was selected with the most feasible and applicable requirements to the Italian framework, given that – according to the tuning above described – some of them were already implemented from some Italian industrial areas even without mandatory legal requirements, confirming in this way the good starting point of Italian industrial system and that several requirements are seen as win-win, since they allow to get best environmental performances with at the same time economic benefits or better legal compliance.

According to the cited methodology an ItalianCED model has been developed. It implements a seven-level rating system to support the progressive improvement of sustainability and circularity in industrial areas, starting from a base-level. The model comprises 85 requirements in management, environmental, social and economic areas (Table 2). An industrial area that fulfil the base-level, with at least 19 of the 85 requirements, as shown in the next table, , including the mandatory presence of a industrial area manager, can be defined and recognised as a CED. The model allows CEDs to progressively improve their performance by fulfilling additional qualifying requirements beyond the base-level, ranging from level "F" to level "A." following the scheme in Table 2.

Table 2. Rating system scheme of CED model.

UNIDO categories	CED categories	No. of requirements	Relative percentage	Req. no. per level	Req. no. per level	Req. no. per level	Req. no. per level	Req. no. per level	Req. no. per level	Req. no. per level
				Base-level	F	E	D	C	B	A
Park Management	**CED management**	32	38%	7	11	15	19	24	28	32
Environment	**Environment**	29	34%	7	10	14	18	21	25	29
Economic	**Economic**	11	13%	2	4	5	7	8	10	11
Social	**Social**	13	15%	3	5	7	8	10	11	13
	Total requirements of CED model	85	100%	19	30	41	52	63	74	85

Conclusion

Within the framework of the National Strategy for Circular Economy and the European current regulatory framework, e.g. the EU Action Plan for the Circular Economy, the proposed CED model offers a structured approach for Italian industrial areas to evolve into sustainable and circular ecosystems, facilitating the progressive transition from a base-level required for the recognition as CED to higher levels. The qualification as a CED and the achievement of higher levels could allow industrial areas to access various benefits as incentives, facilitations, regulatory simplifications, etc. and, primarily, to have best performances from several point of view including at local and territorial levels.

From an industrial development perspective, the model promotes the following aspects:

- technological and process innovation of resident organizations;
- resource management within and outside the area;
- development of shared infrastructures;
- improvement of environmental and social impacts;
- collaboration among organizations, Local Authorities and the surrounding territory;

- employment and organizational growth.

ENEA can guarantee its support for the implementation of model and the qualification of CED. By applying a consistent framework across several Italian industrial contexts, the model enables a comprehensive assessment of sustainability and circularity performance, fostering the adoption of targeted strategies for system-level improvement and ensuring alignment with national and European policies on ecological transition.

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Extracting secondary raw materials and second-hand electronic components from waste printed circuit boards by thermo-mechanical

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Abstract

Waste electronics (PCBs) are a valuable source for the recovery of precious metals and critical raw materials (CRMs). At the state-of-the-art, gold and silver are already extracted from PCBs, being mainly present in components, whereas copper is almost the only metal present in the board. Secondary raw material extraction is affected by the soldering alloy which is a contaminant for liquid metallurgy and pyro-metallurgy processes. If a gentle disassembly process would be available, also second-hand electronic components could be recovered from waste PCBs. In this study, a thermo-mechanical disassembly process, currently under patenting (namely "impact desoldering"), is proposed which is able to detach the electronic components and the soldering alloy from the boards. The residual contamination from the soldering is minimal both on the components and the boards, and the same alloy can be easily recovered for furher use. Separation is made by impact after heating at low temperature, the same used for the original soldering process. An experimentation has been carried out with on a small amount of waste boards, and an ingot of the soldering alloy has been melted in the end. Cleaned PCBs have been subsequently processed with a further thermo-mechanical process to extract copper, by rolling.

Keywords: Waste electronics; Thermo-mechanical disassembly; Recycling; Critical Raw Materials (CRMs).

Introduction

Huge availability of high valued raw materials which are difficult to collect and known as critical raw materials (CRMs) is fundamental for advanced technologies, digitalization and renewable energies. To date 34 materials have been identified and listed as CRMs [1] and the development of new solutions, which are also promoted by the European Union, aiming to collect these resources, is an urgent need. In this view, the large amount of global electronic waste (e-waste) offers a source of wealth to extract CRMs and precious metals from recovered electronic components even if only 22.3% of this waste is recycled [2]. The strategy based on recovery strategic materials from waste is commonly referred to as urban mining and can be applied to different fields. Waste electronic boards (e-boards) are complex systems consisting in a non-conducting fiberglass laminate which integrates conductive copper (Cu) layers and different electric and electronic components (capacitors, resistors, crystal oscillators, microchips) soldered on it through tin (Sn) alloy. For this reason, electronic boards contain high values precious metals such as gold (Au), palladium (Pd) and silver (Ag) and strategic metals like Cu and Sn [3]. In Figure 1 a typical PCB with recoverable constituents is shown.

The recycling strategies applied to electronic boards develop in different steps being mechanical processing (or dismantling), upgrading and refining [4]. Mechanical processing aims to separate materials and components into different categories through hammers, screwdrivers and conveyors. In the further step, physical processes involving grinders and crushers allow us to obtain small parts and metallic and non-metallic parts are then separated. Furthermore, chemical strategies based on the main techniques of pyrolysis, gasification, depolymerization through supercritical fluids and hydrogenolytic can be used to separate organic and inorganic parts [5].

Figure 1. Example of waste PCB and recovered constituents: electric and electronic components, tin alloy and copper layer and fiberglass ply.

Refining step is based on metal extraction which can be pursued through melting obtained by pyrometallurgical processes or dissolution through liquid by hydrometallurgical processes or their combination [6, 7]. Finally, the purification of dissolved metals is obtained by liquid/liquid extraction (solvent extraction), precipitation/cementation and electrolyte refinements (electrowinning/electro-recovery).

In the first step of PCBs managing, removal of the welded joints, known as desoldering is an essential step to recover electronic components which can be carried out through heating a medium or infrared and laser heating. A further important step is also managing the layered structure of PCB substrates to recycle fiberglass and copper layers which can be lead by a recent approach based on microwave bath using solvents such as dimethyl formamide. Following this last trend the current research aims to use a novel appraoch to recycle all PCBs' constituents using an innovative technique based on thermo-mechanical disassembly already used for polymeric matrix composite recycling [8, 9]. This approach limits contamination and oxidation of recovered components.

Methods

Different kinds of waste PCBs, 4 kg of total mass, have been collected from electronic devices such as computers and they all consisted of four main constituents being electric and electronic components, soldering alloy, Cu layers and fiberglass layers for PCB subtrates. The whole recycling strategy is shown in Figure 2 where the two main steps of desoldering and thermo-mechanical disassembly can be identified. In particular, desoldering was carried out by pre-heating PCBs in a muffle furnace Nabertherm L45/12/B140 (Lilienthal, Germany) for 15 min at 250 °C. Heating allowed melting of soldering tin alloys and electronic components were recovered after controlled impacts.

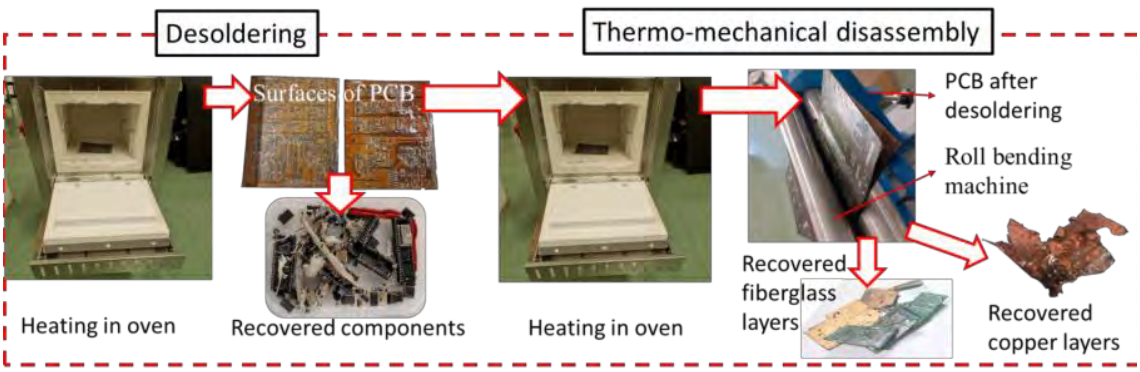

Figure 2. Two-step procedure aberthern to recycle waste-PCBs' constituents.

On average, 3 cycles of heating and controlled impacts were required to recover the only soldering alloy, used to obtain a massive ingot, and electronic components. Afterwards, the same heating cycle was carried out on desoldered PCBs which were then deformed through a roll bending machine equipped with rollers having a 30 mm nominal diameter. This procedure allowed to recover the fiberglass layers and the copper trucks after several heating and deformation cycles.

Results and Discussion

An amount of 20 boards has been used in the experimentation; they have different dimensions ranging from the minimum of 10×6.5 mm2 to the maximum of 160×100 mm2. The temperature of 250 °C for pre-heating was chosen to compensate the fact that the oven door was continuosly opened. Three consecutive impacts, produced on a cold metallic plate to have fast solidification of the soldering alloy after its removal, have been carried out on each PCB to maximize the mass of recovered components. Optimal desoldering is obtained when the alloy is fully removed from all the holes where the components were originally placed, a result which cannot be replicated by machining because of the produced contamination. The performed three impacts were not always sufficient to desolder all the boards. In fact, 40% of the boards were almost fully desoldered and 35% were sufficiently managed, indeed 25 % comprising the largest board were partially threated. In the worst desoldering cases, there were large areas were components are fully recovered and other areas (up to 50%) completely unaffected. For large boards, the bad results depends on difficulties in transferring the impact energy to the components. At the end of the experimental phase, 2.3 kg are the processed PCBs being 58.7% of the initial mass. Moreover, recovered components and soldering alloy account for 1.46 kg and 0.106 kg corresponding to 37.1% and 2.7 % of the whole mass respectively. Lost mass of 0.06 kg, about 1.5%, depended on several occurrences such as the ejections of very small components and alloy droplets, or the degradation of such plastics. In Figure 3 the main results in terms of recovered constituents are shown.

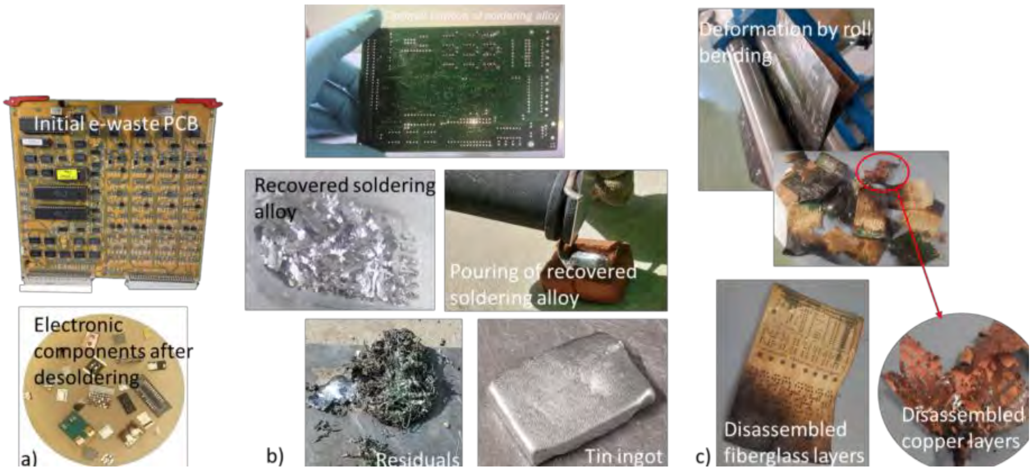

Figure 3. Main findings of the recycling process: recovery of electronic components a); recovery and re-manufacturing of soldering alloy b); recovered fiberglass and copper layers c).

The recovered soldering alloy was then cast within a sand mold and a small ingot, 72.g in mass was finally extracted. Upon puring phase, 21.8 g resulted contaminated because of slag, impurities and embedded wires (Figure 3 b). The recycling procedure ended with thermo-mechanical disassembly to recover fiberglass and copper layers from PCBs. Good results were obtained even if for large electronic boards it was difficult to have homogeneous heating because of laboratory procedure and this lead to technical issues in separating all layers. İn the best case, copper layers inside the waste PCBs and copper tracks from the external surfaces were fully separated.

Conclusion

The current research aims to develop a novel model of circular economy based on recovery most of the constituents of waste PCBs according to the principles of urban mining. The developed lab-scale novel approach based on desoldering of electronic components, thermo-mechanical disassembly to recover different layers of PCB substrates and XRF analysis to investigate the content of CRMs in the recovered components reached all the established goals. In fact, notwithstanding the variability of managed PCBs and the different manual operations, all the electronic components have been desoldered from the substrates, the soldering alloy has been fully or partially recovered, fiberglass layers, copper layers and copper trucks have been separated with minimal contamination as well. Moreover, the recovered soldering alloy has been reprocessed to develop a second life product. Disassembled components have been interested to minimal heat and impact energy and are potentially re-usable. That is the base at the concept of the Ma.Cri.No. project which is continuing this experimentation, focusing on the component re-use. In such cases, disassembly can be done with minimal impact o absence of impact, into a static oven, as in the Ma.Cri.No. approach.

Acknowledgements

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Developing industrial symbiosis networks: insights from southern Italy

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Abstract

Since 2010, ENEA has been actively developing and implementing a portfolio of projects aimed at fostering Industrial Symbiosis (IS) in Italy. These initiatives support companies in adopting systemic and cooperative approaches to resource optimization through the exchange of materials, energy flows, water, services, and expertise. In particular, as a partner of the BRIDGeconomies consortium, with territorial responsibility for the southern Italian regions, ENEA has implemented, among its sustainability services for enterprises, two IS working tables in the regions of Campania and Apulia. Afterwards, an Operative Handbook (OH) was developed for one of the synergies selected from those emerging during the roundtables, intended as a support tool for companies. Specifically, this OM focuses on the environmental, economic and regulatory feasibility of the IS pathway related to the reuse of waste from the coffee roasting process, particularly coffee silverskin, as a functional ingredient for the production of baked goods.

Keywords: CIndustrial symbiosis; Environmental impacts; Coffee silverskin; Functional ingredient; Resourse valorization.

Introduction

The term "symbiosis" refers to a close and prolonged biological association between two organisms in which at least one partner benefits and neither is harmed. It is widely used in ecology to describe interspecific interactions that range from mutualism to commensalism [1, 2]. Applying this concept to the industrial context, industrial symbiosis (IS) emerges as a strategic approach for optimizing resource utilization through the exchange of materials, energy, water, skills, infrastructure, and other assets. Within this framework, a company's surplus resources can be used by another company as inputs in its production processes, thereby valorizing resource streams. IS extends beyond the mere reuse of waste and by-products, which typically involves the exchange of firm-specific materials between two or more parties. It also encompasses the sharing of utilities and infrastructure, including the joint management of energy, water, and wastewater, as well as the collective provision of services such as transportation or catering. Industrial districts represent an ideal setting for implementing IS. However, significant benefits can also be achieved when small and medium-sized enterprises (SMEs) are dispersed within a defined geographical area. The advantages of IS are multifaceted, encompassing environmental, economic, and social dimensions [3]. By adopting innovative strategies for resource sharing and reuse, IS can move towards the principles of a circular economy while simultaneously reducing environmental impacts.

Within the framework of the Enterprise Europe Network (EEN), and as a partner of the BRIDGeconomies consortium with territorial competence in Southern Italy, ENEA has implemented two IS working tables in the Campania and Apulia regions. These initiatives were designed as part of ENEA services to support the sustainability of SMEs, in order to foster the adoption of a systemic and collaborative approach for the sharing and transfer of resources, such as by-products, waste heat, services, skills, and expertise.

Methods

To this end, ENEA applied a methodology developed over the past decade through various projects (Figure 1). This methodology focuses on raising awareness and engaging companies through tailored communi ation strategies, common language frameworks, and dedicated networking activities and tools, specifically designed to create territorial business networks [4]. Among others, ENEA has developed SYMBIOSIS® (www.industrialsymbiosis.it/piattaforma), the first IS platform in Italy aimed to support the interaction between companies and other relevant stakeholders, such as local authorities and regulatory bodies. The platform is designed to match supply and demand and to activate resource transfers, also providing additional operational tools such as regulatory databases, Life Cycle Assessment (LCA) and Ecodesign tools, and collections of best practices, particularly targeted to SMEs [5].

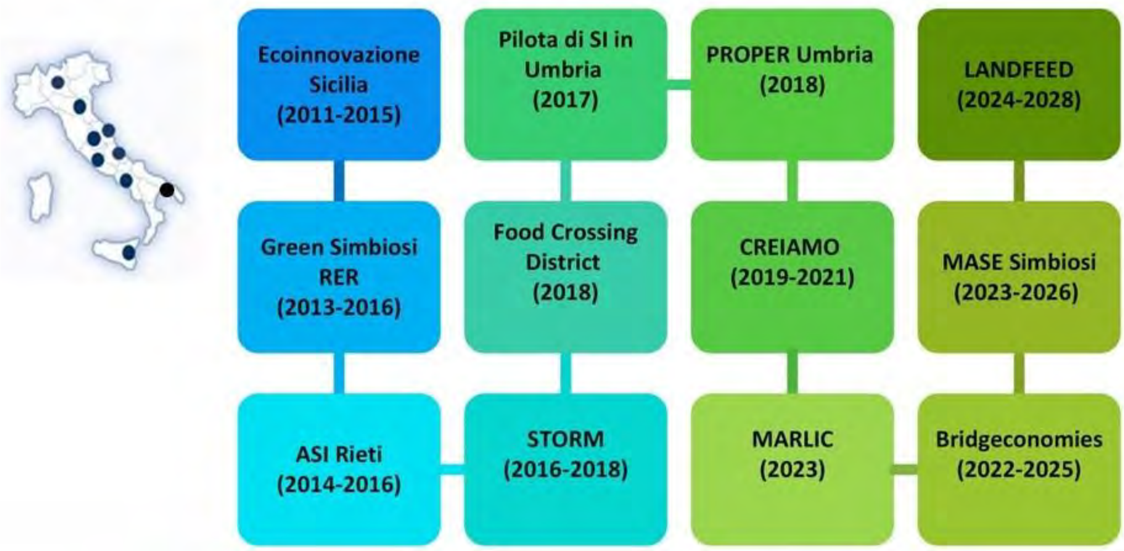

Figure 1. Projects carried out by ENEA on Industrial Symbiosis.

The BRIDGeconomies case study

Within the framework of the BRIDGeconomies project, with the support of local associations and chambers of commerce, a total of 44 SMEs from diverse productive sectors participated in the working tables held in Salerno in Campania Region (13 July 2023) and Taranto in Apulia Region (24 October 2024). During the roundtables, 390 resources, including material and energetic flows as well as knowledge and assets, were mapped, and 260 potential synergies among companies were initially identified: 51% related to input needs and 49% to outputs released. For illustrative purposes, Figure 2a shows the breakdown of the resources shared during the Salerno working table, whereas Figure 2b presents the synergies across input and output resources, categorized by resource type.

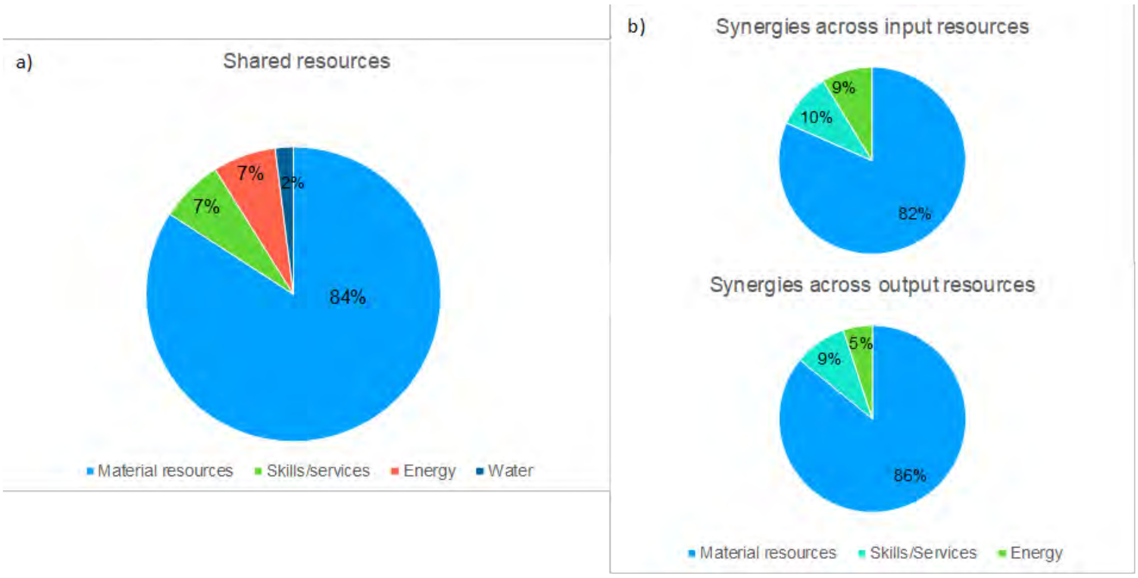

Figure 2. Breakdown of shared resources (a) and of synergies across input and output resources (b), in relation to the Salerno Industrial Symbiosis working table.

Follow-up of working tables

Following post-event data analysis and the identification of additional potential synergies, each opportunity was assessed for feasibility from legal-administrative, technical, economic, environmental, and performance perspectives. For a selected group of high-potential synergies relevant to participating companies, an Operative Handbook (OH) was developed to support the practical implementation of an IS scenario. The OH consists of two parts. The first part contains the 'Summary Scheme' which provides, for each step of the IS process, all references to regulatory, technical, and other relevant tools necessary for the effective implementation of the synergy, while the second part is a 'Technical Dossier', including the relevant regulatory, technical, and logistical documentation.

The BRIDGeconomies OM focused in particular on the valorisation of agro-industrial residues and their reuse in the food sector. Indeed, among the flows identified during the Salerno and Taranto working tables, the most representative stream, selected for its data availability and replicability potential, was represented by coffee silverskin (CS), a residue from the roasting process in a company located near Salerno. The current disposal pathway, which involves compost production, was compared with an alternative scenario in which CS is reused as a functional ingredient in bakery products, improving their nutritional profile thanks to its high fiber and antioxidant content. A thorough analysis of regulatory, environmental, and economic enablers and constraints was conducted to guide the involved companies in the practical implementation of this IS model. At regulatory level, the key issue concerning the use of CS in the food sector depends on its proper classification under Italian law. If CS is legally defined as a 'waste', its direct use as functional ingredient in baked products would be severely restricted due to stringent waste management regulations. Conversely, if it can be classified as a 'by-product', according to all the requirements of Legislative Decree 152/2006 Article 184-bis, as further clarified by Ministerial Decree 264/16, it would potentially be used in food applications, provided that food safety regulations (EC Regulations 852/2004 and 178/2002 together with relevant national legislation) are also met. This involves assessing potential contaminants, ensuring hygienic processing, and ultimately demonstrating that the consumption of food products containing CS does not pose a risk to human health. Moreover, EU Regulation 2015/2283 on novel foods is the main and most significant regulatory hurdle to address. Since CS was not consumed to a significant extent in the EU before the critical date of 15 May 1997, it falls within the definition of a novel food. As a result, any intended use for food purposes requires a mandatory and comprehensive pre-market authorization procedure, as established by this regulation. From the environmental point of view, the assessment of the performance of two alternative scenarios, namely CS composting (Business-as-Usual scenario) and CS reuse as functional ingredient in baked products (IS scenario), was carried out in a life cycle perspective [6]. The Life Cycle Assessment (LCA) results indicate that implementing the IS scenario, in which all the CS produced in one year by the investigated company is used as a functional ingredient in baked goods, would allow a reduction of 2 tons of CO_2 eq emitted into the atmosphere. The IS scenario would also yield considerable environmental benefits across the other impact categories analysed (namely, acidification, climate change, particulate matter, marine eutrophication, freshwater eutrophication, terrestrial eutrophication, human toxicity, both carcinogenic and non-carcinogenic, ozone depletion, photochemical ozone formation, resource use, including fossil, minerals and metals, and water use). Indeed, while the BaU scenario entails environmental burdens across nearly all impact categories, the IS scenario delivers environmental benefits in most of them. In conclusion, even if CS composting allows the recovery of compost, thus avoiding the production and use of 12 kg of synthetic NPK fertilizers per ton of CS disposed, the results of the IS scenario, that involves the substitution of 950 kg of wheat flour per ton of CS, show that the latter scenario is far more environmentally advantageous [6]. Finally, the economic assessment highlights that implementing the IS scenario can generate significant economic benefits, both in terms of reduced operational costs for the company managing the CS disposal and increased company margins for the bakery. In particular, compared to the BaU scenario, the synergy implementation between the coffee roasting company and the bakery allows a 34% reduction in operational costs, confirming the importance of adopting IS and circular economy practices in local production systems.

Conclusion

Industrial symbiosis is widely recognized as a key driver in the shift from a linear to a circular economic model, extending the lifespan of resources, increasing efficiency, and reducing waste. It generates clear social and environmental benefits, while also creating new business opportunities by transforming waste into valuable products. The methodology developed by ENEA and applied to the BRIDGeconomies case study, proves to be effective. Through the selection of the most promising synergies between companies of a defined geographical context, involved in the IS working table, new opportunities were created for the collaboration in the sharing of infrastructure and services, the creation of new added-value products and the strengthening of the local economic and productive system.

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Circular business models and Eco-industrial innovation: the POREM case in the regenerative agriculture value chain

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Abstract
Over 60% of European soils are currently degraded due to organic carbon loss and biodiversity decline. This study explores the LIFE POREM project, which implements industrial symbiosis by transforming poultry manure into a high-value bioactivator for restoring degraded soils through a patented enzymatic process. The research evaluates the economic and environmental impacts of this innovation in Italy across three circular business model configurations. Results indicate a national production potential of 40,6 million tons per year, covering over 4.200 km^2 of agricultural land. The estimated market value ranges from 1 to 2 bilion euros annually. Regions such as Veneto, Emilia-Romagna, and Lombardy represent the most strategic clusters, accounting for approximately 75% of potential production. Environmentally, the process reduces CO2eq emissions by 80% during production while enhancing soil fertility and nutrient cycling. The findings confirm that circular value chains and industrial symbiosis-based business models are not only operational tools but also key managerial and theoretical levers for scaling regenerative agriculture through ecosystem-level value creation and territorial embeddedness.

Keywords: Circular Economy; Industrial symbiosis; Regenerative agriculture; Italy; Soil health.

Introduction

The European Union faces a critical soil health crisis, with more than 60% of soils classified as degraded due to the loss of organic carbon, erosion, and salinization. Soil health is the fundamental pillar of Regenerative Agriculture (RA), a framework designed to produce safe food within the planet's carrying capacity while addressing challenges like drought, floods, and rising farming costs. The global food system is responsible for 25% of GHG emissions, necessitating eco-innovative solutions [1, 2, 3, 4].

From a management perspective, soil degradation also constitutes a structural risk for agri-food value chains, as the depletion of natural capital undermines long-term productivity, increases production costs, and exposes firms to regulatory, market, and climate-related uncertainties. Recent management literature emphasizes how circular economy strategies can transform environmental constraints into sources of competitive advantage by redesigning value creation, delivery, and capture mechanisms across interconnected actors rather than within individual firms [5, 6]. In this context, industrial symbiosis emerges as a key organizational mechanism enabling firms to reduce transaction costs, internalize externalities, and co-create value through coordinated resource flows, particularly in territorially embedded sectors such as agriculture [7, 8]. Despite growing conceptual interest, empirical evidence on scalable circular business models in RA remains limited, especially regarding their economic feasibility, governance structures, and territorial deployment at regional and national scales.

The POREM project addresses part of this gap by proposing a circular solution through industrial symbiosis, transforming poultry manure into a bioactivator designed for degraded soil recovery via a patented bioprocess (EP1314710). This process utilizes specific plant mixtures (e.g., Graminaceae and Apiaceae) with enzymatic activities, termed VAP (Vegetable Active Principles), to create a product that improves soil fertility, organic carbon levels, and biodiversity. By integrating industrial symbiosis into routine management, POREM aims to restore soil as a valuable farm asset while mitigating climate change [9].

Methods

The study assesses the socio-economic weight and potential impact of POREM's circular value chains in Italy. The methodology utilizes 2020 data from Eurostat and AIDA, alongside 2024 information from the Italian Veterinary Information System [10]. The assessment is measured through three dimensions:

1. Estimation of the annual potential production quantity of POREM in Italy.
2. Market value estimation at base prices (€250/t for the bulk product and €500/t for the pelletized).
3. Mapping of the number of enterprises involved (poultry farmers, fertilizer producers, and end-user farms).

The analysis considers three business model configurations (a, b, and c) that describe different interaction modes between VAP producers, poultry farmers, fertilizer producers, and end users to optimize the circular value chain (Figure 1) [10].

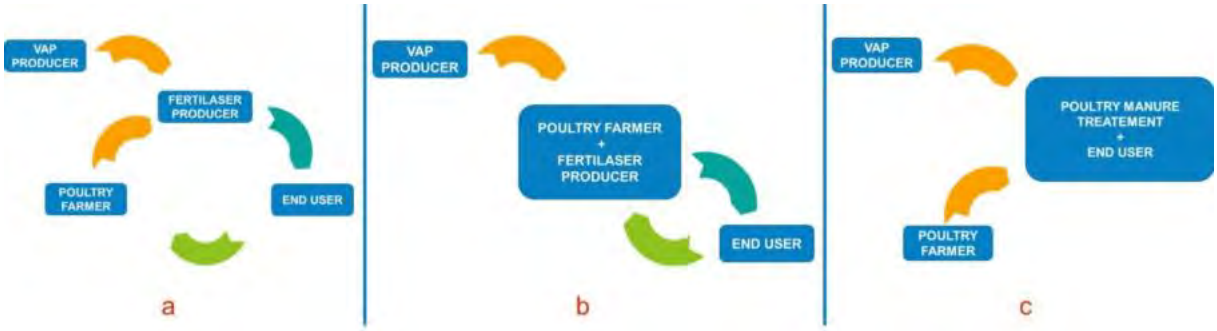

Figure 1. POREM circular business models through industrial symbiosis [10].

Results

The research highlights significant potential for the POREM model in the Italian context.

Economic and quantitative impacts. The estimated annual potential production of POREM in Italy is 4,19 million tons, derived from approximately 5,59 million tons of poultry manure. At the European level (EU 27), this potential reaches 40,6 million tons. Nationally, the treatable agricultural surface exceeds 4.276 km^2 per year. The market value for POREM in Italy is estimated between 1 and 2 billion euros annually.

Environmental performance. The POREM production phase achieves an 80% reduction in CO_2eq emissions compared to traditional nutrients. The bioactivator further contributes to environmental sustainability by improving nutrient cycling, water capacity, and reducing ammonia emissions.

Systemic and regional implications. The study identifies around 27.000 potential entities involved in the Italian value chain, including 361 poultry farms (Table 1), 191 fertilizer producers (Table 3), and over 26.500 agricultural firms (Table 2). The North-East of Italy shows the highest potential for industrial symbiosis synergies. Specifically, three regions cover nearly three-quarters of the national production potential: Veneto (34,6%), Emilia-Romagna (18,9%), and Lombardy (16,9%).

Table 1. Poultry farms potentially eligible for the POREM business model in the Italian regions, broken down by enterprise size.

Region	Large	Medium sized	Small	N.A.	Total
Abruzzo	0	0	10	3	13
Calabria	0	0	7	2	9
Campania	0	0	32	13	45
EmiliaRomagna	4	10	23	5	42
FriuliVenezia Giulia	0	2	2	3	7
Lazio	0	0	14	8	22
Lombardy	1	3	13	3	20
Marche	2	2	8	2	14
Molise	1	1	7	4	13
Piedmont	1	2	9	2	14
Apulia	0	1	22	10	33
Sardinia	0	0	17	0	17
Sicily	0	3	30	20	53
Tuscany	0	0	6	3	9
Umbria	0	1	10	5	16
Veneto	1	3	20	9	33
N.A.	0	0	0	1	1
Total	10	28	230	93	361

Source: Authors' own elaboration on data [11]

Table 2. Agricultural firms potentially eligible for the POREM business model in the Italian regions, broken down by enterprise size.

Region	Large	Medium sized	Small	N.A.	Total
Abruzzo	2	12	378	167	559
Calabria	0	8	449	170	627
Calabria	2	13	827	501	1.343
Campania	3	32	1.781	850	2.666
EmiliaRomagna	13	85	906	287	1.291
FriuliVenezia Giulia	4	31	216	52	303
Lazio	5	52	2.061	929	3.047
Liguria	0	5	160	59	224
Lombardy	9	79	1.395	433	1.916
Marche	3	16	412	117	548
Molise	1	5	140	78	224
Piedmont	4	22	494	165	685
Apulia	5	55	2.404	1.081	3.545
Sardinia	2	27	700	259	988
Sicily	6	42	2.472	1.442	3.962
Tuscany	20	148	1.616	513	2.29
TrentinoAlto Adige	3	50	235	49	337
Umbria	0	15	428	165	608
Aosta Valley	0	1	13	4	18
Veneto	17	60	960	271	1.308
N.A.	0	0	3	26	29
Total	99	758	18.050	7.618	26.525

Source: Authors' own elaboration on data [11]

Table 3. Fertilizer producers potentially eligible for the POREM business model in the Italian regions, broken down by enterprise size

Region	Large	Mediumsized	Small	N.A.	Total
Abruzzo	1	1	2	0	4
Calabria	0	0	2	1	3
Calabria	0	2	2	1	5
Campania	0	1	8	6	15
EmiliaRomagna	3	5	13	4	25
FriuliVenezia Giulia	0	2	4	1	7
Lazio	0	0	6	3	9
Liguria	0	0	2	0	2
Lombardy	1	9	20	4	34
Marche	0	0	5	1	6
Molise	0	0	0	1	1
Piedmont	0	1	6	0	7
Apulia	1	3	4	1	9
Sardinia	0	0	5	1	6
Sicily	1	1	10	4	16
Tuscany	0	1	11	0	12
TrentinoAlto Adige	0	0	4	0	4
Umbria	0	0	1	1	2
Veneto	1	4	12	4	21
N.A.	0	0	0	3	3
Total	8	30	117	36	191

Source: Authors' own elaboration on data [11]

Discussion

POREM demonstrates how industrial symbiosis and circular business models can scale RA practices. By transforming a waste stream (poultry manure) into a bioactivator, the project aligns with the objectives of the EU Soil Mission to regenerate biodiversity and increase soil organic matter. The socio-economic sustainability of the model is evidenced by its potential to improve economic prosperity for farmers, while enhancing human and environmental health.

From a theoretical point of view, this study contributes to circular economy and management theory by extending circular business model research beyond the firm level to a system-level, territorially embedded perspective. It advances industrial symbiosis theory by empirically demonstrating a shift from resource-efficiency-oriented exchanges toward regenerative outcomes, including soil restoration and biodiversity enhancement [7]. Moreover, by comparing alternative circular business model configurations, the findings enrich ecosystem and network governance theories, highlighting governance adaptability as a key explanatory factor for the scalability of regenerative and circular business models across diverse regional and organizational settings.

From a managerial perspective, the POREM project demonstrates that circular business models based on industrial symbiosis can enhance both environmental performance and economic resilience in agri-food systems. By coordinating poultry farmers, bio-input producers, fertilizer manufacturers, and agricultural end users, the project confirms that value creation increasingly occurs at the ecosystem level rather than within individual firm boundaries, in line with recent management literature on collaborative value networks and sustainability-oriented ecosystems [6, 12]. The three business model configurations identified highlight the importance of governance flexibility, showing how different coordination mechanisms can facilitate scalability and adaptation to heterogeneous regional contexts. The strong territorial concentration of production potential further suggests that cluster-based strategies play a critical role in accelerating the diffusion of circular innovations. For managers, this implies that competitiveness depends on the ability to engage in inter-firm collaboration and shared value creation, while for policymakers it underscores the relevance of place-based support measures that enable industrial symbiosis [8, 13].

Future developments should further refine the analysis at the provincial level by considering usable agricultural areas and logistics within the high-potential clusters identified in Northern Italy, with the aim of promoting networking activities among local companies aimed at fostering the implementation of a circular value chain based. In conclusion, soil remains the most valuable asset for a farm, and circular innovations like POREM are vital to protecting this resource and restoring degraded soils.

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Valorization of Critical Raw Materials recovered from lithium-Ion batteries: A resource and economic analysis of a potential supply chain in Italy

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Abstract
The circular economy promotes material reuse and recycling, driving major investments in Italy and Europe. The European Green Deal and Italy's National Recovery and Resilience Plan support this transition, particularly for critical raw materials (CRMs), essential yet economically risky for Europe. The European Commission's CRM Act, incorporated into Italy's legal framework, emphasizes CRM supply diversification. Lithium-ion batteries (LIBs), crucial for renewable energy and sustainable mobility, are a key focus. This study employs Material Flow Analysis (MFA) to evaluate CRM recycling potential in LIBs in Italy, analysing the economic feasibility of recycling processes. Different scenarios explore how CRM prices and energy costs affect profitability of the recycling of the vehicles registered in 2022 in Italy. Results suggest a primarily profitable recycling industry, with opportunities to implement industrial symbiosis principles. The study underscores the need for robust recycling infrastructure to ensure economic and environmental sustainability, enhancing CRM recovery in Italy.

Keywords: Critical raw materials (CRMs); Lithium-ion batteries (LIBs); Material flow analysis (MFA); economic analysis, Circular economy; scenario analysis.

Introduction

The circular economy is a systemic approach aimed at extending material lifecycles through reuse and recycling, in order to reduce waste generation [1] and deliver economic, environmental, and social benefits [2]. In recent years, both the European Union and its Member States have promoted the transition toward circularity through dedicated policy frameworks. At the EU level, two action plans [3, 4], part of the European Green Deal and the Clean Industrial Deal [5, 6], define concrete measures to support sustainable economic growth. At the national level, Italy adopted its National Strategy for the Circular Economy in 2022 under the National Recovery and Resilience Plan [7].

A key application area of circular economy principles concerns critical raw materials (CRMs), a list of materials that are considered critical for economic importance and supply risks, representing a weakness in Europe [8]. To address these challenges, the European Commission introduced the Critical Raw Materials Act, establishing targets and metrics for supply diversification through domestic extraction and recycling [9]. These guidelines were subsequently adopted into Italian legislation in 2024 [10], that followed initiatives such as the establishment of a permanent national technical committee on CRMs in 2021 [11].

Among the strategic sectors identified by the EU for decarbonization and digitalization [9], lithium-ion batteries (LIBs) play a central role due to their high energy density and electrochemical performance. LIB technologies vary according to application, with lithium cobalt oxide (LCO) batteries prevalent in electronic devices [12] and lithium iron phosphate (LFP), nickel manganese cobalt (NMC), and nickel cobalt aluminum NCA chemistries widely adopted in the automotive sector. Given the strong concentration of LIB production in Asia, recycling-based recovery of CRMs within Europe is increasingly relevant to enhance supply reliability.

Currently, pyrometallurgical and hydrometallurgical processes dominate LIBs recycling. Although pyrometallurgy is a technologically mature and widely implemented approach [13], it is energy-intensive and requires additional refining steps [14]. By contrast, hydrometallurgy enables higher metal recovery rates with lower energy demand but may produce toxic gases and generates large amounts of wastewater [14, 15].

Material flow analysis (MFA) is widely applied to assess recycling systems [16], with most studies focusing on China and Europe due to their strategic roles in the LIB value chain [9, 17]. Within this context, this study evaluates the economic potential of recycling CRMs from LIBs in the Italian car fleet through an economic assessment of costs and revenues followed by scenario-based sensitivity analysis.

Methods

This study assesses the recycling potential of critical raw materials (CRMs) from lithium-ion batteries (LIBs) in Italy through an integrated material flow analysis (MFA) and economic evaluation. The MFA ensures mass balance and models material flows using Sankey diagrams, with end-of-life LIB inputs estimated from the Italian electric vehicle fleet. The recycling chain combines pyrometallurgical and hydrometallurgical processes, starts from battery discharging, followed by the pyrometallurgy that produces slag and alloy further treated in hydrometallurgy. Process efficiencies and material recovery percentages are primarily based on literature data [18], while wastewater flows are estimated through proportional allocation assumptions. The economic assessment quantifies costs and revenues for each material used or recovered, using inflation-adjusted unit values, including wastewater treatment costs derived from Italian tariff structures [19]. Scenario analyses explore the sensitivity of results to variations in CRM prices and energy costs, and future recycling demand is projected based on EV deployment and the average battery lifetime assumption of eight years.

Findings and discussion

The MFA highlights that the pyrometallurgical stage generates substantial slag, making subsequent hydrometallurgical treatment essential to allow a profitable CRMs recovery. Hydrometallurgical processing is associated with high consumption of sulfuric acid and sodium hydroxide and produces approximately 100,000 tons of wastewater, exceeding four times the mass of processed batteries. CRM recovery rates are high - 63% for lithium carbonate and above 90% for cobalt, nickel, manganese, and aluminum - consistent with literature benchmarks [18].

Base model		
Item	Costs (€)	Revenues (€)
sulfuric acid	-2,785,741 €	
sodium hydroxide	-17,643,029 €	
landfill fees	-143,872 €	
limestone	-4,057,074 €	
hydrogen peroxide	-4,234,602 €	
energy	-1,817,291 €	
iron	-644,347 €	
wastewater	-82,658,029 €	
lithium (Li2CO3)		23,515,689 €
cobalt (CoSO4)		14,951,613 €
nichel (NiSO4)		41,198,949 €
manganese (MnSO4)		1,855,390 €
copper		16,550,955 €
aluminium hydroxide		1,201,737 €
silicon dioxide		892,986 €
calcium sulfate		8,047,452 €
steel		1,009,606 €
aluminium		11,655,485 €
iron hydroxide		7,454,366 €
Total	-113,983,985 €	128,334,231 €
Per unit	-2,301.03 €	2,590.73 €
Per ton	-3,992.22 €	4,494.82 €
Profit per unit	289.69 €	

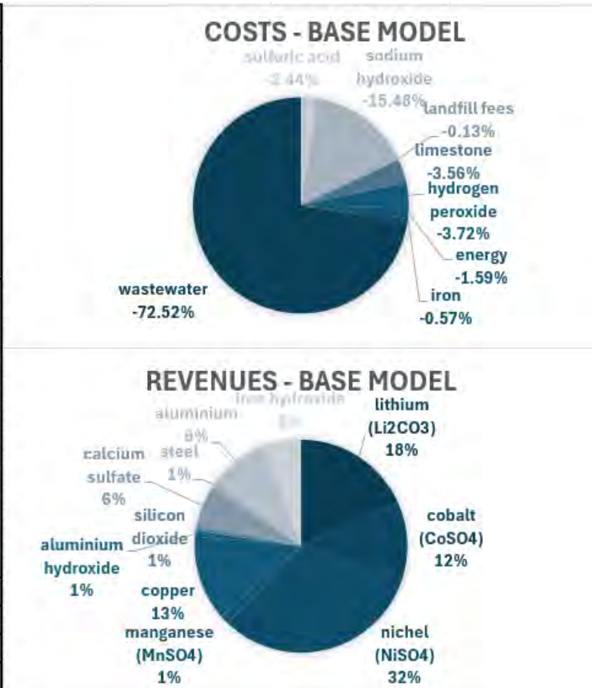

Figure 1. Economic details of the base model and percentual distribution of costs and revenues.

From an economic perspective (figure 1), wastewater treatment is the most relevant cost, accounting for over 70%, with sodium hydroxide representing the most significant cost item. CRMs contribute approximately 75% of total revenues, confirming their economic importance. At full processing capacity, the estimated profit is about €300 per battery. Compared to previous studies [20], revenues are higher, because a greater number of materials were considered, while costs are higher due to the inclusion of wastewater treatment. Scenario analyses identify CRM prices as the most influential variable, while energy costs become relevant when associated with wastewater increasing expenses. Long-term projections (2030–2035) indicate substantial growth in material flows and revenues, reinforcing the strategic role of LIB recycling in Italy's circular economy.

Conclusions

This study evaluates the feasibility of establishing a lithium-ion battery (LIB) recycling industry in Italy, with a focus on recovering critical raw materials (CRMs). By combining Material Flow Analysis (MFA) and an economic assessment, it quantifies material availability and evaluates profitability under different scenarios, showing that recycling is generally economically viable (table 1).

Table 1. Summary of the results emerged from the scenario analysis

	Base	**CRM + 10%**	**CRM - 10%**	**CRM + 15%**	**CRM - 15%**
Base	297,25 €	518,76 €	75,74 €	629,52 €	-35,02 €
E + 80%	267,90 €	-	-	-	-
E - 80%	326,60 €	-	-	-	-
E* + 80%	17,60 €	239,12 €	-203,91 €	349,87 €	-314,66 €
E* - 80%	576,90 €	798,41 €	355,38 €	909,16 €	244,63 €

Source: own source

The implications of this work are related to the advancements on the studies in the field on CRMs through MFA, the urgent need to implement strategies to handle the growing demand of recycling, and the opportunity of Italy to be pioneer in this emerging industry. Some limitations of this work should be highlighted, such as the assessment of water usage in an annual timeframe and the assumption of an entire fleet with a single battery type, that simplifies the model. Further analysis can enrich this study by incorporating data on plant construction, while Life Cycle Assessment methodology or studying industrial symbiosis potential implementation would complement the findings by quantifying environmental benefits, reinforcing the study's contribution to circular economy discourse.

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The by-product regulatory framework for industrial symbiosis an ENEA proposal

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Abstract
The legal and administrative facilitation of industrial side-stream sharing through industrial symbiosis is supported by the 'by-product' framework, as outlined in Article 184-bis of Legislative Decree 152/2006. Nevertheless, in Italy current application remains hindered by operational and regional inconsistencies. To address this, ENEA has conducted an extensive review of the regulatory landscape, putting forward new procedural tools designed to bolster legal certainty and standardize by-product management across the national territory.

Keywords: Industrıal Symbıosıs; by-product; legal-administrative procedures.

Introduction

This paper presents ENEA's proposal for the systematic and certain application of by-product regulations in Italy. By-product classification is the functional requirement underlying the operational implementation of Industrial Symbiosis (IS) for industrial streams.

Since industrial activities are normally not allowed to have waste as inputs, sharing scrap streams in IS processes requires that these streams must be classified as “by-products” to enable their transfer within interactions between two or more industries. In practice, the application of this classification is hindered by several critical issues to the conditions established under Article 184-bis of Legislative Decree 152/2006. From an administrative perspective, there are no specific or explicit authorizations that unambiguously and reliably qualify materials as by-products. However, significant operational difficulties are encountered by the various actors involved along the scraps supply chain, together with challenges arising from the different regulations of the regions within the same national territory. For several years, ENEA has been developing tools and methodologies to support industrial symbiosis [1] and, within the framework of an agreement with the Ministry of Environment and Energy Security, has put forward a specific proposal for the practical application of by-product regulations in order to enable the implementation of IS synergies of scraps streams, certainly referred as "by-product" category. This proposal includes both procedural and regulatory tools.

Findings

Given the definition of "by-products" offered by the Directive 2008/98/ECT and its italian implementation in DLgs 152/2006, the proposal provides for a reorganization of the by-product definition and recognition currently in force in Italy with the aim of facilitating and standardizing the application of by-product legal regime throughout the national territory, as well as recognizing existing regional by-product lists. It also proposes the repeal of Ministerial Decree 264/2016 and the related guidance documents. Furthermore, the proposal introduces new procedures for the recognition of by-products and their proper use. These procedures are based on elements such as dedicated databases and implementing bodies. The key strength of the proposal lies in maximizing the value of experiences already implemented at the Italian level, including the various regional "by-product lists", and in ensuring the involvement of all the stakeholders already engaged in the process. The proposal aims to systematize existing practices into a single, coherent framework through a regulatory reorganization of the by-product regime. In this context, the regulatory and procedural proposals developed by ENEA, in consultation with Ministry of Environment and Energy Security, as outlined above, include:

- A new decree reorganizing the regulations governing by-products (BP).
- A procedure for the recognition of BP and the registration of BP uses.
- Two national databases (DBs) were established as part of these procedures:
  - ✓ By-product Records DB
  - ✓ By-product Use DB.

The proposed draft decree would provide for a reorganization of the regulations currently governing by-products, repealing Ministerial Decree 264/2016 and the related explanatory circulars. The objective is to facilitate and standardize the application of the by-product framework throughout the national territory, while formally recognizing regional by-product lists. More specifically, the new decree would establish:

- The National Committee on By-Products (NCBP), supported by:
  - ✓ A Technical Secretariat, established within the Ministry of Environment and Energy Security
  - ✓ A Technical Body, established within ENEA;

- Procedures for the assessment and recognition of by-product records, to be registered in the in the BP Records Database (BP Records DB);
- Procedures for the assessment and recognition of by-product actual uses to be registered in the BP Uses Database (BP Uses DB);
- Two national databases (DBs) - the BP Records DB and the BP Uses DB - integrated into the IS Metaplatform;
    - A By-products Helpdesk, aimed at supporting stakeholders in the application of the regulatory framework.

The National Committee on By-Products (NCBP) should be established at the Ministry of Environment and Energy Security and be composed of one representative designated by each of the following institutions: the Ministry of Environment and Energy Security, the Ministry of Enterprises and Made in Italy, Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA), The Italian Institute for Environmental Protection and Research (ISRA), the National System for Environmental Protection (SNPA), the State-Regions Conference, the Union of Chambers of Commerce, the Italian Confederation of Craft Trades, and other Trade Associations. The NCBP should collaborate with Technical Secretariat and Technical Body. The NCBP's planned functions would include:

- Promoting and coordinating national actions and interventions aimed at implementing national and European legislation on by-products;
- Evaluating the investigations prepared by the Technical Body and, where accepted, approving the corresponding By-Product Records and By-Product Use Records. Where appropriate, the NCBP may reject applications or refer them back to TB for further information or clarification.

The Technical Secretariat should be established within the Ministry of Environment and Energy Security (MASE) and be responsible for managing incoming and outgoing document flows. The Technical Body should carry out technical investigations related to applications for the recognition of by-products submitted by companies, trade associations and other stakeholders, as well as investigations for registration in the BP Uses Database (BP Uses DTB). The Technical Body should submit the results of these investigations to the Committee for evaluation. In accordance with the proposal, the Technical Body should also be responsible for the development and management of the BP Records Database and the BP Uses Database within the IS MetaPlatform. Finally, it should operate the By-Product Helpdesk.

The National By-Products Helpdesk should be a service provided by the Ministry of the Environment and Energy Security and operated by ENEA, with the aim of ensuring harmonized information nationwide on the correct application of by-product recognition procedures. The Helpdesk will be available as a dedicated feature of the IS Metaplatform (https://metapiattaforma.enea.it/). It will be responsible for responding to queries submitted by companies, organizations, and other stakeholders concerning the application of the procedures, as well as for promoting training and information activities, such as seminars, conferences and webinars.

By-Product (BP) Records Database (DB)

According to the proposal, the database should consist of by-product records approved at the regional level by formal resolution - where Technical Tables/Working Groups on by-products are established – as well as records approved at the national level through mutual recognition procedures. Existing BP Records currently available on the Chamber of Commerce portal will be incorporated into the BP Records DB following preliminary technical investigations and approval by the Committee. In addition, by-products records already approved by the Ministry and listed in Annex 1 to Ministerial Decree 264/2016 will also be included in the BP Records DB. The BP records will contain, inter alia, information on by-product's characteristics, its origin, its intended use, and the quality requirements applicable to its use. The DB will be accessible and searchable upon registration.

By-Product Uses Database (DB)

According to the proposal, the database should include information on the by-product's compliance with an approved data sheet, the quantities of by-product involved, the producer and the user, as well as information concerning the commercial agreement between the parties. The certificate of registration in the DB for By-Product Uses (SP) will serve as a transport document for the by-product within the national territory. In order to remain registered in the DB for By-Product Uses (SP), an annual usage report must be completed and submitted to the Technical Body. The DB will be accessible and searchable by the NCBP, the Technical Body, and any interested third parties subject to the applicable level of confidentiality.

Discussion

The present contribution has been developed within the framework of the cooperation agreement between ENEA and the Ministry of Environment and Energy Security - General Directorate for Circular Economy concerning "the implementation of activities aimed at supporting Industrial Symbiosis projects through regulatory and financial tools" (2022-2026). All the activities and contents presented are currently ongoing. The final work packages are under validation and are being discussed with the Ministry of Environment and Energy Security.

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