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Economic and environmental optimisation of mixed plastic waste supply chains in Northern Italy comparing incineration and pyrolysis technologies

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ABSTRACT

In the quest for sustainable plastic waste management, understanding economic and environmental implications enables optimal selection of treatment technologies. This study presents a multi-objective mixed integer linear programming framework to optimise the supply chain for mixed plastic waste in Northern Italy. Two technologies are considered: incineration and pyrolysis. Results offer quantitative insights into economic and environmental performance, balancing trade-offs between maximising gross profit and minimising greenhouse gas (GHG) emissions. Economic optimisation favours incineration for treating mixed plastic waste, resulting in the highest gross profit of 115 M€ per year, and the highest net GHG emissions of about 680 kt CO_2^{eq} per year. When the aim is environmental optimisation, pyrolysis is preferred due to its lower GHG emissions of 387 kt of CO_2^{eq} per year and yielding a gross profit of 54 M€ per year. Trade-off Pareto optimal solutions were analysed to identify reasonable trade-off configurations between the two objectives.

1. Introduction

Plastics are the world's largest synthetic consumer product (Plastics Europe, 2022). However, the same resilient properties that lead to high annual production (reaching 390 million tonnes in 2021) also create a major environmental problem when it comes to their end-of-life management, which poses an escalating threat to the sustainability of our planet (Borrelle et al., 2020). Plastic waste can be classified into two categories: post-industrial plastic waste, consisting of waste generated during the manufacturing processes, and post-consumer plastic waste, consisting of consumer plastic products disposed at their end-of-life (Ragaert et al., 2017). Post-industrial plastic waste is typically cleaner and easier to handle than post-consumer plastic waste that is inherently more contaminated, and therefore, more challenging to manage. The most common method of recycling post-consumer plastics is through mechanical recycling, where materials recovery facilities (MRFs) sort plastics into bales of Polyethylene Terephthalate (PET) and High-Density Polyethylene (HDPE). Downstream MRFs, the remaining unsorted mixed plastics waste (MPW) has limited economic value and is often incinerated or sent to landfills. These strategies are not sustainable when considering the handling of a constantly increasing volume of plastic (Kunwar et al., 2016), while chemical recycling, such as pyrolysis, is gaining importance as a flexible and robust alternative, as it enables the utilisation of MPW as a feedstock and it complies with the transition towards a circular economy (Dogu et al., 2021). Chemical recycling methods, such as pyrolysis, provide sustainable alternatives to conventional waste disposal methods and contribute to the efficient management of plastic waste. Pyrolysis enables plastic waste to be converted into wax/oil products to be used as heavy fuel substitutes or as materials in the petrochemical industry (Kusenberg et al., 2022a). Given the large-scale impact and long-term consequences of plastic packaging waste (PPW), effective management solutions are needed, which in turn necessitates a better understanding of how to design optimal supply chains (SCs) for PPW management, from both an economic and environmental perspective. In particular, an optimal management of the residual PPW (i.e., MPW) through the selection of the best treatment technologies, is of paramount importance to head towards a circular economy of plastics. To this end, Mixed Integer Linear Programming (MILP) is recognised as a powerful tool for determining the optimal combination of choices in different fields and applications, such as energy or industrial systems (Kallrath, 2000) and, more broadly, this technique has been used extensively in SC design and optimisation (Garcia and You, 2015). Moreover, multi-objective MILP approaches allow for exploring trade-offs between competing objectives, such as environmental and economic optimal performances of the SC (Cui et al., 2017). In their study, Lau et al. (2020) emphasised the importance of innovation in resource-efficient business models, reusable systems,

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List of symbols

Acronyms

CHP	Combined heat and power
COREPLA	Consorzio Nazionale per la raccolta, il riciclo e il recupero degli imballaggi in plastica
GHG	Greenhouse gas
GWP	Global warming potential
HDPE	High-density polyethylene
LCA	Life cycle assessment
LDPE	Low-density polyethylene
LHV	Low heating value
MRF	Material recovery facility
MILP	Mixed integer linear programming
MPW	Mixed plastic waste
MSW	Municipal solid waste
PET	Polyethylene terephthalate
Po	Polyolefins
PP	Polypropylene
PPW	Plastic packaging waste
PS	Polystyrene
RMPW	Remaining mixed plastic waste
SC	Supply chain
TRL	Technology readiness level
WCS	Western Canadian select

Sets

pr	Northern Italian provinces $\{n_{1-47}\}$
s	Plant size *{Small, Medium, Large}*
so	Northern Italian sorting centres $\{n_{48-59}\}$
In	Northern Italian incinerators $\{n_{60-83}\}$
r	Northern Italian refineries $\{n_{84-86}\}$
k	Treatment technologies i.e., incineration, *Po Pyrolysis* and *PoPS Pyrolysis* $\{k_{1-3}\}$

Scalars

ε^{sort}	GHG emission factor for sorting centres [7.163 t CO_2^{eq}/kt MPW]
ε^{In}	GHG emission factor for incineration plants [1.5 kt CO_2^{eq}/kt MPW]
$\varepsilon^{Av,In}$	Avoided GHG emissions from incineration 0.45 [kt CO_2^{eq}/kt MPW]
$\varepsilon^{Av,Po\ pyro}$	Avoided oil extraction and transport GHG emissions [0.17 kt CO_2^{eq}/kt MPW]
$\varepsilon^{Av,PoPS\ pyro}$	Avoided oil extraction and transport GHG emissions [0.204 kt CO_2^{eq}/kt MPW]
i	Interest rate [15%]
$LD^I_{n,n'}$	Fixed linear distance to an incineration plant [150 km]
$LD^L_{n,n'}$	Fixed linear distance to a landfill [50 km]
LHV	Lower heating value [MJ/kg]
MP^{El}	Average market price for electrical power in the Italian Power Exchange market [124,989 €/GWh]
MP^{Mech}	Market price of the mechanically-recyclable polymers sorted by overall pyrolysis plant [378,500 €/kt]
N	Plant life [15 y]
η^{W_MPW}	Average waste-to-MPW conversion factor [0.521]
η^{Mech}	MPW-to-mechanically-recyclable polymers conversion factor for pyrolysis plants [0.0393]
η^{El}_{In}	MPW-to-electrical power conversion factor [1.8 GWh/kt]
R	Earth radius 6372.785 [km]
ρ	Density of pressed bales of MPW [0.3 t/m^3]
$\overline{STC^I}$	Average specific treatment cost for the Northern Italian incineration plants [151,475 €/kt]
$truckE$	Average GHG emission for a truck [900 g CO_2^{eq}/km/truck]
$truck^{MPW}_{cap}$	Quantity of waste and MPW a truck can carry [9.3 t]
$truck^{Oil}_{cap}$	Quantity of pyrolysis oil which a truck can carry [43 t]
$truck^{R}_{cap}$	Quantity of residues which a truck can carry [63 t]
T^l	Landfill gate tariffs [210 €/t]
T^t	Gate tariffs for all treatment plants [210 €/t]
τ	Tortuosity factor for Northern Italian territory [1.4]
UTC^{MPW}	Unitary transport cost for MPW [222 €/kt/km]
UTC^{Oil}	Unitary transport cost for oil [127 €/kt/km]
V	Volume of truck [30 m^3]

Parameters

$C^P_{k,s}$	Plant capacity of treatment plant k of size s [kt/y]
$c_{k,s}$	Corrective factor accounting for cost savings if pyrolysis co-exists with a refinery
C_{so}	Capacity of each Northern Italian sorting centre [kt/y]
$CAPEX$	Capital expenditures [M€/y]
ε^{Pyro}_{Py}	GHG emission factors for *Po Pyrolysis* and *PoPS Pyrolysis* plants [t CO_2^{eq}/ kt MPW]
$LD_{n,n'}$	Matrix of linear distances between nodes n and n' [km]
MP^{Oil}_{Py}	Oil market price [€/kt]
$m^{W,Av}_{pr}$	Quantity of waste available in each Northern Italian province pr [kt/y]
η^R_k	MPW-to-solid residues conversion factor for treatment plant k [kt/kt]
η^{Oil}_{Py}	MPW-to-oil conversion factor [kt/kt]
η^{RMPW}_{Py}	MPW-to-remaining MPW conversion factor [kt/kt]
$OPEX$	Operational expenditures [M€/y]
$STC_{k,s}$	Specific treatment cost [M€/y]
TCI	Total capital investment [M€]
UTC	Unitary transport cost [€/kt/km]

Continuous variables

$E^{Av,k}$	k technology avoided GHG emissions, $k = \{In$ (incineration, *Pyro* (pyrolysis)$\}$ [kt CO_2^{eq}/y]
$E^{Av,Tot}$	Total avoided GHG emissions [kt CO_2^{eq}/y]
E^{Net}	Net GHG emissions [kt CO_2^{eq}/y]
E^{sort}	Sorting centres GHG emissions [kt CO_2^{eq}/y]
$E^{sort,tot}$	Total sorting GHG emissions [kt CO_2^{eq}/y]
$E^{sort,pyro}$	Additional sorting centres GHG emissions [kt CO_2^{eq}/y]
E^{Tot}	Total direct GHG emissions [kt CO_2^{eq}/y]
E^{transp}	Transport GHG emissions [kt CO_2^{eq}/y]
$E^{j,transp}$	j fraction transport GHG emissions, $j = \{$MPW, Oil, Residues, RMPW, waste$\}$ [kt CO_2^{eq}/y]
E^{treat}	Treatment GHG emissions [kt CO_2^{eq}/y]
$E^{treat,k}$	k technology GHG emissions, $k = \{In$ (incineration, *Pyro* (pyrolysis)$\}$ [kt CO_2^{eq}/y]
GP	Annual gross profit [€/y]
$m^{MPW}_{so,t,k,s}$	MPW quantity going from a sorting centre to a treatment location t in a plant k of size s [kt/y]
$m^{MPW,\ Av}_{so}$	MPW quantity available in a sorting centre so [kt/y]
$m^{MPW,\ Plant}_{t,k,s}$	MPW quantity treated in a location t with plant k of size s [kt/y]
$m^{MPW,\ sort}_{t,k,s}$	Overall MPW quantity sent out of a sorting centre so [kt/y]
$m^{Mech}_{t,Py,s}$	Quantity of mechanically-recyclable polymers in the additional sorting centre of a refinery [kt/y]
$m^{Mech,Tot}_{t,Py,s}$	Total quantity of mechanically-recyclable polymers in the additional sorting centre of a refinery [kt/y]
$m^{Oil,Av}_{t,Py,s}$	Quantity of oil produced by a pyrolysis plant [kt/y]
$m^{Oil}_{t,Py,s,refi}$	Quantity of oil produced by a pyrolysis plant sent to an oil refinery [kt/y]
$m^{R}_{t,k,s}$	Quantity of residues produced in a treatment location t, a

	plant k of size s [kt/y]
$m^{R,Tot}$	Quantity of total residues produced [kt/y]
$m^{RMPW}_{t,Py,s}$	Remaining MPW sorted out by an MRF of a pyrolysis plant [kt/y]
$m^{RMPW,Tot}_{t,Py,s}$	Total remaining MPW sorted out by an MRF of a pyrolysis plant [kt/y]
$m^{R,RMPW}_{t,Py,s}$	Additional share of solid residues by incinerating RMPW sorted out in MRF of pyrolysis plant [kt/y]
$m^{w}_{pr,so}$	Waste flowrate from a province to a sorting centre [kt/y]
Rev^{El}	Revenues from selling electricity [€/y]
Rev^{Mech}	Revenues from selling mechanically-recyclable polymers [€/y]
Rev^{Oil}	Revenues from selling pyrolysis oil [€/y]
$Rev^{T,tot}$	Revenues from gate tariffs cashed in [€/y]
PTC	Remaining MPW incineration cost [€/y]
$P^{El}_{t,In,s}$	Electrical power produced by MPW incineration [GWh/y]
$P^{El,RMPW}_{t,Py,s}$	Electrical power produced by the remaining MPW incineration [GWh/y]
$P^{El,Tot}$	Total electrical power produced by the supply chain [GWh/y]
TC	Total annual cost [€/y]
TLC	Total landfilling cost [€/y]
$TPTC$	Total MPW treatment cost [€/y]
TTC	Total transport cost [€/y]
TTC^{j}	j fraction transport cost, j = {MPW, Oil, Residues, RMPW, waste} [€/y]
TR	Total annual revenues [€/y]

Binary variable

$\alpha^{LD}_{Pyr,Refi}$	1 if oil is produced in a pyrolysis plant that is not in a refinery location, 0 otherwise
$\lambda^{Plant}_{t,k,s}$	1 if a plant of technology k and size s in a treatment node t is selected to treat MPW, 0 otherwise.

sustainable materials, waste management technologies, and government policies to address the environmental impact of plastic waste accumulation and greenhouse gas emissions caused by plastic production and inadequate waste management. Recent studies introduced different optimisation models for designing plastic waste SCs, addressing the challenges associated with plastic waste management. For instance, Chaudhari et al. (2021) reviewed the available dataset and models for plastic waste SC processes in the United States and conducted a preliminary analysis at system-level on closed-loop recycling of PET bottles (Chaudhari et al., 2022). Various models have been proposed to optimise plastic waste management. Avisoet al. (2023) developed a mathematical programming model to optimise plastic recycling networks, with the objective of maximising the amount of recycled plastic while reducing pre-sorting requirements and landfill waste. Lim et al. (2023) proposed a mixed-integer nonlinear programming optimisation model to determine the most profitable sorting and recycling strategies for plastic waste. Hu et al. (2022) introduced a web platform that enables the modelling and optimisation of SCs presenting a case study for plastic waste recycling. Castro-Amoedo et al. (2021) proposed a MILP model for plastic waste management networks in western Switzerland, minimising net present cost and environmental impacts. Some studies focused on optimisation models for specific types of waste; for instance, Zhao and You (2021) developed a "consequential life cycle optimisation" framework to determine the economically optimal and environmentally sustainable technology pathway for waste HDPE chemical recycling. Ooi et al. (2023) developed a framework to analyse the impact of emissions trading schemes on municipal solid waste (MSW) management in Malaysia. While some studies focused on optimising SCs for different fractions of plastic waste (Lase et al., 2023), there is a specific research gap when it comes to understanding the unique characteristics and challenges associated with MPW management. Furthermore, existing literature has predominantly examined specific treatment technologies, such as waste-to-energy through incineration (Istrate et al., 2023; Ng et al., 2014; Pluskal et al., 2022) and chemical recycling (Dogu et al., 2021; Zhang et al., 2021), but there is limited research that compares and evaluates the trade-offs between these treatment options in terms of their economic performance (e.g., gross profit) and their environmental impact (e.g., greenhouse gas emissions). This study aims to provide quantitative insights into the economic and environmental performance of optimal MPW SCs in the context of Northern Italy. The problem is formulated through a spatially-explicit, multi-objective MILP model and explores the trade-offs between maximising gross profit and minimising GHG emissions of the MPW SC. By conducting this analysis, the study aims to offer valuable insights into the selection of treatment technologies, i.e., waste-to-energy (direct incineration) and chemical recycling technology (pyrolysis) for MPW, while considering both economic and environmental criteria. The final aim is to support the development of sustainable and efficient MPW management strategies in Northern Italy.

This paper is organised as it follows. Section 2 describes the materials and methods, and Section 3 elaborates further on the mathematical model formulation. Optimisation results are presented in Section 4, and discussed in Section 5. Some final remarks will conclude the article.

2. Materials and methods

The problem is formulated as a spatially-explicit multi-objective MILP modelling framework, for the economic and environmental optimisation of MPW SCs in the context of North Italy. The geographic nodes are described through a set n comprising 47 provinces, 12 sorting centres, 24 incinerators, and 3 refineries. In particular, the set $n = \{n_{1-86}\}$ comprises:

- $pr = \{n_{1-47}\}$ = the 47 Northern Italian provinces;
- $so = \{n_{48-59}\}$ = the 12 Northern Italian sorting centres;
- $In = \{n_{60-83}\}$ = subset of n comprising the 24 Northern Italian incinerators;
- $r = \{n_{84-86}\}$ = subset of n comprising the 3 Northern Italian refineries.

The geographic coordinates of nodes are presented in the Supplementary Material, alongside other relevant data (e.g., the waste quantities for the 47 Northern Italian provinces, the plastic waste capacity of the sorting centres, and the available capacity of the incinerators). Fig. 1B presents a spatial representation of upstream and downstream SC nodes.

As for chemical recycling plants, this study considers only those technologies with a Technology Readiness Level (TRL) of 8 or higher, based on the assessment by Solis and Silveira (2020), which leads to the choice of taking into account pyrolysis as possible treatment option, alongside waste-to-energy plants in the form of incinerators. This study takes into account the currently existing network of Northern Italian incinerators, while pyrolysis plants, which are not present nowadays in this area, can be installed near incineration plants as a result of the optimisation. This allows for a direct comparison (in terms of economic and environmental competitiveness) of the Northern Italian network of incineration plants with the other considered technologies for chemical recycling. Additionally, we assume that pyrolysis plants can be also located nearby existing refineries, as the co-existence of these in the same location may allow for a synergistic deployment and, possibly, a reduction of costs.

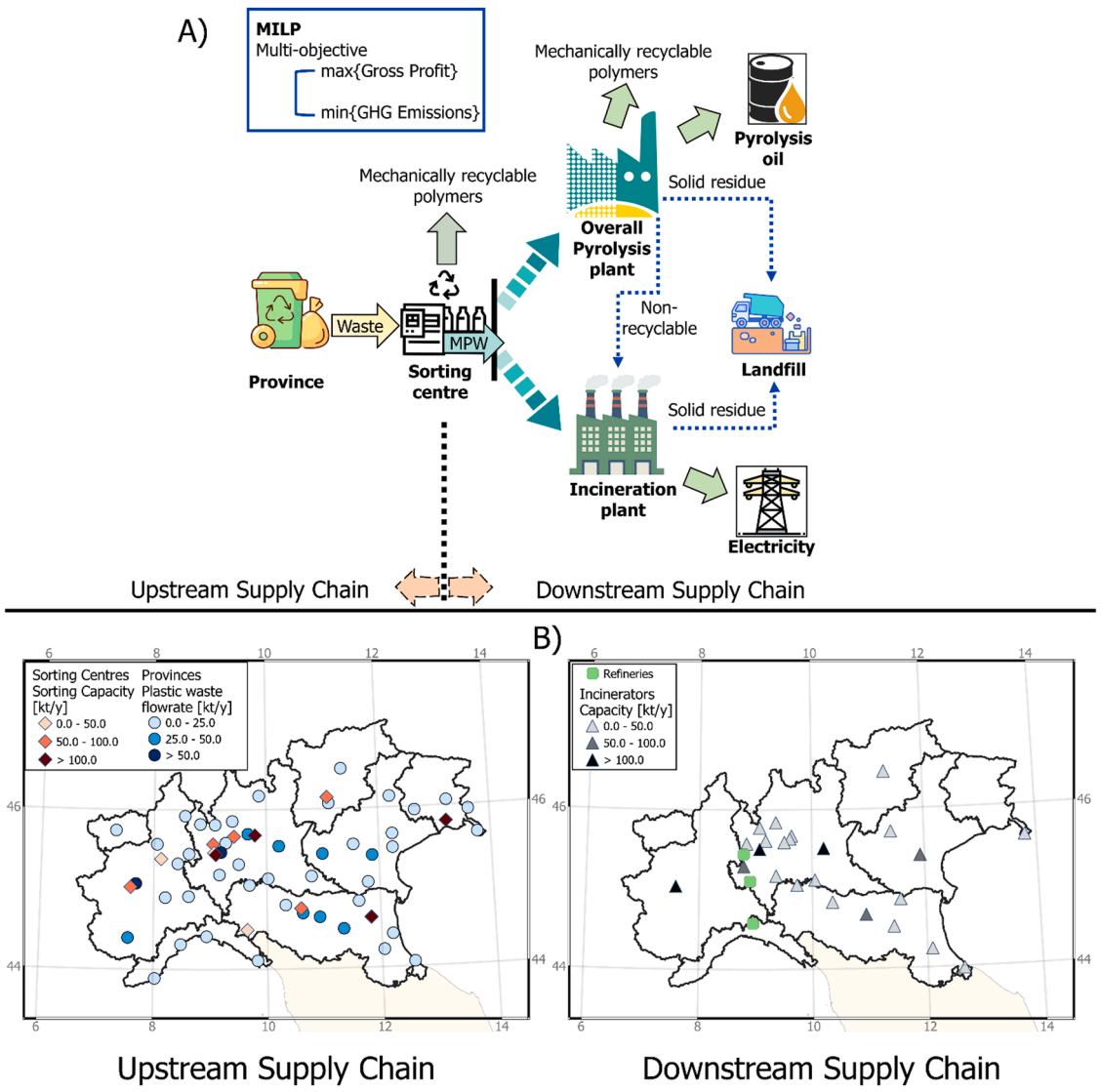

Fig. 1. Mixed plastic waste SC representation: (A) upstream and downstream SC scheme – graphical representation of the boundaries of the research work; (B) upstream and downstream spatially-explicit nodes of the modelling framework.

The MPW SC is here divided into two sections: the upstream SC, represented by provinces and sorting centres, and the downstream SC, comprising MPW treatment technologies (Fig. 1A). In particular, the upstream SC involves the transportation of PPW from provinces to sorting centres. Upon arrival at the sorting centres, the PPW is separated into mechanically recyclable fractions and the remaining MPW. Within the downstream supply chain, the MPW fraction is transported to a treatment plant such as incineration or pyrolysis. These treatments yield different outputs, with incineration generating electric power, while pyrolysis producing oil. The oil produced at pyrolysis plants is further transported to refineries for additional processing. The model considers road transport as the only transportation option, as it reflects the current practices for plastic waste management in Northern Italy.

2.1. Upstream SC: modelling assumptions and inputs

The upstream SC is responsible for transporting PPW from the provinces to the sorting centres. As this model focuses on MPW SCs, the sorting centres do not consider post-industrial PPW and non-PPW fractions (such as mechanically-recyclable polymers and metals). In this context, with the term "waste" we will refer to the PPW received by the sorting centres, including PPW from municipalities and district centres. The waste collected is attributed to the relevant province rather than individual municipalities (for simplicity, we assume the location of each province in its corresponding capital). The annual waste quantity for each province in 2021, received by COREPLA sorting centres and assigned to the province of origin, was obtained from the COREPLA website (COREPLA, 2022).

The sorting centres are characterised in terms of geographic location, plant capacity, and waste-to-MPW conversion factor. As the model focuses on MPW treatment, costs and revenues of sorting centres are considered outside the system boundaries (while their environmental performance will be still taken into account). As for MPW composition, this study assumes the solids content is 77%, with 71% carbon and water content of 23%, and a Lower Heating Value (LHV) of 26 MJ/kg (Cossu et al., 2017; Mastellone, 2020). The list of sorting centres was obtained from the COREPLA website (COREPLA, 2022). It is worth noticing that the sorting centres may have plant sections dedicated to sorting waste materials other than plastic, such as glass or paper waste. As a result, the capacities mentioned for the sorting centres are specific to the plant sections that handle plastic waste (retrieved from company websites).

In determining the environmental performance of sorting centres, we take as a reference an advanced sorting plant located in Northern Italy characterised by Rigamonti et al. (2014). By considering the electricity

consumption of the process units of that sorting centre, the specific electricity consumption amounted to 29 kWh/t plastic processed (Rigamonti et al., 2014). The indirect emissions associated with the electricity consumption of sorting centres were derived from the Italian grid carbon intensity, equal to 247 g CO_2^{eq}/kWh (EEA, 2020), which results in 7.163 t CO_2^{eq}/kt MPW.

2.2. Downstream SC: modelling assumptions and inputs

In the downstream SC, the options for MPW treatment include the current network of incinerators in Northern Italy and the option to install pyrolysis plants. Incinerators burn waste to generate electrical power or combined heat and power (CHP). CHP incinerators rely on the availability of nearby thermal users, and their economic and environmental evaluations require specific data that are site-dependant. Therefore, to give general validity to the study, all incinerators are classified as facilities that solely generate electricity. This is a conservative choice, as the economic benefits deriving from the thermal integration of incineration plants with end-users may bring in additional revenues from the selling of heat (e.g., low-temperature heat for residential use). Pyrolysis plants need to send the generated oil to refineries. The model incorporates this requirement by considering the existing network of oil refineries in North Italy (UNEM, 2021) and the associated costs and environmental impact of transporting oil from a pyrolysis plant to a refinery. Additionally, pyrolysis plants can be located in the same areas as the refineries. Solid residues generated from the treatment plants are sent to landfills. To simplify the model, a fixed linear distance of 50 km between treatment plants and landfills is assumed, without considering landfill capacities. Incineration plants rely on data from actual and already existing plants, while for the installation of chemical recycling plants, we consider three possible plant sizes (*Small, Medium,* and *Large*).

The techno-economic performance of treatment technologies is evaluated based on mass balances, energy balances, and economic parameters such as total capital investment (*TCI*), operational expenditure (OPEX), and specific treatment costs (*STC*). In particular, the Specific Treatment Cost (*STC*, €/kt) is defined as:

$$STC = \frac{CAPEX + OPEX}{C} \quad (1)$$

where *C* is the plant capacity (kt/y), OPEX is the Operational Expenditure (M€/y) and CAPEX is the annualized Capital Expenditure (M€/y), calculated based on the Total Capital Investment *TCI* (M€) updated using (CEPCI, 2019) according to:

$$CAPEX = TCI \cdot \frac{i \cdot (1+i)^N}{(1+i)^N - 1} \quad (2)$$

where all plants *k* of all sizes *s* assume the interest rate *i* equal to 15% and the plant life *N* equal to 15 years. Table 1 presents the *TCI*, OPEX, and *STC* of the selected chemical recycling technologies, while average values are reported for incinerators (see full data on the 24 incinerators in the Supplementary Material).

Additionally, each treatment technology is characterised in terms of greenhouse gas (GHG) emissions factor and avoided GHG emissions factor. The choice of focussing on GHG emissions rather than performing a comprehensive LCA analysis is justified by the boundaries of our study, within which other major impacts of plastic waste (e.g. ecological effects of abandoned plastics or human health effects due to microplastics) are not relevant.

The inputs for the model consist of GHG emission factors for each stage, measured in kt of CO_2 equivalent emissions per kt of input MPW. CO_2^{eq} emissions (CO_2, CH_4, N_2O expressed in CO_2^{eq}), are comprehensively analysed, incorporating all GHG sources such as transportation, energy requirements, and MPW treatment emissions. The overall GHG emissions factor for MPW treatment technologies is derived by comparing direct GHG emissions with avoided GHG emissions. The substitution of fossil fuel sources and the utilization of MPW for electricity generation (incineration) or pyrolysis oil production (pyrolysis plants) contribute to the environmental benefit represented by the avoided emissions with respect to benchmark traditional technologies. To ensure accuracy and reliability, the overall GHG emissions factors obtained through calculations are compared with data from life cycle assessment studies: Cossu et al. (2017); Gear et al. (2018); Jeswani et al. (2021); Khoo (2019); Quantis (2020); Tomić et al. (2022). This comparison helps validate and verify the emission factors used in the model. Table 2 offers a summary of the GHG emissions factors at each stage of the SC.

2.2.1. Incineration

The relevant quantities to be defined are operating costs, solid residues, electrical power output, and capacities. For cost functions, data from Economopoulos (2010) are used, adjusted to a MPW feed. Co-incineration of other waste materials is not considered. Solid residues

Table 2
Summary of the GHG emissions factors for the stages of MPW SC.

SC stage	GHG emissions factor kt CO_2^{eq}/kt MPW	Avoided GHG emissions kt CO_2^{eq}/kt MPW
Sorting centres	$7.163 \cdot 10^{-3}$	
Incineration		
Averaged from LCA studies [¥]	1.5	
Computed in this work	1.966	0.446
Pyrolysis		
Averaged from LCA studies [†]	0.66	
Computed in this work		
Po Pyrolysis	0.562	0.170
PoPS Pyrolysis		0.204
Transport	kt CO_2^{eq}/km/truck	
Calculations	$9.053 \cdot 10^{-7}$	–

[¥] (Cossu et al., 2017; Gear et al., 2018; Jeswani et al., 2021; Khoo, 2019; Quantis, 2020; Tomić et al., 2022).
[†] (Jeswani et al., 2021; Khoo, 2019; Quantis, 2020; Tomić et al., 2022).

Table 1
Capacity, Total Capital Investment TCI [M€], Operational Expenditure OPEX [M€/y], and Specific Treatment Cost STC [€/kt] of each plant size for the chemical recycling technology (pyrolysis). Data referred to incineration plants are given in terms of minimum and maximum values; full data can be found in Supplementary Material. Po Pyrolysis consists of pyrolysis of the polyolefin fraction, and PoPS Pyrolysis includes polyolefin and polystyrene fractions.

Technology	*Plant size*	*Capacity* [kt/y]	*TCI* [M€]	*OPEX* [M€/y]	*STC* [€/kt]
Incineration	Site specific	min-max	min-max	min-max	min-max
		75.0–981.1	64.4–504.3	2.483–15.026	180,036–103,150
Overall *Po Pyrolysis*	Small	26.0	12.352	3.412	212,483
	Medium	65.0	20.046	5.376	135,453
	Large	104.0	30.208	6.503	112,206
Overall *PoPS Pyrolysis*	Small	19.7	11.033	3.159	256,012
	Medium	50.3	19.730	4.536	160,536
	Large	78.8	22.432	6.159	126,783

from MPW incineration are assumed to be ashes and sent to a landfill, equivalent to 7.6% wt/wt ash content in the MPW feed (AIDIC, 2014). Considering an LHV of 26 MJ/kg for MPW and a conversion efficiency of 25% (Neuwahl et al., 2020), the estimated electricity production from MPW incineration is 1.8 GWh/kt MPW. Capacities of Northern Italian incinerators for non-hazardous waste are obtained from the (ISPRA, 2022). If specific incinerator capacity is unavailable, estimates are made using assumptions from (UTILITALIA, 2019) based on hourly capacity, assuming 24-hour operation per day and 330 operating days per year (7920 h per year). *TCI* and OPEX for each incineration plant are estimated using corresponding cost functions and incinerator capacity. Notably, the capacities of incinerators in Torino (TO), Milano (MI), and Brescia (BS) exceed the usual range but are still subjected to the same cost functions. A significant portion of Italian incinerator capacities is allocated to other waste materials, limiting the capacity available for MPW incineration. The procedure to estimate the scaled-down capacity of the incinerators is reported in the Supplementary Material providing the corresponding data.

The global warming potential GWP of the LCA studies of Cossu et al. (2017); Gear et al. (2018); Jeswani et al. (2021); Khoo (2019); Quantis (2020); Tomić et al. (2022), expressed as kt CO_2^{eq}/kt MPW) are summarised in the Supplementary Material. Generally, the results consider the avoided impact of electricity production in the case of incineration, providing a net climate change impact for the treatment technology. A rough estimation, based on the average values from these studies, suggests that incineration has a GWP of approximately 1.5 kt CO_2^{eq}/kt MPW. From calculations, following the methodology used in Hestin et al. (2015) and the IPCC (2006) on incineration and open burning of waste and thoroughly presented in the Supplementary Material, the GHG emissions factor from incineration is estimated at 1.966 kt CO_2^{eq}/kt MPW as summarised in Table 2. This value aligns with the emissions factors reported in the LCA studies before subtracting the avoided impacts. Energy production from the incineration of waste has associated benefits, including the avoidance of GHG emissions from fossil fuel-based energy production. As the potential for energy production is calculated considering an LHV of MPW of 26 MJ/kg and considering an electricity conversion efficiency of 25% (Neuwahl et al., 2020), the avoided GHG emission factor from incineration results equal to 0.446 kt CO_2^{eq}/kt MPW. Accordingly, the net GHG emissions factor for incineration, given by the difference between direct and avoided emissions, of 1.520 kt CO_2^{eq}/kt MPW. This value is similar to the average value found in the LCA studies (for instance, Tomić et al. (2022) report a value of 1.5 kt CO_2^{eq}/kt waste).

2.2.2. Pyrolysis

The pyrolysis process depends on feed composition, reactor type, and operating conditions. The goal is to maximise oil yield while burning the by-products like char and gases to meet energy requirements (Fivga and Dimitriou, 2018; Qureshi et al., 2020). To ensure the successful operation of a plastic-to-oil pyrolysis plant, specific feed requirements must be met. This includes removing metals to prevent unwanted reactions and limiting rubber, textiles, and paper. Avoiding PVC and PET is crucial to prevent oil contamination. Sorting the MPW fractions before entering the reactor ensures these requirements are fulfilled. Each pyrolysis plant is coupled with a sorting plant for this purpose. The costs and efficiencies of both the sorting and pyrolysis plants are considered. The combination of these two facilities is referred to as the *overall pyrolysis plant*. Following Fivga and Dimitriou (2018), a fluidised bed reactor was considered, and a shredder unit was included in the pyrolysis plant, since it is required for this type of reactor. This study accounts for feed composition by using two pyrolysis feeds: *Po Pyrolysis* consists of only the polyolefin fraction, producing Brent oil-like quality, and *PoPS Pyrolysis* includes polyolefin and polystyrene fractions, resulting in heavier oil similar to Western Canadian Select (WCS). Plastic fractions and their percentages in the MPW are obtained from Mastellone (2020).

Regarding the mass balances, the oil yield of the pyrolysis reactor is 0.858 kt oil/kt MPW and the cost functions are the same as the ones in Fivga and Dimitriou (2018) for both the *Po Pyrolysis* plant and the *PoPS Pyrolysis* plant. Likewise, the energy balances are assumed to be the same, with the combustion of pyrolysis by-products fully meeting the thermal energy requirements of the pyrolysis reactor. The *TCI* and OPEX are provided for the smallest plant size, while for the two larger sizes the *TCI* is estimated using the six-tenth rule, and the OPEX is estimated by linear interpolation. Feed pre-sorting and pre-treatments are not included in Fivga and Dimitriou (2018). The mass balances of the sorting plant are taken from Mastellone (2020). Multiplying the fraction of Po (27% of MPW) and the fraction of Po+PS (36% of MPW) recovered by the oil yield, the overall MPW-to-oil conversion factors are 0.232 kt oil/kt MPW for *Po Pyrolysis* and 0.309 kt oil/kt MPW for *PoPS Pyrolysis*. The mechanically-recyclable polymer fraction is assumed to be a mixture of PET and HDPE that is sold to mechanical recycling companies. From Mastellone (2020), the percentage of mechanically-recyclable polymers recovered is 3.93% on a MPW mass basis. The inert materials in the MPW are considered solid residues that are sent to landfill, resulting in a total solid residue fraction of 15.81% for *Po Pyrolysis* and 17.11% for *PoPS Pyrolysis* on a MPW mass basis. The remaining MPW (RMPW) after the additional sorting in the coupled sorting plant represents 57.1% on a MPW basis for *Po Pyrolysis* and 48.1% for *PoPS Pyrolysis*. It is assumed that the remaining fraction is sent to incineration. The coupled sorting plant capacity must match the pyrolysis plant capacity. Consequently, for each pyrolysis plant size, the coupled sorting plant capacity has been calculated and reported in Supplementary Material. The *TCI* and OPEX of the sorting plant are obtained from Cimpan et al. (2016). When determining the OPEX for the combined sorting and pyrolysis plant, linear interpolation is used, while the *TCI* is calculated with the six-tenth rule, except for capacities ranging from 50 to 75 kt/y, where linear interpolation is applied to estimate their *TCI*.

Fivga and Dimitriou (2018) consider a fluidised bed reactor for the pyrolysis process. To accommodate this type of reactor, a shredder is included in the overall pyrolysis plant. Its OPEX is assumed to be negligible while its *TCI* is estimated with the Lang approach based on the purchase cost C_p retrieved from Cimpan et al. (2016). It is assumed that the shredder capacity is 1.5 times the size of the sorting plant. Consequently, the *TCI* is scaled accordingly using the six-tenth rule.

For the overall pyrolysis plant, the *TCI* and OPEX are obtained by summing the *TCI* and OPEX of the pyrolysis plant, the coupled sorting centre, and the shredder, and they are reported in Table 1.

According to the *mass balances* and *energy balances* derived from Fivga and Dimitriou (2018), the GHG emission factor for the pyrolysis process is primarily attributed to the combustion stage of the gases and char, with a GHG emission factor of 0.47 kt CO_2^{eq}/kt MPW based on stoichiometric calculations reported in the Supplementary Material. The GHG emissions from plant electricity requirements contribute 0.09 kt CO_2^{eq}/kt MPW. Prior to the reaction, pyrolysis requires an additional sorting step, which is assumed to have GHG emissions equivalent to a generic sorting centre. The avoided GHG emission factor due to electricity production is 0.07 kt CO_2^{eq}/kt MPW. The main avoided emissions are attributed to the production of pyrolysis oil as a substitute for crude oil, considering the GHG emissions associated with extraction, flaring and venting, fugitive emissions, and crude oil transport. The GHG emissions factor for crude oil production is obtained from Masnadi et al. (2018). The avoided GHG emissions factor relative to the initial quantity of MPW is 0.103 kt CO_2^{eq}/kt MPW, for *Po Pyrolysis*, and 0.137 kt CO_2^{eq}/kt MPW for *PoPS Pyrolysis*. Considering only the pyrolyzed fraction, the overall GHG emissions factor for the pyrolysis process is 0.39 kt CO_2^{eq}/kt MPW, for *Po Pyrolysis*, and 0.36 kt CO_2^{eq}/kt MPW for *PoPS Pyrolysis*, as shown in Table 2. The remaining MPW that is sent to incineration will consider the GHG emissions factor correspondingly. Averaging the overall GHG emission factor in LCA studies for the pyrolysis process results in a value of 0.66 kt CO_2^{eq}/kt MPW. The LCA studies take into account also the GHG emissions from the incineration/landfill of the

fraction of initial MPW that is not pyrolyzed due to sorting and pyrolysis efficiencies.

2.3. Transport stage: modelling assumptions and inputs

Five product types are transported across the entire supply chain, i.e., waste (from provinces to sorting centres), MPW (from sorting centres to treatment plants), RMPW (from pyrolysis to incineration plants), oil (from pyrolysis plants to refineries), and solid residues (from treatment plants to landfills). In the Italian territory, road transport is extensively utilised for waste, MPW, and solid residues due to its flexibility and the absence of intermodal transport infrastructure. As a result, road transport serves in this study as the sole mean of transportation. The matrix of linear distances between nodes n and n' ($LD_{n,n'}$) is computed using the spherical law of cosines.

We assume to transport MPW in the form of pressed bales with a density ρ of 0.3 t/m^3. These bales are loaded onto trucks having a volume V of 30 m^3 and the transportation costs are equal to 2 €/km. Using this information, the truck unitary transport cost for MPW (UTC^{MPW} [€/kt/km]) can be calculated as:

$$UTC^{MPW} = \frac{2}{\rho \cdot V} \tag{3}$$

obtaining that UTC^{MPW} is equal to 222 €/kt/km. It is assumed that the unitary transport cost for transporting waste, RMPW, and solid residues is equal to UTC^{MPW}. The unitary transport cost for oil (UTC^{Oil} [€/kt/km]) is obtained from the Cost Figures for Freight Transport report (Panteia, 2023), which represents the cost for transporting liquid chemicals and equals to 127 €/kt/km. When selecting the location of a pyrolysis plant from amongst the options that include incinerators, it was assumed that the remaining MPW requiring incineration must be transported to a different incineration plant. To simplify the analysis, a fixed linear distance of 150 km was chosen. However, if the pyrolysis plant is co-existing with a refinery, the RMPW portion can be treated in the incineration plant of that refinery. In this case, the linear distance is set to 0.

As for transport-related GHG emissions (CO_2, CH_4, N_2O expressed in CO_2^{eq}) related to the Italian vehicle fleet, which has a significant portion of pre-Euro legislation vehicles. As a result, the current (2021) Northern Italian vehicle fleet emits around 900 g CO_2^{eq}/km/truck. Standard truck capacities of 30 m^3 for MPW and residue transport and 43 m^3 for pyrolysis oil are assumed.

3. Mathematical modelling framework

The multi-objective spatially-explicit MILP model aims at maximising the annual gross profit (GP [€/y]), and minimising the net GHG emissions (E^{Net} [$kt\ CO_2{}^{eq}/y$]) of the mixed plastic waste supply chain:

$$Objectives = \max\{GP\}; \min\{E^{Net}\} \tag{4}$$

In particular, a first implementation of the economic model was provided in Cieno et al. (2023), while the mathematical framework for the environmental optimisation and the multi-objective optimisation (i.e., costs against GHG emissions) are novel features of this study. In the following subsections, the equations of the mathematical framework are presented. The following sets and subsets are defined:

- $n = \{n_{1-86}\}$ = all 86 nodes in the model;
- $pr = \{n_{1-47}\}$ = subset comprising the 47 Northern Italian provinces;
- $so = \{n_{48-59}\}$ = subset comprising the 12 Northern Italian sorting centres;
- $t = \{n_{60-86}\}$ = subset comprising the treatment locations i.e., the locations of the 24 Northern Italian incineration plants and of the 3 Northern Italian refineries;
- $In = \{n_{60-83}\}$ = subset comprising only the 24 Northern Italian incineration plants;
- $r = \{n_{84-86}\}$ = subset comprising the 3 Northern Italian refineries;
- $k = \{k_{1-3}\}$ = set of the 3 MPW treatment technologies i.e., incineration, *Po Pyrolysis* and *PoPS Pyrolysis*;
- $Py = \{k_{2-3}\}$ = subset comprising only the pyrolysis i.e., *Po Pyrolysis* and *PoPS Pyrolysis*;
- $s = \{s_{1-3}\}$ = set of the three plant sizes (small, medium, large).

3.1. Mass balances

All quantities are expressed in kt/y. Each province pr must send all waste to the sorting centres so:

$$\sum_{so} m^{W}_{pr,so} = m^{W,Av}_{pr} \ \forall\ pr \tag{5}$$

where $m^{W}_{pr,so}$ is the quantity transferred from a province to a sorting centre, and $m^{W,Av}_{pr}$ is the waste available in each Northern Italian province. The total waste entering a sorting centre so cannot exceed the sorting centre capacity C_{so}:

$$\sum_{pr} m^{W}_{pr,so} \le C_{so} \ \forall\ so \tag{6}$$

The MPW quantity $m^{MPW,Plant}_{t,k,s}$ to a plant k of size s in a treatment node t is calculated as the sum over all sorting centres so of the MPW quantity transferred from a sorting centre to a treatment plant present in location t of technology k and size s:

$$m^{MPW,Plant}_{t,k,s} = \sum_{so} m^{MPW}_{so,t,k,s} \ \forall\ t,k,s \tag{7}$$

In each sorting centre, the total outflow MPW $m^{MPW}_{so,t,k,s}$ to treatment plant locations t of technology k of size s, must match the overall MPW quantity sent out $m^{MPW,sort}_{so}$, directly linked to the total available MPW $m^{MPW,Av}_{so}$ at the sorting centre. This condition allows for the distribution of the MPW quantity to multiple treatment plant locations:

$$m^{MPW,sort}_{so} = \sum_{t,k,s} m^{MPW}_{so,t,k,s} \ \forall\ so \tag{8}$$

The total available MPW $m^{MPW,Av}_{so}$ at each sorting centre is calculated as the sum over each province pr of the waste quantities received from the provinces, multiplied by the average waste-to-MPW conversion factor η^{W-MPW} that equal to 0.521, obtained as the ratio of plastic exiting the Italian sorting centres to the total waste received in 2019 (COREPLA, 2020). This estimation, based on the national average, approximates the waste-to-MPW conversion factor for each centre:

$$m^{MPW,Av}_{so} = \sum_{pr} m^{W}_{pr,so} \cdot \eta^{\mathrm{W\_MPW}} \ \forall\ so \tag{9}$$

Two constraints are set on $m^{MPW,sort}_{so}$ correlating the overall quantity of MPW that goes out of the sorting centre $m^{MPW,sort}_{so}$, and the total available $m^{MPW,Av}_{so}$ MPW in the sorting centre so:

$$0.999 \cdot m^{MPW,Av}_{so} \le m^{MPW,sort}_{so} \le m^{MPW,Av}_{so} \ \forall\ so \tag{10}$$

The upper bound sets that for each sorting centre so the total MPW quantity sent out cannot exceed the total MPW available in the sorting centre. The lower bound imposes that at least 99.9% of the MPW available is sent out to the treatment plants, so that no MPW remains in the sorting centres. For what concerns the capacity constraints of the treatment plants, there are some considerations to be made. For pyrolysis plants, the input cannot exceed plant capacity, but must cover at least 70%. For incineration plants only a very small MPW quantity is sufficient 0.1 kt/y MPW due to the diverse waste types treated in incineration plants. In contrast, pyrolysis plants are dedicated solely to

MPW treatment. A higher lower limit for pyrolysis plants ensures economic feasibility.

$$0.7 \cdot C^{P}_{Py,s} \cdot \lambda^{Plant}_{t,Py,s} \leq m^{MPW,Plant}_{t,Py,s} \leq C^{P}_{Py,s} \cdot \lambda^{Plant}_{t,Py,s} \ \forall\ t, Py, s \tag{11}$$

$$0.1 \cdot \lambda^{Plant}_{t,In,s} \leq m^{MPW,Plant}_{t,In,s} \leq C^{P}_{In,s} \cdot \lambda^{Plant}_{t,In,s} \ \forall\ t, In, s \tag{12}$$

where $C^{P}_{Py,s}$ is the capacity of pyrolysis plants, and $C^{P}_{In,s}$ is the capacity of an incineration plant; $\lambda^{Plant}_{t,k,s}$ is a binary variable that is equal to 1 if there exists a treatment location t with a technology k of a size s, or 0 otherwise. Incineration plants have one possible size, *large*:

$$\lambda^{Plant}_{t,In,s} = 0 \ \forall\ t, In, s \notin Large \tag{13}$$

If a plant k is chosen for a node, it must be the only technology possible for that node:

$$\sum_{k,s} \lambda^{Plant}_{t,k,s} \leq 1 \ \forall\ t \tag{14}$$

The fractions of residue to be landfilled from the initial quantity of MPW entering the treatment plant are denoted by $\eta^{R}_{k} = [0.076, 0.1581, 0.1711]$ for {incineration, *Po Pyrolysis, PoPS Pyrolysis*} as presented in Sections 2.2.1 and 2.2.2. The residues quantity is calculated according to:

$$m^{R}_{t,k,s} = m^{MPW,Plant}_{t,k,s} \cdot \eta^{R}_{k} \ \forall\ t, k, s \tag{15}$$

where $m^{R}_{t,k,s}$ is the solid residues produced by a plant of technology k of size s located in a node t.

An additional share of solid residues is produced by incinerating the remaining mixed plastic waste (RMPW) sorted out before the pyrolysis plants. This amount is calculated by multiplying the RMPW quantity generated by each pyrolysis plant by the MPW-to-residues incineration conversion factor η^{R}_{In}, equal to 0.076:

$$m^{R,RMPW}_{t,Py,s} = m^{RMPW}_{t,Py,s} \cdot \eta^{R}_{In} \ \forall\ t, Py, s \tag{16}$$

where $m^{R,RMPW}_{t,Py,s}$ is the additional solid residue quantity produced by incinerating the residual MPW from pyrolysis sorting centres and $m^{RMPW}_{t,Py,s}$ is the residual MPW sorted out, not sent to pyrolysis plant, calculated as:

$$m^{RMPW}_{t,Py,s} = m^{MPW,Plant}_{t,Py,s} \cdot \eta^{RMPW}_{Py} \ \forall\ t, Py, s \tag{17}$$

where η^{RMPW}_{Py} is the MPW-to-RMPW conversion factor for pyrolysis plants. They differ whether the plant is a *Po Pyrolysis* plant (= 0.571) or a *PoPS Pyrolysis* plant (=0.481) discussed in Section 2.2.2. The total remaining MPW from pyrolysis sorting is therefore:

$$m^{RMPW,Tot}_{so} = \sum_{t,Py,s} m^{RMPW}_{t,Py,s} \tag{18}$$

The quantity of oil produced by a pyrolysis plant $m^{Oil,Av}_{t,Py,s}$ located in a treatment location t, and of size s is calculated by multiplying the MPW quantity entering the plant and the MPW-to-oil conversion factor η^{Oil}_{Py} equal to 0.232 for *Po Pyrolysis* and 0.309 for *PoPS Pyrolysis* discussed in Section 2.2.2:

$$m^{Oil,Av}_{t,Py,s} = m^{MPW,Plant}_{t,Py,s} \cdot \eta^{Oil}_{Py} \ \forall\ t, Py, s \tag{19}$$

All the oil generated in the pyrolysis plants must be directed to refinery:

$$\sum_{refi} m^{Oil}_{t,Py,s,r} = m^{Oil,Av}_{t,Py,s} \cdot \alpha^{LD}_{Pyr,Refi} \ \forall\ t, Py, s \tag{20}$$

where $m^{Oil}_{t,Py,s,\ r}$ is the oil quantity going from a pyrolysis plant to a refinery; $\alpha^{LD}_{Pyr,Refi}$ is a binary variable: it is equal to 1 if the oil is produced in a pyrolysis plant that is not coupled with a refinery. The quantity of mechanically-recyclable polymers $m^{Mech}_{t,Py,s}$ generated due to the additional sorting centre in a pyrolysis plant, of size s, placed in a treatment location t is given by:

$$m^{Mech}_{t,Py,s} = m^{MPW,Plant}_{t,Py,s} \cdot \eta^{Mech} \ \forall\ t, Py, s \tag{21}$$

where η^{Mech} is a scalar representing the MPW-to-mechanically-recyclable polymers conversion factor and is equal to 0.0393 discussed in Section 2.2.2. The total quantity of mechanically-recyclable polymers produced in the SC ($m^{Mech,Tot}$) is calculated as the sum of the quantities of each plant:

$$m^{Mech,Tot} = \sum_{t,Py,s} m^{Mech}_{t,Py,s} \tag{22}$$

The total amount of residues that must be landfilled is given by:

$$m^{R,Tot} = \sum_{t,k,s} m^{R}_{t,k,s} + \sum_{t,k,s} m^{R,RMPW}_{t,Py,s} \tag{23}$$

The electrical power produced by an incineration plant present in a treatment location t ($P^{El}_{t,In,s}$ [GWh/y]) is calculated as:

$$P^{El}_{t,In,s} = m^{MPW,Tot}_{t,In,s} \cdot \eta^{El}_{In} \ \forall\ t, In, s \tag{24}$$

where η^{El}_{In} is the MPW-to-electrical power conversion factor [GWh/kt] and is equal to 1.8. The additional electric power produced by incineration of RMPW is calculated based on:

$$P^{El,RMPW}_{t,Py,s} = m^{RMPW}_{t,Py,s} \cdot \eta^{El}_{In} \ \forall\ t, Py, s \tag{25}$$

The total electrical power produced by the SC ($P^{El,Tot}$ [GWh/y]) is calculated as the sum over each plant of the electrical power produced directly by incineration plants and the electrical power produced by the RMPW incineration:

$$P^{El,Tot} = \sum_{t,In,s} P^{El}_{t,In,s} + \sum_{t,Py,s} P^{El,RMPW}_{t,Py,s} \tag{26}$$

3.2. Economic optimisation model

Gross profit GP [€/y] of Eq.(4) is obtained by subtracting the total annual costs (TC [€/y]) from the total annual revenues (TR [€/y]):

$$GP = TR - TC \tag{27}$$

Total revenues TR [€/y] of Eq.(27) comprise gate tariffs cashed in $Rev^{T,tot}$ [€/y], the revenues generated from selling mechanically-recyclable polymers Rev^{Mech} [€/y], and revenues from selling pyrolysis oil Rev^{Oil} [€/y], and the electric power produced Rev^{El} [€/y].

$$TR = Rev^{T,tot} + Rev^{Mech} + Rev^{Oil} + Rev^{El} \tag{28}$$

The gate tariff values for the Northern Italian incineration plants are heterogeneous and roughly in the same range of the gate tariff values for solid residues disposal in landfills (COREPLA, 2020). This study assumes a gate tariff for treatment T^{t} of 210 €/t of treated MPW equal to the gate tariff of landfill T^{l}. Moreover, T^{t} is assumed to be the same for all technologies k, plant sizes s and treatment locations t. The market price of the mechanically-recyclable polymers MP^{Mech} is 378 €/t, assuming a mixture of PET and HDPE and their average value based on respective auction prices in 2019 (COREPLA, 2020). Revenues obtained from pyrolysis oil takes into account the averaged price over years 2021–2022 (MP^{Oil}_{Py}): the pyrolysis of polyolefin fraction produces an oil similar to Brent oil (551 €/t), while the pyrolysis oil obtained from polyolefin and polystyrene fractions is similar to WCS (403 €/t). The market price of electric power MP^{El} is 125 €/MWh (reflecting the average value of 2021 in the Italian Power Exchange trading market). The revenues components of Eq.(28) are calculated as:

$$Rev^{T,tot} = \sum_{t,k,s} m_{t,k,s}^{MPW,\ Plant} \cdot T^{t} \tag{29}$$

$$Rev^{Mech} = m^{Mech,Tot} \cdot MP^{Mech} \tag{30}$$

$$Rev^{Oil} = \sum_{t,Py,s} m_{t,Py,s}^{Oil,\ Av} \cdot MP_{Py}^{Oil} \tag{31}$$

$$Rev^{El} = \mathrm{P}^{\mathrm{El,Tot}} \cdot \mathrm{MP}^{\mathrm{El}} \tag{32}$$

The total cost TC [€/y] of Eq.(27) includes 3 main components: the total cost of MPW treatment ($TPTC$ [€/y]), the total cost of landfilling (TLC [€/y]), and total cost of transportation (TTC [€/y]):

$$TC = TPTC + TLC + TTC \tag{33}$$

Total MPW treatment cost ($TPTC$ [€/t]) of Eq.(33) sums up two components: the overall plant-specific treatment cost ($STC_{k,s}$ [€/kt]) of plant k and size s times the MPW quantity treated in the plant k of size s ($m_{t,k,s}^{MPW}$ [kt/y]), and the incineration costs of the remaining MPW fraction (PTC [€/y]):

$$TPTC = \sum m_{t,k,s}^{MPW} \cdot STC_{k,s} \cdot c_{k,s} + PTC \tag{34}$$

Here, the corrective factor $c_{k,s}$ is crucial in accounting for cost savings in pyrolysis plants situated alongside refineries. Specifically, the corrective factor $c_{k,s}$ equals 1 for all technologies and plant sizes, except for pyrolysis plants co-existing with a refinery location. It is assumed that these plants yield significant cost savings, reducing the total capital investment (TCI) by 15%. Accordingly, the corrective factors are for the case of *Po Pyrolysis{small, medium, large}* = [0.944, 0.943, 0.935], and *PoPS Pyrolysis{small, medium, large}* = [0.945, 0.937, 0.943].

The incineration costs for the remaining mixed plastic waste (RMPW) are calculated by multiplying the RMPW quantity $m^{RMPW,\ Tot}$ by the average specific treatment cost of Northern Italian incineration plants $\overline{STC^{I}}$ (i.e., the average of the STC reported in Supplementary Material, equal to 151,475 €/kt).

$$PTC = m^{RMPW,\ Tot} \cdot \overline{STC^{I}} \tag{35}$$

The total cost of landfilling (TLC [€/y]) of Eq.(33) takes into account the quantity of the total residues produced (m^{R} [kt/y]) multiplied by the landfill gate tariff T^{l}(210 €/t of residues):

$$TLC = m^{R} \cdot T^{l} \tag{36}$$

Total cost of transportation (TTC [€/y]) of Eq.(33) considers the costs of transporting waste, MPW, remaining MPW, oil, and residues (TTC^{w}, TTC^{MPW}, TTC^{RMPW}, TTC^{Oil}, TTC^{R}, respectively, all in [€/y]), each term calculated based on their corresponding Unitary Transportation Cost (UTC [€/kt/km]) and the linear distance between nodes ($LD_{n,n'}$), which is calculated by means of the spherical law of cosines being R the radius of the Earth (d'Amore and Bezzo, 2017a).

$$TTC = TTC^{w} + TTC^{MPW} + TTC^{RMPW} + TTC^{Oil} + TTC^{R} \tag{37}$$

$$LD_{n,n'} = \cos^{-1}[\sin(lat_{n}) \cdot \sin(\mathrm{lat_{n'}}) + \cos(\mathrm{lat_{n}}) \cdot \cos(lat_{n'}) \cdot \cos(\mathrm{long_{n}} - long_{n'}) \cdot \mathrm{R} \tag{38}$$

$$TTC^{w} = \sum_{pr,so} m_{pr,so}^{W} \cdot LD_{n,n'} \cdot UTC^{MPW} \cdot \tau \tag{39}$$

τ is the average tortuosity factor τ for the Northern Italian territory, a corrective factor that accounts for the inhomogeneities in the travel paths and is implemented as a scalar equal to 1.4. Likewise, TTC^{MPW} and TTC^{Oil}:

$$TTC^{MPW} = \sum_{so,t,k,s} m_{so,t,k,s}^{MPW} \cdot LD_{n,n'} \cdot UTC^{MPW} \cdot \tau \tag{40}$$

$$TTC^{Oil} = \sum_{t,Py,s,r} m_{t,Py,s,r}^{Oil} \cdot LD_{n,n'} \cdot UTC^{Oil} \cdot \tau \tag{41}$$

For TTC^{RMPW}, assuming that pyrolysis and incineration plants are not co-located, a fixed linear distance LD^{I} (150 km) has been considered between a pyrolysis plant and the incineration plant treating its RMPW. A corrective factor c_{t}^{LD} is implemented for this linear distance, that is 1 for all treatment locations t except for refinery locations, where it is 0, assuming to use the incinerator of the refinery.

$$TTC^{RMPW} = \sum_{t,Py,s} m_{t,Py,s}^{RMPW} \cdot LD^{I} \cdot c_{t}^{LD} \cdot UTC^{MPW} \cdot \tau \tag{42}$$

Regarding TTC^{R}, in order to simplify the model, the numerous landfills in North Italy are not explicitly modelled as separate nodes. Instead, a fixed linear distance LD^{L} (50 km) is assumed for transporting solid residues from a plant to a landfill:

$$TTC^{R} = m^{R,Tot} \cdot LD^{L} \cdot UTC^{MPW} \cdot \tau \tag{43}$$

3.3. Environmental optimisation model

The net GHG emissions (E^{Net} [kt CO_2^{eq}/y]) of Eq.(4) is defined as the difference between the total direct GHG emissions E^{Tot} of the supply chain and total avoided GHG emissions $E^{Av,Tot}$, all expressed in kt CO_2^{eq}/y.

$$E^{Net} = E^{Tot} - E^{Av,Tot} \tag{44}$$

Total direct GHG emissions E^{Tot} of Eq.(44) is the sum of transport GHG emissions E^{transp}, sorting GHG emissions $E^{sort,tot}$, and MPW treatment GHG emissions E^{treat}, all expressed in kt CO_2^{eq}/y.

$$E^{Tot} = E^{transp} + E^{sort,tot} + E^{treat} \tag{45}$$

The transport related GHG emissions E^{transp} of Eq.(45) represents the sum of transporting waste, MPW, oil, remaining MPW and residues ($E^{w,transp}$, $E^{MPW,transp}$, $E^{oil,transp}$, $E^{RMPW,transp}$, $E^{R,transp}$) all in kt CO_2^{eq}/y. They are all calculated based on the number of trucks used to transport each of the materials, linear distance between nodes n and n' ($LD_{n,n'}$) and the truck specific GHG emission factor.

$$E^{transp} = E^{w,transp} + E^{MPW,transp} + E^{Oil,transp} + E^{RMPW,transp} + E^{R,transp} \tag{46}$$

$$E^{w,trans} = \left[\sum_{pr,so} \frac{m_{pr,so}^{w}}{\mathrm{truck}_{cap}^{MPW}} \cdot LD_{n,n'}^{pr,so} \cdot truckE\right] \cdot \tau \tag{47}$$

$$E^{MPW,trans} = \left[\sum_{so,t,k,s} \frac{m_{so,t,k,s}^{MPW}}{\mathrm{truck}_{cap}^{\mathrm{MPW}}} \cdot LD_{n,n'}^{so,t} \cdot truckE\right] \cdot \tau \tag{48}$$

$truck_{cap}^{MPW}$ represents the quantity of MPW a truck can transport equal to 9.3 t/truck; $truckE$ is the emission factor of each truck, equal for each kind of material transported and approximately equal to 900 g of CO_2^{eq} per km and per truck; τ is the tortuosity factor.

$$E^{Oil,trans} = \left[\sum_{t,Py,s,\ r} \frac{m_{t,Py,s,r}^{Oil}}{\mathrm{truck}_{cap}^{\mathrm{Oil}}} \cdot LD_{n,n'}^{t,refi} \cdot truckE\right] \cdot \tau \tag{49}$$

where $truck_{cap}^{Oil}$ represents the quantity of oil a truck can transport, equal to 43 t/truck.

$$E^{RMPW,trans} = \left[\sum_{t,Py,s} \frac{m_{t,Py,s}^{RMPW}}{\mathrm{truck}_{cap}^{MPW}} \cdot \alpha_{\mathrm{Pyr,Inc}}^{\mathrm{LD}} \cdot LD_{n,n'}^{I} \cdot truckE\right] \cdot \tau \tag{50}$$

$\alpha_{Pyr,Inc}^{LD}$ is a correction factor if the pyrolysis plant is located next to a refinery: every refinery has an incinerator, so $\alpha_{Pyr,Inc}^{LD}$ equal to 0; otherwise, $LD_{n,n'}^{I}$ is 150 km to an incineration plant.

$$E^{R,trans} = \left(\frac{m^{R,Tot}_{t,k,s}}{\text{truck}^{R}_{cap}} \cdot LD^{L}_{n,n'} \cdot truckE \right) \cdot \tau \quad (51)$$

$truck^{R}_{cap}$ is the quantity of residue a truck can transport equal to 63 t/truck, with a fixed linear distance $LD^{L}_{n,n'}$ of 50 km.

The sorting centre GHG emissions $E^{Sort,tot}$ of Eq.(45) takes into account both the sorting centres E^{sort} and the additional sorting centres in the overall pyrolysis plant $E^{sort,pyro}$, expressed in kt CO_2^{eq}/y:

$$E^{sort,tot} = E^{sort} + E^{sort,pyro} \quad (52)$$

$$E^{sort} = \sum_{pr} m^{W}_{pr,so} \cdot \varepsilon^{sort} \quad (53)$$

$$E^{sort,pyro} = \sum_{so,t,Py,s} m^{MPW,out}_{so,t,Py,s} \cdot \varepsilon^{sort} \quad (54)$$

where E^{sort} are the GHG emissions of the sorting centre; ε^{sort} is the emission factor for a sorting centre facility. $E^{sort,pyro}$ accounts for the GHG emissions of the additional sorting centres coupled with pyrolysis plants.

The treatment GHG emissions E^{treat} of Eq.(45) is the sum of GHG emissions corresponding to incineration $E^{treat,In}$ and pyrolysis $E^{treat,Pyro}$. All terms are calculated based on the quantity that is treated and the corresponding GHG emission factor. If pyrolysis is the selected treatment technology, $E^{treat,Pyro}$ contains both the GHG emissions related to pyrolysis process and incineration of the remaining MPW. All terms are expressed in kt CO_2^{eq}/y.

$$E^{treat} = E^{treat,In} + E^{treat,Pyro} \quad (55)$$

$$E^{treat,In} = \sum_{t,In,s} m^{MPW,Plant}_{t,In,s} \cdot \varepsilon^{In} \quad (56)$$

$$E^{treat,Pyro} = \sum_{t,Py,s} m^{MPW,Plant}_{t,Py,s} \cdot \varepsilon^{Pyro}_{Py} + E^{RMPW,inc} \quad (57)$$

$$E^{RMPW,inc} = m^{RMPW,Tot}_{so} \cdot \varepsilon^{In} \quad (58)$$

where ε^{In} is the incineration emission factor, ε^{Pyro}_{Py} is the pyrolysis emission factor. $E^{RMPW,inc}$ is the share of GHG emissions due to incinerating the remaining MPW that cannot be pyrolyzed.

Total avoided GHG emissions $E^{Av,Tot}$ [kt CO_2^{eq}/y] of Eq.(44) is the sum of the avoided GHG emissions from incineration and pyrolysis respectively ($E^{Av,In}$, $E^{Av,Pyro}$ in kt CO_2^{eq}/y).

$$E^{Av,Tot} = E^{Av,In} + E^{Av,Pyro} \quad (59)$$

The avoided emissions from incineration $E^{Av,In}$ of Eq.(59) takes into account both the incinerated MPW and the incinerated remaining MPW when pyrolysis is selected for MPW treatment.

$$E^{Av,In} = \sum_{t,In,s} m^{PL,Plant}_{t,In,s} \cdot \varepsilon^{Av,In} + \sum_{t,Py,s} m^{RPL}_{t,Py,s} \cdot \varepsilon^{Av,In} \quad (60)$$

where $E^{Av,In}$ is the avoided GHG emissions due to the production of electricity from incineration; $\varepsilon^{Av,In}$ is the avoided emission factor for incineration. For what concerns pyrolysis, the avoided emissions are related to avoided extraction and avoided transportation for crude oil, expressed through the avoided emissions factor $\varepsilon^{Av,Pyro}$:

$$E^{Av,Pyro} = \sum_{t,Py,s} m^{Oil,Av}_{t,Py,s} \cdot \varepsilon^{Av,Pyro} \quad (61)$$

4. Results

The optimisation of the MPW SC was performed on a DELL Precision 7560 laptop with Intel(R) Core (TM) i7–11850H @ 2.50 GHz 2.50 GHz and 64 GB RAM. Specifically, the MILP mathematical model was implemented in GAMS 43.3.0 and solved through CPLEX. Results are presented in terms of economic optimum, environmental optimum, and trade-off solutions.

4.1. Economic optimisation: results

The objective of the economic analysis is to identify the most advantageous technology selection and distribution of material quantities within the SC, with the goal of maximising the annual gross profit *GP* [M€/y]. The economic optimum yields a gross profit of 115 M€/y, with net GHG emissions of 680 kt CO_2^{eq}/y. Fig. 2 illustrates the complete MPW SC, depicting both the upstream and downstream sections (Figs. 2A and B). Additionally, it presents also the economic and environmental performance of the supply chain (Figs. 2C and D).

Fig. 2A reveals that the waste quantity from each province is predominantly directed to the nearest sorting centre. This suggests that despite the potential benefits of sending waste to closer treatment plants, the costs of transportation outweigh those advantages. In Fig. 2B, it can be seen that only incineration plants in Northern Italy are selected, while no pyrolysis plants are chosen. This is because incineration technology can handle various types of waste, resulting in larger plant sizes and greater cost benefits due to economies of scale effects. Moreover, while not the focus of our study, it is worth mentioning that incinerators can offer an additional economic benefit by supplying low-temperature district heating. Furthermore, it is clear that despite the presence of closer incineration plants, the sorting centres opt to send their MPW to the incineration plant situated in Brescia (BS), where a substantial total MPW quantity of 210 kt/y is treated. This preference is not surprising, given that the Brescia incineration plant is, by a significant margin, the largest one within the SC. Consequently, it exhibits the lowest specific treatment costs, as indicated in the Supplementary Material. The second-largest incinerator, located in Milan, serves as the second choice for MPW treatment, processing approximately 121 kt MPW/y. In contrast, the remaining three incinerators within the supply chain receive lower amounts of MPW from the sorting centres, ranging from 57 kt to 14 kt per year respectively. From Fig. 2C, it can be observed that the total MPW treatment cost (*TPTC* [M€/y]) is the largest component of costs, accounting for approximately 66% of the total cost. All treatment costs are attributable to MPW incineration. The second largest contribution to the total cost comes from transportation costs, with waste transport making the most significant contribution to the overall transportation costs. Landfill costs amount to less than 10%. Summing up all costs components, results in a total cost of about 76 M€/y. In terms of total revenues, gate tariffs, and electricity make almost equal contributions, resulting in total revenues of about 191 M€/y. By deducting the total cost from the total revenues, a gross profit of 115 M€/y is obtained. The environmental performance of the economic optimum presented in Fig. 2D indicates a net annual GHG emissions of 680 kt CO_2^{eq}/y. This figure is derived by subtracting the avoided GHG emissions from the total GHG emissions of the supply chain. The majority of GHG emissions come from the incineration of MPW, while the contribution of the sorting and transport stages is not significant, resulting in a total of 876 kt CO_2^{eq}/y. Since incineration is the chosen technology for MPW treatment, all the avoided GHG emissions are attributed to electricity generation, amounting to 196 kt CO_2^{eq}/y.

4.2. Environmental optimisation: results

The environmental optimum provides insights into the changes occurring within the MPW supply chain, specifically in terms of technology selection and material quantities distribution, when the primary goal is to minimise overall GHG emissions, instead of profits. The environmentally optimal configuration results in net GHG emissions of 387 kt CO_2^{eq}/y, which is a decrease of 43% compared to the GHG emissions resulting from the optimal configuration in terms of profit. This reduction in emissions corresponds to a Gross Profit of 54 M€/y,

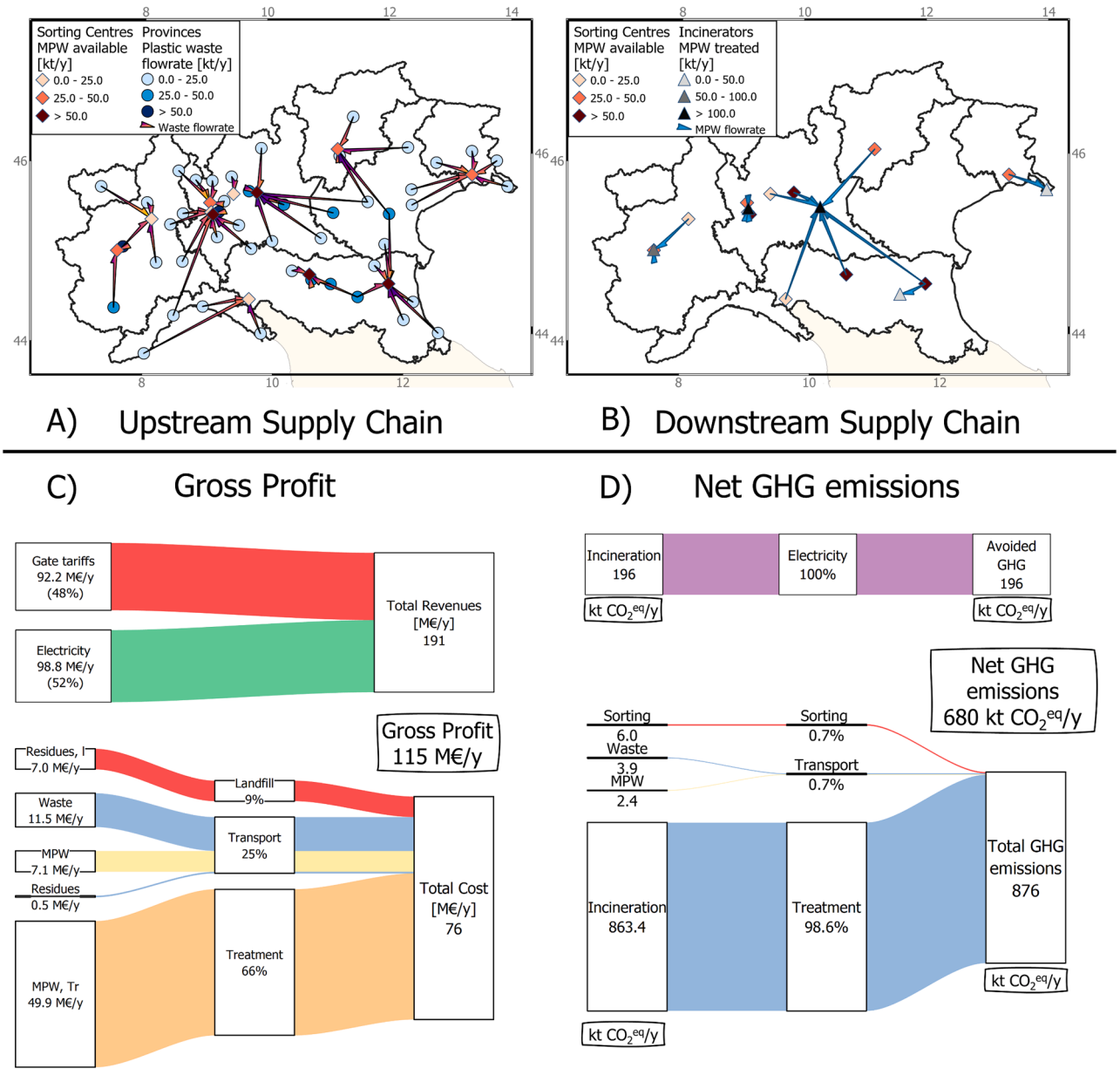

Fig. 2. Economic optimal solution: A) upstream supply chain containing the waste quantities sent from provinces to sorting centres; B) downstream supply chain showing the MPW quantities sent from sorting centres to treatment technologies; C) gross profit [M€/y] defined as the difference between total revenues and total cost, and the Sankey diagrams for the two components; D) net GHG emissions calculated as the difference between total and the avoided GHG emissions [kt CO_2^{eq}/y], and the Sankey diagrams illustrating the contribution of each stage of the components.

which is less than half the gross profit obtained in the best economic configuration. Fig. 3 provides an overview of the key findings, which will now be discussed in detail.

In the upstream SC (Fig. 3A), the waste is transported from the provinces to the closest sorting centre. On the other hand, the downstream SC (Fig. 3B) reveals that pyrolysis is the only treatment technology selected and that all the possible plant sizes are chosen (*small, medium*, and *large*). Consequently, the resulting oil needs to be transported to a refinery. However, due to the higher density of oil compared to that of the waste and MPW, and lower quantities, in terms of the environmental configuration of the SC, priority is given to transporting the waste to the nearest sorting centre and the MPW to the nearest pyrolysis plant, rather than emphasising the transportation of the oil to its final destination. In this scenario, the quantity of MPW incinerated is half of what was observed in the economic case, resulting in GHG emissions that are also halved, but still, the majority of treatment-related GHG emissions arise from the incineration of the remaining MPW (Fig. 3D). Pyrolysis, on the other hand, makes a relatively small contribution to the overall GHG emissions. In terms of avoided GHG emissions, the value is 38% lower compared to the results of the best economic SC. As for the economic performance of the best environmental SC, the total revenues are slightly higher than those obtained in the best economic SC (+5.2%), while transport costs are almost unchanged. However, these higher revenues are compensated by a significantly increased cost in the treatment stage. In fact, the selection of pyrolysis plants in all size categories (4 *small*, 5 *medium*, and 2 *large PoPS Pyrolysis* plants) results in a disadvantage in terms of total cost, due to considerably higher *STC* for the smaller sizes (Table 1), giving a total cost that is almost twice the total cost of the best economic SC.

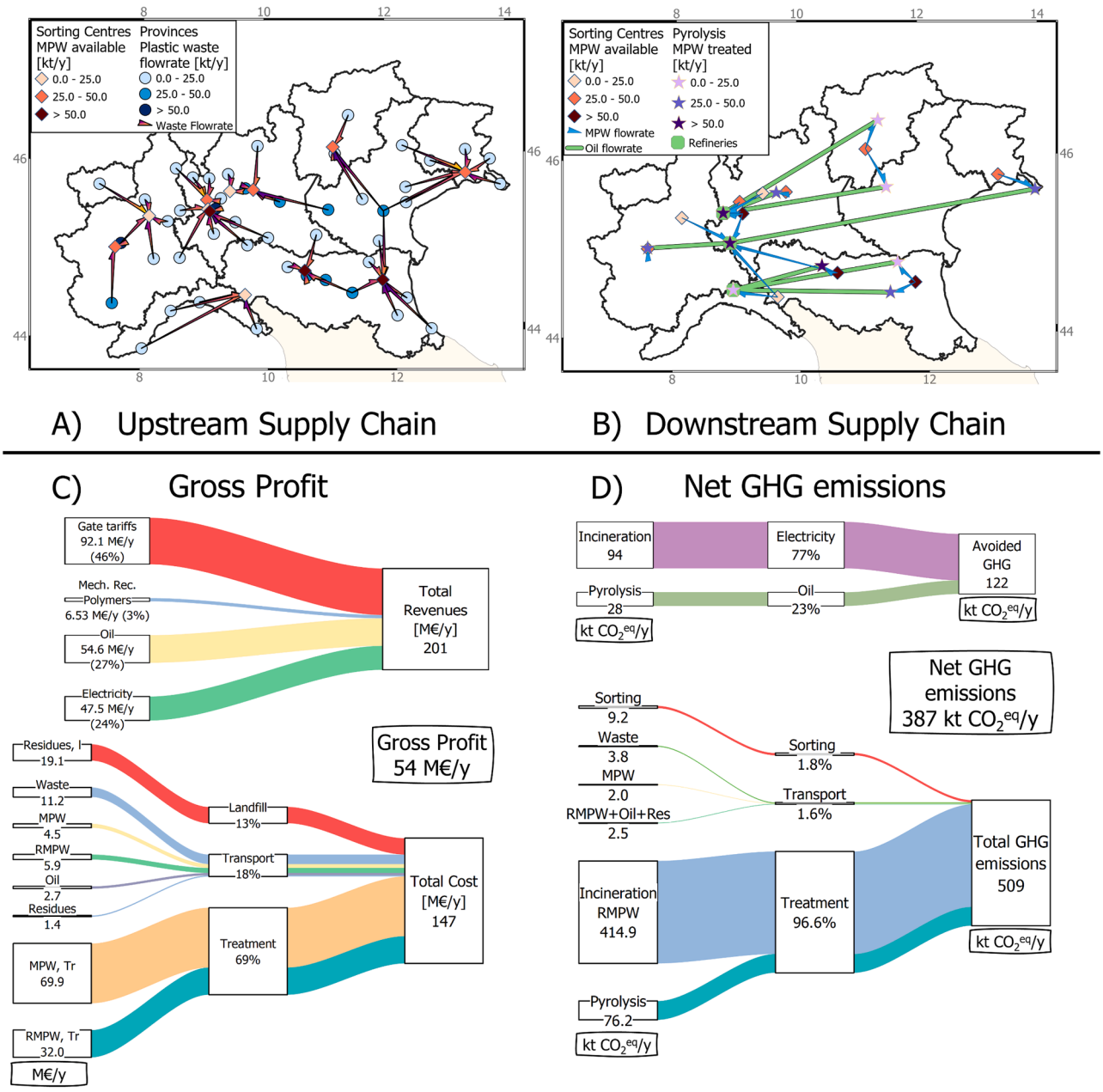

Fig. 3. Environmental optimal solution: A) upstream supply chain; B) downstream supply chain; C) gross profit [M€/y], and the Sankey diagrams for total cost and total revenues; D) net GHG emissions [kt CO_2^{eq}/y], and the Sankey diagrams illustrating the contribution of each stage to the total and avoided GHG emissions.

4.3. *Multi-objective optimisation: results*

Having two conflicting objectives, a Pareto front can be identified, meaning that an improvement in one objective (e.g., economic outcome) leads to a worsening in the other one (e.g., environmental results). As such, each optimal solution represents a trade-off between the two conflicting objectives (Fig. 4A). In general, it can be observed that when shifting from the economic optimum towards the environmental one, pyrolysis plants start being included in the SC, until a complete substitution of the incinerations, leading to a significant improvement of the environmental performance, at the cost of worsening the economic ones. In particular, two trade-off solutions were identified (highlighted with red circles in Fig. 4A). The interest in the first one, named *Case1* (Fig. 4B), is given by the fact that it has almost identical total GHG emissions of the best SC in environmental terms while ensuring a better economic performance (+28% in net profit). The second trade-off configuration, labelled as *Case2* (Fig. 4C), is chosen to reflect an intermediate solution between the two extreme ones.

Analysing the *Case1* Pareto optimal solution and referring to the corresponding Sankey diagrams in Fig. 4B, it is evident that there is a significant improvement in economic performance with minimal impact on net GHG emissions when compared to the best environmental SC. The primary difference lies in the size and placement of the pyrolysis plants. In the environmental results, all three sizes of pyrolysis plants are distributed across the Northern Italian regions. However, the trade-off solution of *Case1* consists of more concentrated, large-sized pyrolysis plants that benefit from economies of scale effects and coexistence with refineries, as presented in the downstream supply chain of Fig. 5A.

The trade-off solution *Case2* entails 4 *large* pyrolysis plants (1 *PoPS Pyrolysis* – Granarolo-Bologna location, and 3 *Po Pyrolysis* in coexistence with the refineries) and 3 incinerators (Trieste, Brescia, Torino) as it can be observed on the SC in Fig. 5B. This solution exhibits a better economic

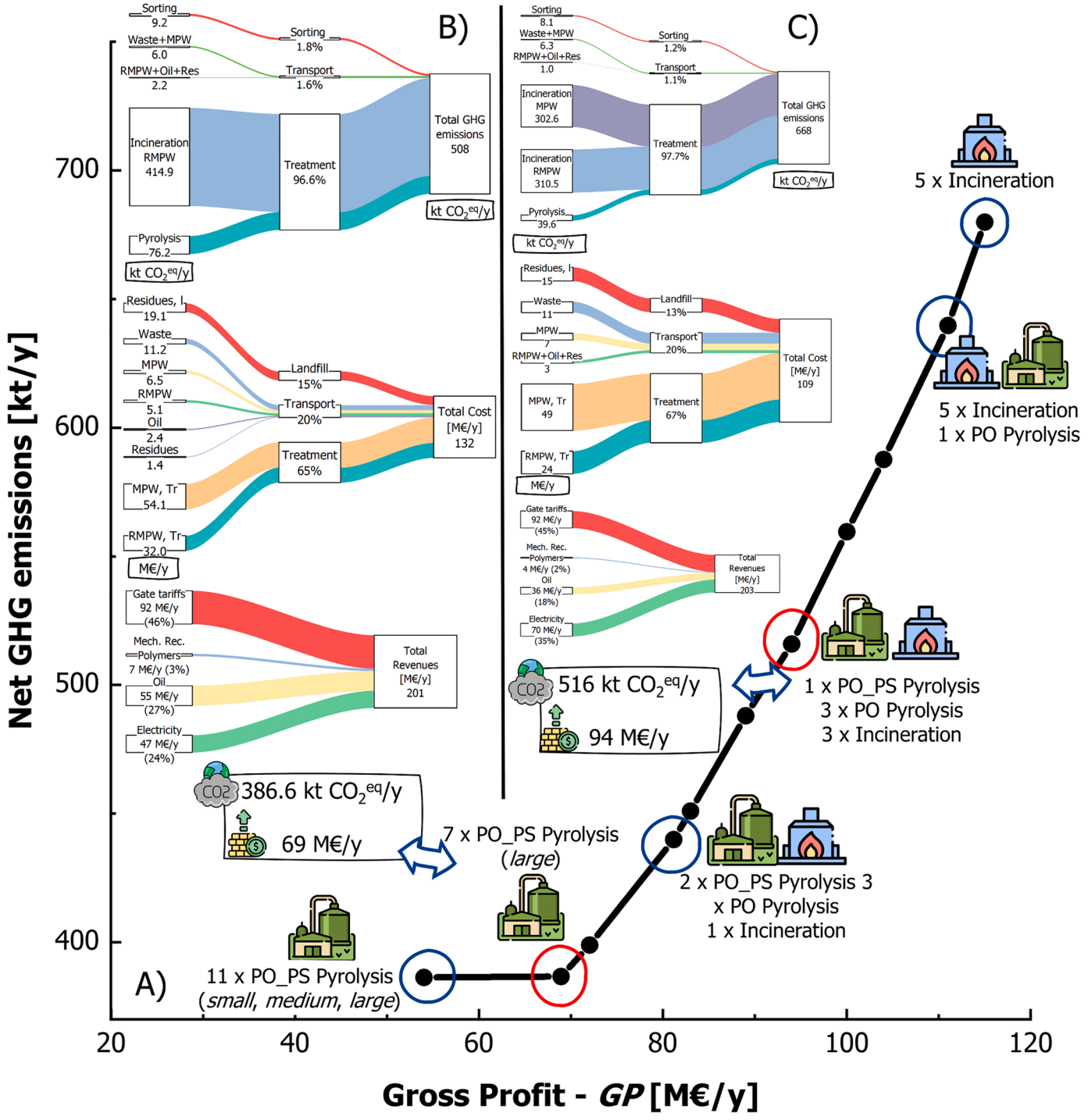

Fig. 4. A) Pareto curve presented in terms of Gross Profit (GP) and net GHG emissions. Different Pareto optimal solutions are highlighted, presenting the technology selection and the number of plants selected. Two of them (highlighted with a red circle) will be further discussed; B) Sankey diagrams for Total Revenues, Total Costs, and Total GHG emissions for Case1 (7 pyrolysis) trade-off solution; C) Sankey diagrams for Total Revenues, Total Costs, and Total GHG emissions for the Case2 (4 pyrolysis, 3 incineration) trade-off solution.

performance with respect to the best environmental SC, with a gross profit of 94 M€/y (+74%), and better environmental performance than the best economic SC, with net GHG emissions of 516 kt CO_2^{eq}/y (−24%); hence, it represents a reasonable trade-off between the two objectives.

5. Discussion

Some results were not surprising as it was quite expected that incineration would outperform the other technologies in economic terms. Also note that we did not consider the exploitation of heat generated during incineration for home heating, because the economics depend on the specific integration with the local residential area. However, there is no doubt that such integration would provide additional value both economically and environmentally. Conversely, it should be observed that the expected transition towards renewable sources for power generation will reduce the environmental benefits of burning plastics to produce electricity.

In the case of pyrolysis, too, our model only focuses on the

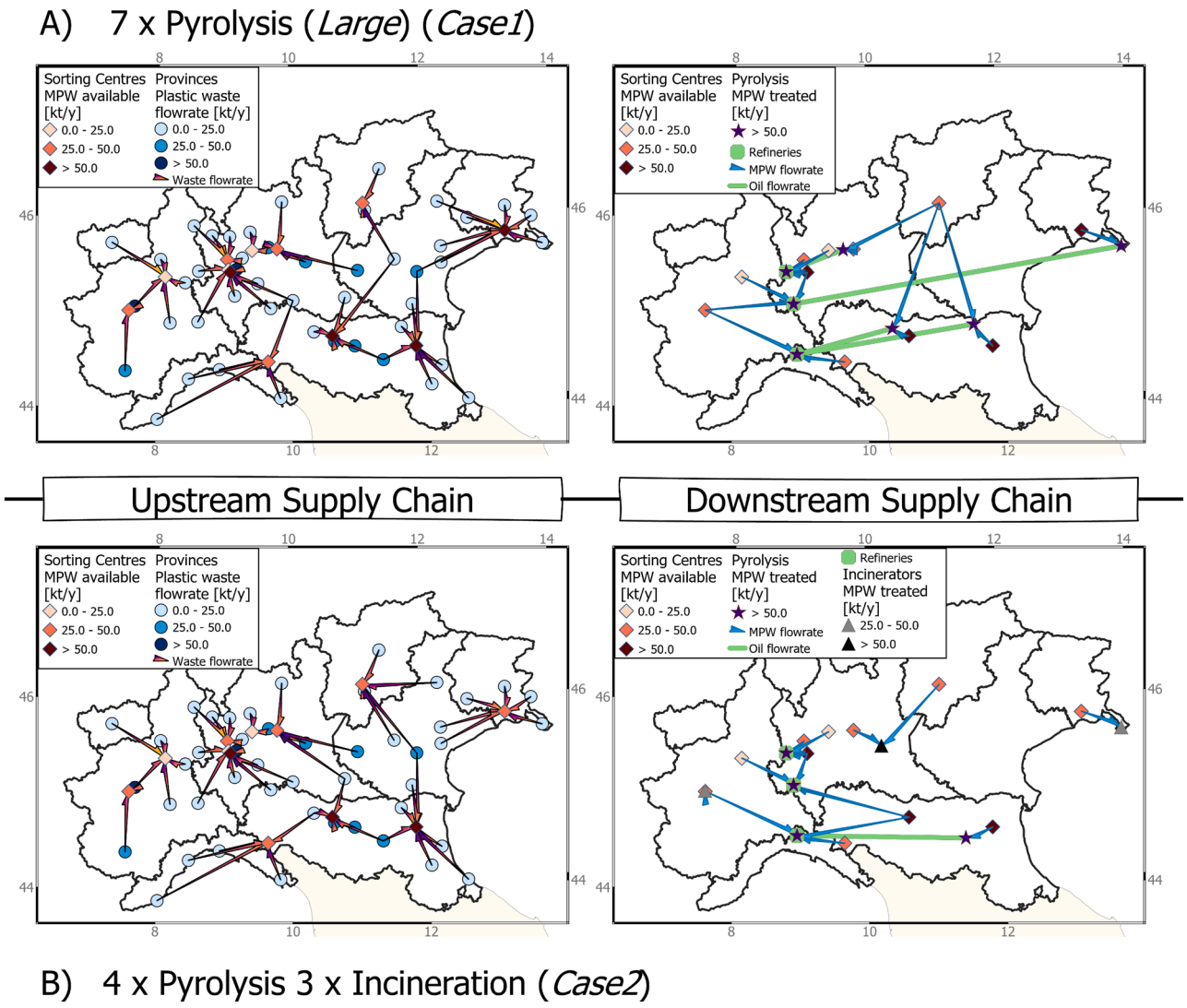

Fig. 5. Upstream and downstream supply chain configurations for: A) the Case1 (7 PoPS Pyrolysis) trade-off Pareto optimal solution; B) the Case2 (4 pyrolysis, 3 incineration) trade-off solution.

production of pyrolysis oil as a substitute for crude oil. Alternatively, pyrolysis oil could be sent directly to cracking units for further processing (Kusenberg et al., 2022b). Evaluating the economic and environmental performance of various utilization pathways for pyrolysis oil can provide further insights into the advantages and limitations of pyrolysis as a treatment technology for mixed plastic waste.

Finally, it should be noted that our study only focused on pyrolysis as an alternative to incineration. Gasification, which may potentially lead to a variety of chemicals such as hydrogen (Lan and Yao, 2022; Chari et al., 2023) or C1-chemicals, is certainly worth investigating, although it is typically a high capital investment and energy intensive process. Similarly, there are several options at a lower TRL level (e.g. hydrocracking, plasma pyrolysis, microwave assisted pyrolysis) with a highly promising potential. However, the uncertainty on several parameters may lead to questionable and unreliable results. Approaches that explicitly account for uncertainty in technological performance (e.g. d'Amore and Bezzo, 2017b) could be used to support these types of analyses.

6. Conclusion

In this study, a multi-objective mixed integer linear programming framework was proposed for managing the supply chain of mixed plastic waste in Northern Italy. The optimisation yielded quantitative insights into the economic and environmental performance of the supply chain, enabling the identification of the optimal treatment technology under economic vs. environmental trade-offs by considering as potential technologies incineration and pyrolysis. In particular:

- results show that when prioritising economic optimisation, incineration emerges as the exclusive choice for treating mixed plastic waste, resulting in the highest gross profit of 115 M€/y. However, this also leads to the highest net greenhouse gas emissions, reaching 680 kt CO_2^{eq}/y;
- when the aim is the environmental optimisation, pyrolysis is selected as the preferred technology due to its lower greenhouse gas emissions. Net greenhouse gas emissions are reduced to 387 kt CO_2^{eq}/y; however, the gross profit decreases to 54 M€/y (i.e., −53% with respect to the best economic network);
- two trade-off optimal solutions are analysed: *Case1* (only pyrolysis plants selected) demonstrates nearly identical net GHG emissions as the environmental optimum, while showcasing improved economic performance with a gross profit of 69 M€/y; *Case2* (both pyrolysis and incineration selected) represents a reasonable trade-off between the two objectives, yielding a gross profit of 94 M€/y and net GHG emissions of 516 kt CO_2^{eq}/y.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.compchemeng.2023.108503.

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