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Municipal solid waste management instruments that influence the use of the refuse as fuel in developing countries: A critical review

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Abstract

Landfills are the destination of most of the refuse generated whereas composting, material recycling, and Waste-to-Energy (WtE) technologies are not commonly employed in developing countries. However, the destination for energy purposes could be supplied with this refuse, improving the viability of energy use. Thus, this article raises some questions to identify aspects that could encourage its use as refuse-derived fuel (RDF) in these countries. Among them, does environmental education affect the municipal solid waste (MSW) source separation with emphasis on a destination? Can selective collection and extended producer responsibility (EPR) affect the MSW for energy recovery? Is there competition between the recycling market and the energy market for RDF? A systematic review of the literature was conducted to gather data and provide answers to such questions. This enabled to observe that EPR, selective collect expansion and source separation influence the quantity and quality of waste sent for energy use. Both internal and external factors impact on source separation. Additionally, there is evidence to support that despite several studies showing their technical, economic, environmental and social viability, the methods of energy usage of the refuse still need to improve their deployment in developing countries. In addition to identifying the main research gaps to be filled in future studies, the article also identified the instruments of MSW management that are to be applied in developing countries to divert recyclable and organic waste from landfill.

Keywords

Refuse-derived fuel, source separation, environmental education, extended producer responsibility, selective collection, Theory of Planned Behaviour

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Introduction

Municipal solid waste (MSW) output has increased due to population growth, economic expansion, new product and service development and the unsustainable consumer behaviour, such as intensive packaging generation (Goh et al., 2022). As a result, 2.24 billion tonnes of MSW were generated worldwide in 2020 and the estimate is that it will reach 3.38 billion tonnes in 2050 (Kaza et al., 2021). Given this scenario, it is necessary to diversify the opportunities for disposal beyond landfills, especially concerning MSW generated in developing countries. These countries seek as a reference from developed countries that encourage recycling (material recycling and composting) and waste energy recovery (Kaza et al., 2018).

In the European Union (EU), the regulatory frameworks established for the MSW management (Kumar and Samadder, 2017; Wang et al., 2020) promoted an increase in recycling by around 47%, and energy generation by 28%, leaving only 24% of refuse sent to landfills (Eurostat, 2022). Dublin, Helsinki, Ljubljana, Stockholm and Tallinn, for example, are cities that have selectively collected MSW percentages above 30% (Seyring et al., 2015). However, unlike Europe, in developing countries the growing generation of MSW was not accompanied by a planned infrastructure to deal with the volume generated (Chaves et al., 2014; Moya et al., 2017). Countries in Latin America, for example, are still struggling to eliminate the illegal dumpsite, establishing landfills as a top priority for waste disposal (Margallo et al., 2019). In Colombia and Brazil in 2018, 80.4% and 59% of

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MSW were sent to landfills, 16.5% and 41% to illegal disposal, and 3.1% and 0% were sent to energy recovery plants, respectively (Alzate-Arias et al., 2018; SNIS, 2023).

Developing countries still confront difficulties in MSW management due to deficient legal frameworks and a lack of technical knowledge (Bui et al., 2022). For example, the lack of preferential policies for the recycling industries (subsidies and tax relief) caused delays in developing the recycling market (Chen et al., 2018; Dutra et al., 2018). In addition, MSW recycling is more difficult to perform compared with other waste types due to the difficulty of sorting and its dispersion in urban centres (Mu and Zhang, 2021), making the selective collection more expensive per tonne waste collected (4.5 times) than conventional collection (Franca et al., 2019; Galavote et al., 2023). These factors contribute to deficiencies in the recycling system and, consequently, an increase in the amount of refuse generated and disposed of in landfills.

However, the destination for energy purposes could be supplied with this refuse, enhancing the viability of energy use. In this case, an alternative is its use for RDF production (Chaves et al., 2021a, 2021b; Edo-Alcón et al., 2016; Hemidat et al., 2019). RDF is a fuel produced by waste materials processed to achieve Lower Heating Value (LHV) (Jąderko-Skubis, 2021), notably generated in mechanical-biological treatment units (MBT) (Świechowski et al., 2020) or sorting units (Slomski et al., 2020; Tiburcio et al., 2021). Its components include: MSW rejected fraction (paper, cardboard, plastics, textiles, wood and leather); waste tyres; sludge and coal dust; sewage sludge; oils, solvents, and paints; textile, rubber, waste; meat and bone meal (Chaves et al., 2021b; Jąderko-Skubis, 2021; Yang et al., 2021d). In cement kilns, incinerators (including gasification and pyrolysis plants), or other industries, this material is used as a secondary fuel in the form of pellets or chopped (Rezaei et al., 2020; Shumal et al., 2020; Thawani et al., 2020).

Even though the use of RDF generates several benefits, some local conditions-related factors must be taken into consideration when analysing its viability: the waste management elements that can influence its amount and composition as the educational policies, the expansion of the selective collection, the Extended Producer Responsibility (EPR), the activity carried out by the market (formal and informal) of recycling as a secondary raw material, making it necessary to elucidate the socioeconomic and environmental challenges (GIZ, 2017). Regarding the educational policies, it is notably reported that due to the lack of environmental education in developing countries, the percentages of source separation are very low (GIZ, 2017; Rezaei et al., 2020; Vershinina et al., 2021), influencing the common heterogeneity of waste in these places (Tomić et al., 2022).

Additionally, in developing countries, the presence of a high percentage of humidity (>20%) is common, due to the presence of organic waste (food, yard waste and others) and inert materials in MSW (stones, sand, construction debris, among others) that reduce the LHV of RDF (Azam et al., 2020; Hemidat et al., 2019; Tyagi et al., 2021). In this regard, the collection modality contributes significantly to MSW calorific value since they influence the amount and composition of RDF (Bessi et al., 2016; Rezaei et al., 2020). Just as, the EPR that favour reverse logistics and a circular economy by making producers and importers legally and financially accountable for their products during the post-consumption phase (collection, recycling and disposal of these products) (Kumar et al., 2021; Winternitz et al., 2019).

Another aspect to be mentioned in developing countries is the social importance attributed to the recycling market, which appropriately prioritizes energy generated in MSW management (GIZ, 2017; Wang et al., 2020). According to Świechowski et al. (2020) and Psomopoulos et al. (2022), the increased recycling of paper, plastics, among others materials reduces the RDF's calorific value. It forces cement and incinerator industries to hunt for higher-quality alternative fuels.

Given these notes, some questions are still relevant. Firstly, is there agreement in the literature on how the environmental education component affects the MSW source separation with emphasis on a destination? Can policies to expand the selective collection and the EPR affect the waste sent for heat treatment with energy recovery? Finally, is there an environment of competition between the formal and informal recycling market and the energy market for RDF?

Considering these questions, this article's main contribution was to identify, through a detailed examination of the literature, the knowledge gaps regarding the use of refuse as RDF and the components of MSW management that could be used in developing countries to divert recyclables from ending up in landfills.

Material and methods

A systematic literature review aims to evaluate and combine research evidence, frequently following review-specific principles, in a narrative format with tabular support (tables, charts and figures) (Grant and Booth, 2009). These reviews, which present findings concisely and rich in content, are crucial because they provide an overview of existing studies (Dang and Weiss, 2021; Thomé et al., 2016). Therefore, a systematic literature review was used to collect information and data to identify factors that could encourage the use of rejects disposed of in landfills (developing countries) such as RDF. Figure 1 shows the steps employed for this.

After the step of definition of the research question, it was carried out the keywords' defining step. The keywords were searched in articles, books and documents related to the theme. The identified terms have been entered into databases to assess their relevance. Finally, the keywords have been definite around five themes: environmental education, source separation, recycling, refuse-derived fuel (RDF) and EPR, which were combined between themselves.

For the next step (search in databases), it has chosen Scopus and Web of Science databases due to their enhanced relevance to the scientific literature (Khudzari et al., 2018; Solis et al., 2019) and ease of access to articles (Salvador et al., 2019). The database search occurred through three combinations of keywords (Table 1) and Boolean operators. In the first combination, the

Figure 1. Steps to obtain the article portfolio.

Table 1. Combinations of keywords used to search in the databases.

Combination of keywords			Databases	Period
No	First column	Second column		
1	environmental education, environment education, ambient education, environmental awareness, an educational intervention, environmental communication, educational campaign, environmental behaviour	source separation, waste separation, waste sorting, separation of waste, the behaviour of waste separation, waste source-separated, waste classification, separate collection intentions, sorting behaviour, separate waste collection	Scopus Web of Science	2017–2022
2	garbage collection, selective collect, door-to-door, delivery stations, delivery points, selective collection, kerbside, waste sorting, recycling collection, source separation, EPR, responsibilities extended, producer responsibility, producer responsibility, the liability of the producer, manufacturer responsibility	RDF, waste-derived fuels, solid recovery fuel, thermal treatment, thermochemical treatment, thermochemical conversion, thermal waste-to-energy (WtE) technologies, thermal conversion, thermochemical systems, waste-to-energy, thermo-chemical process, thermal conversion technologies, incineration, direct burning, co-combustion, combustion processes, gasification, the thermal degradation process, co-gasification, pyrolysis, the thermal degradation process		
3	refuse derived-fuel, waste-derived fuels, solid recovery fuel	waste recycling, material recycling, material recycled, waste recycled, packaging waste, recyclable waste, recyclable materials, recyclable rubbish, recyclables, recycling target, recycling goal, recycling market, target for recycling, the goal for recycling, plastic waste, recycling, reverse logistics		

first and second column were connected using the Boolean 'AND' operator. The Boolean 'OR' operator was employed to separate the words in each column. The second and third combinations underwent the same procedure. To reach the most recent literature, the period of the search covered between 1 January, 2017, and 8 October, 2022 (the last 5 years). Additionally, the search keywords were restricted to the title, author's keywords, and abstracts, yielding 594 articles.

After the search for articles in databases, the articles were filtered, as indicated in Figure 2. At this step, all the articles were gathered and inserted in a software Microsoft Excel® spreadsheet containing relevant information such as year, title, authors, impact factor and citation numbers, among other things. Then, the following filtering techniques have used: removal of duplication; removal of articles with a title, abstract, or keywords that were not conditional on the subject under study.

In the last step, 181 articles were read completely to verify compatibility with the research questions, and 113 of these were chosen for the final portfolio. The articles were selected to respond to the questions presented. As a result, it considered articles that:

- 1° Combination: It identified barriers and strategies that encourage MSW source separation, investigated the influence of external and psychosocial factors on source separation, evaluated the influence of environmental communication and education on source separation, compared the effects of environmental education policies and other policies (technical, educative, economic instruments) and articles that reported the programmes implemented to encourage source separation.
- 2° Combination: It detailed the development of municipal waste management techniques, such as energy generation and selective collection, reported the evolution of municipal waste management strategies as selective collection and energy generated, evaluated technically and environmental scenarios of MSW management strategies inclusive increased source separation, selective collection, energy recovery and investigated the effects of EPR on circular economy in different countries.

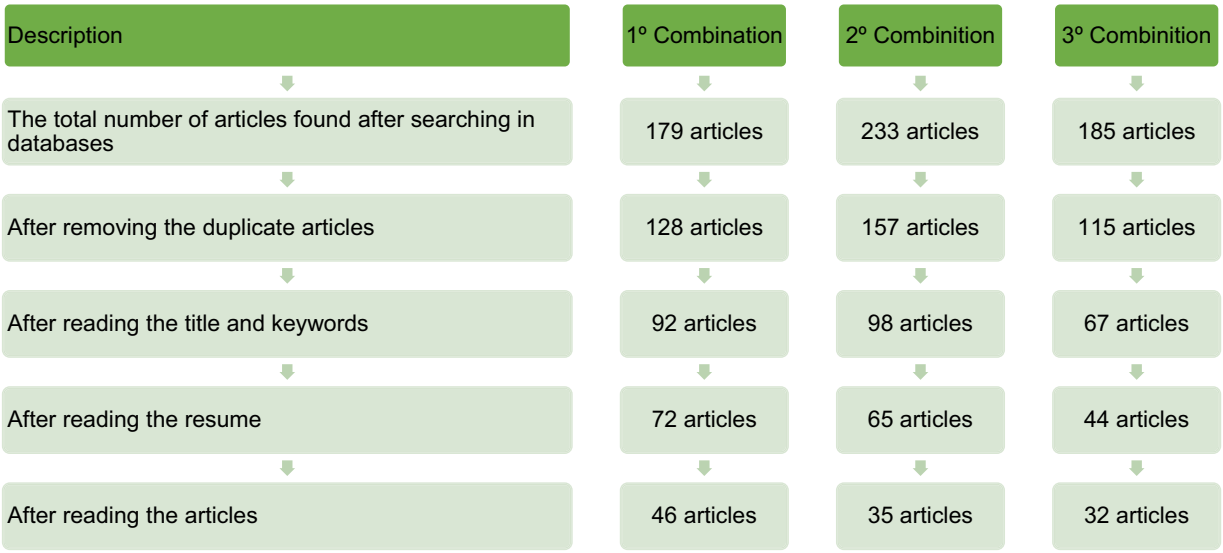

Figure 2. Procedures performed in the filtering step and the number of articles obtained.

- 3º Combination: It discussed trends in the use of RDF in various locations; evaluated scenarios about the economic and environmental feasibility of recycling and using RDF, compared MSW disposal alternatives inclusive RDF and recycling; assessed the viability of MBT units that carry out the recycling of materials and the use of refuse as RDF, characterized the MSW to indicate possible treatment options for RDF use and recycling, as well as discussed the competition between the recycling market and the RDF energy market.

It emphasized further that some articles found while reading the portfolio had been considered to support the pertinent issues in this work.

Results and discussion

Results and discussion are presented in four sections. The first subsection reviews aspects and research that discuss the effect of the educational instruments intended for MSW source separation. The second subsection discusses the influence of the EPR and policies to expand the selective collection in thermal treatments and recycling material. The third subsection presents research that addresses the competitive environment between the market for material recycling and the energy market with a focus on RDF. Finally, the fourth subsection presents the research gaps identified through a literature review.

Effect of environmental education on the MSW source separation

Sorting of collected waste, the MSW source separation, and recycling are all distinct waste management processes since, whereas sorting and source separation both involve identifying and categorizing waste into homogeneous fractions, recycling refers to the treatment and use of waste to create new products (Wang et al., 2019). However, they are intimately related because source separation and sorting, which reduce impurities and contaminants to improve recovery, are crucial to the increasing recycling rate (Conke, 2018; Varotto and Spagnolli, 2017).

The main stakeholders involved in this stage are generators and consumers who make the material sorting possible (Jacobsen et al., 2018). Therefore, it is essential to comprehend the factors that encourage public engagement to source separation (Liu et al., 2019). According to Liu et al. (2019), Ma et al. (2020a), Meng et al. (2019), Wang et al. (2021b) and Wang (2021), source separation factors can be categorized as internal (micro-level) and external (macro level). Individual psychology, environmental knowledge, personal habits, social structure, financial resources, class ideals and identity are all examples of internal influences (Liu et al., 2019; Wang et al., 2021b). On the other side, external elements are connected to processing technology, situational conditions and political tools (informational, economic and fiscal instruments) (Hu and He, 2022; Ma et al., 2020b; Wang et al., 2021b).

Internal factors and environmental education. Among internal factors, psychological factors influence source separation behaviour (Cui et al., 2021). Therefore, much research has used the Theory of Planned Behaviour (TPB) to comprehend and predict individual social behaviour related to source separation (Hu et al., 2021; Labib et al., 2021, 2018a, 2018b; Loan et al., 2017; Shen et al., 2019; Wang et al., 2021b; Xiao et al., 2017; Xu et al., 2017). TPB is derived from the Theory of Reasoned Action and provides a theoretical concept model to investigate the influence of behaviour constructs (Hu et al., 2021; Xu et al., 2017). The theory points out that the behaviour of the individual is not only based on his will but also factors related to Attitudes towards behaviour, Subjective Norms (SN), and Perceived Behavioural Control (PBC) (Ulhasanah and Goto, 2018; Wang, 2021).

Table 2. An overview of studies that employed Theory of Planned Behaviour, NAM Theory and Attitude--Behaviour–Condition Theory.

Authors	TPB*	NAM*	A–B–C*	Target audience	Country surveyed
Hu et al. (2021)	x	–	–	University students	Japan
Wang et al. (2021)	x	–	–	Urban population	China
Labib et al. (2021)	x	–	–	Urban population	Saudi Arabia
Shen et al. (2019)	x	–	–	Young population	China
Liao et al. (2018a, 2018b)	x	–	–	Urban population	China
Xiao et al. (2017)	x	–	–	Urban population	China
Loan et al. (2017)	x	–	–	Urban population	Vietnam
Xu et al. (2017)	x	–	–	Urban population	China
Shi et al. (2021)	x	x	–	Rural population	China
Setiawan et al. (2021)	x	x	–	Urban population	Indonesia
Zhang et al. (2020)	x	x	–	Urban population	China
Zhang et al. (2019)	x	x	–	Urban population	China
Goh et al. (2022)	x	x	–	Urban population	Australia
Wang (2021)	x	–	x	Urban population	China
Meng et al. (2019)	x	–	x	Urban population	China
Lou et al. (2022)	x	–	–	Taoist population	China
Schoeman and Rampedi (2022)	x	–	–	Urban population	South Africa
Zheng et al. (2022)	x	–	–	Urban population	China
Zhang et al. (2022)	x	x	x	Urban population	China
Zaikova et al. (2022)	x	–	–	Urban population	Russia & Finland
Wang et al. (2022)	x	–	–	Urban population	China
Oduro-Appiah et al. (2022)	x	–	–	Household heads	Ghana
Ma and Jiang (2022)	x	–	–	Urban population	China
Liu et al. (2022)	x	x	–	Urban population	China
Govindan et al. (2022)	x	–	–	Urban population	China
Arkorful et al. (2022)	x	x	–	Urban population	Ghana
Ao et al. (2022)	x	–	–	Rural population	China
Bardus and Massoud (2022)	x	–	–	Rural population	Lebanon
Zhang et al. (2021)	x	–	x	Urban population	China
Wang et al. (2021c)	x	–	–	Urban population	China
Wang et al. (2021a)	x	–	–	Urban population	China
Negash et al. (2021a)	x	–	–	Experts	Ecuador
Negash et al. (2021b)	x	–	–	Experts	Mongolia
Zheng et al. (2020)	x	–	–	Urban population	China
Reijonen et al. (2021)	x	–	–	Urban population	Finland
Razali et al. (2020)	x	–	–	Urban population	Malaysia
Okonta and Mohlalifi (2020)	x	–	–	Urban population	South Africa
Tian et al. (2019)	x	–	–	Urban population	China
Fan et al. (2019)	x	–	–	Urban population	China & Singapore
Vassanadumrongdee and Kittipongvises (2018)	x	–	–	Urban population	Thailand
Ma et al. (2018)	x	–	–	Urban population	China
Alhassan et al. (2018)	x	–	–	Urban population	Ghana
Liao et al. (2018a, 2018b)	x	–	–	Rural population	China
Wang and Tan (2022)	x	–	–	Rural population	China

A–B–C: Attitude–Behaviour–Condition Theory; NAM: Norm Activation Model Theory; TPB: Theory of Planned Behaviour.

Attitude is used to express whether the evaluation of a given action is positive or negative (Shen et al., 2019; Zhang et al., 2020). SN represents perceived external pressure from people around them or society (Shi et al., 2021; Zhang et al., 2020), such as family, friends, neighbours, colleagues, the government and the media (Setiawan et al., 2021; Xu et al., 2017). On the other hand, the PBC refers to a person's perception of the difficulty in performing a determined behaviour (Shen et al., 2019; Zhang et al., 2020) and describes the opinion about possessing behavioural resources (Xu et al., 2017).

Other studies have combined TPB with Norm Activation Model Theory (NAM) (Setiawan et al., 2021; Shi et al., 2021; Zhang et al., 2019, 2020) and Attitude–Behaviour–Condition Theory (A–B–C) (Meng et al., 2019; Wang, 2021). An overview of the studies using TPB, NAM Theory and A–B–C to determine internal variables influencing the source separation of MSW in various countries is provided in Table 2. In contrast to the TPB, the NAM theory emphasizes moral obligation in motivating the behaviour of source separation; its variables are the awareness of consequences, the ascribed responsibility and the personal norm

(Wang et al., 2019; Xu et al., 2017). The A–B–C states that the behaviour of individuals results from the combined effect of attitude and external conditions, these factors are vital in determining whether individuals will assume source separation behaviour (Meng et al., 2019).

According to some studies (Cui et al., 2021; Hu et al., 2021; Labib et al., 2021; Liu et al., 2022; Lou et al., 2022; Reijonen et al., 2021; Wang, 2021), behavioural intention to source separation is considerably and favourably influenced by Attitude, SN and PBC. Other works mention the more significant importance of behavioural Attitude (Schoeman and Rampedi, 2022), just as the same combined with PBC for Ecuadorian experts (Negash et al., 2021a), Finnish urban population (Reijonen et al., 2021), urban (Ma et al., 2018; Meng et al., 2019) and rural (Hu and He, 2022; Shi et al., 2021) Chinese populations. PBC has a significant impact on some populations, such as young men (Shen et al., 2019; Xu et al., 2017) and Chinese workers (Liao et al., 2018a, 2018b), in countries of the EU (Minelgaitė and Liobikienė, 2019), Australia (Goh et al., 2022), Thailand (Vassanadumrongdee and Kittipongvises, 2018) and in rural Lebanon (Bardus and Massoud, 2022).

This aspect indicates the importance of a convenience (facility) for motivating source separation (Liao et al., 2018a, 2018b; Shen et al., 2019; Xu et al., 2017), whereas SN is significant among young women (Shen et al., 2019), middle-aged adults, middle-income groups (Xu et al., 2017) in China and household heads in Ghana (Alhassan et al., 2018; Oduro-Appiah et al., 2022). In Vietnam (Loan et al., 2017) and Singapore (Tong et al., 2018), moral norm (linked to the degree of consciousness) was a significant factor in shaping segregation behaviour.

The TPB results are crucial to guide interventions (Hu et al., 2021) since identifying factors that motivate/prevent the population's involvement in source separation is extremely important to guide the implementation of policies (Xu et al., 2017; Zhang et al., 2020). Liu et al. (2019), Sadeghi et al. (2020) and Liao et al. (2018a, 2018b) mentioned that environmental education affects behavioural Attitudes, SN, PBC and, consequently, residents' willingness to source separation. Positive behavioural Attitudes, for example, can be encouraged by publicizing the advantages of source separation at programmes (Shi et al., 2021). The authors recommended obtaining feedback from families to support positive Attitudes and promote participation from people who still have a negative opinion of the programme. Shen et al. (2019) also suggested adopting educational initiatives to raise young people's environmental knowledge to encourage positive Attitudes.

Regarding norms (subjective and personal), Zhang et al. (2020), Shen et al. (2019), Goh et al. (2022) and Arkorful et al. (2022) emphasized the need for governments to enforce moralistic education programmes on the populace while exposing them to the genuine environmental issues of society, particularly those connected to waste management. Adequate disclosure strengthens individuals' perception of the consequences of the absence of source separation, further internalizing awareness of implications into a sense of environmental responsibility (He et al., 2020; Zhang et al., 2019). In addition, educational programmes must involve the community and thus better comprehend the traits of its members and emphasize the importance of moral obligations to the community and the environment (Setiawan et al., 2021).

The PBC is related to convenience (Wang et al., 2021b), so the measures adopted must be directed to facilitate source separation (Shen et al., 2019). Xu et al. (2017) mentioned implementing environmental education programmes in schools, and Zhang et al. (2019) disseminated advertisements to promote the correct segregation/classification of waste. Lectures can also have held in classes, communities and companies to popularize the norms and encourage MSW grading abilities, minimizing the difficulties involved in source separation (Shen et al., 2019). In addition, it is significant that the government provides an adequate infrastructure to facilitate the activity of source separation and make the process convenient for the population (Meng et al., 2019).

Other studies have assessed the combined impact of external (public policy) and internal determinants on source separation (Ao et al., 2022; Fan et al., 2019; Govindan et al., 2022; Labib et al., 2021; Ma and Jiang, 2022; Meng et al., 2019; Tian et al., 2019; Wang et al., 2021a; Wang et al., 2022; Zaikova et al., 2022; Zhang et al., 2020, 2021; Zheng et al., 2020). Advertising and education are mentioned by Tian et al. (2019) and Liao et al., (2018a) as having positive effects on consumers' Attitudes, SN and PBC. These effects can still happen directly or indirectly (Wang et al., 2022) and are significant for some populations, such as rural Chinese citizens (Ao et al., 2022; Negash et al., 2021b; Zheng et al., 2020). Ma and Jiang (2022) mention that advertising measures linked to fixed tax also encourage source separation in China. Willingness to pay, for example, can be strengthened through behavioural Attitude, PBC and policy satisfaction (Wang et al., 2021a). On the other hand, recent studies mention other economic incentive methods as Pay-As-You-Throw (charging based on the amount of waste generated) that can promote the involvement of residents in waste sorting as rewards and material and financial penalties (Fan et al., 2019). Many studies claim that Economic incentives were significant for the urban populations of China (Zhang et al., 2022) and South Africa (Okonta and Mohlalifi, 2020) but not for the urban Russian and Finland populations (Zaikova et al., 2022).

External factors: Environmental education and other policy instruments. Political instrument implementation positively influences the population's willingness to source separation since they are guided and forced to do so (Tian et al., 2022). These tools can be classified as legal, economic, technical/operational, educational and planning instruments (Figure 3) (BIPRO, 2013). According to Liu et al. (2019), the most recent studies focus on the influence of external factors and emphasize the role played by environmental education. These studies can be divided into three themes: (1) reward and punishment, where environmental education plays a significant role in increasing perceived policy effectiveness; (2) rating services, where advertising about rating

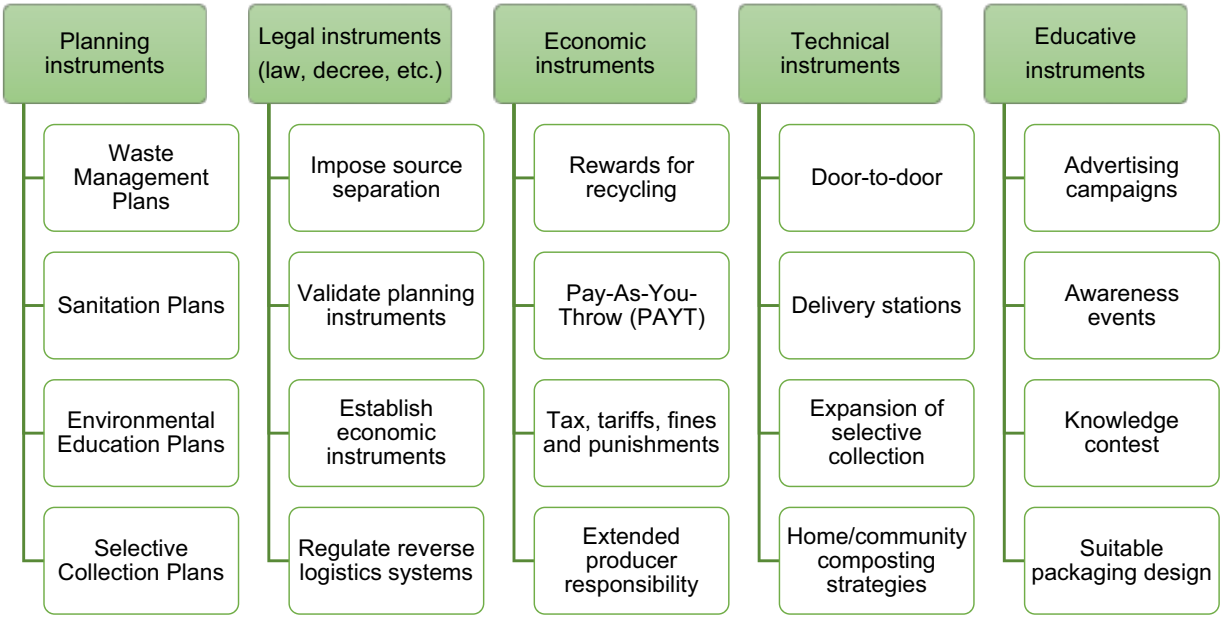

Figure 3. Some examples of policy instruments that affect source separation. Source: Elaborate from BIPRO (2013).

services, facilities and promotion media are crucial for engagement and (3) advertising aimed at raising awareness.

In the EU, for example, Minelgaitė and Liobikienė (2019) and Agovino et al. (2020) found that awareness campaigns significantly influence source separation. In China, information publicity positively affects the intent of source separation in urban (He et al., 2020; Wang et al., 2019) and rural (Ma et al., 2020a) sites, since it is implemented with quality. Some studies also mention the importance of information publicity and quality service infrastructure (Ma et al., 2020a, 2020b). Education-related intervention is also the main driver of source separation in other areas, including Trinidad and Tobago (Lawrence et al., 2020), Vietnam (Tran and Matsui, 2021) and Iran (Sadeghi et al., 2020).

Other authors contrast environmental education strategies' side effects with different policies. Yang et al (2021a, 2021b) concluded that voluntary participation induces an increase in self-identity compared to penalties, which leads to a high level of acceptability of policies and an increased rate of source separation in the rural and urban sites, respectively. The authors also claim that a penalties policy that imposes restrictions on people's behaviour tends to reduce the willingness for sustainable consumption. Xu et al. (2018b) and Li and Wang (2021) point to a more significant influence of environmental education policies compared to economic incentives (subsidies, rewards, charges and others) to encourage source separation.

In contrast, a study by Matiiuk and Liobikienė (2021) found that the only instruments that significantly and favourably affect segregation behaviour are educational and economic. Meng et al. (2018) also point out that charging schemes (economic instruments) can improve the performance of source separation behaviour. Table 3 presents a summary of studies that evaluated the effects of educational policies together with other policy instruments aimed at source separation.

Providing information through educational intervention programmes improves understanding, awareness and, consequently, the population's willingness to source separation (Cui et al., 2021; Liu et al., 2019). This information provides to educate people about waste management problems and disseminate information that will motivate people to take action to address these problems (Matiiuk and Liobikienė, 2021). Interventions in these situations may include awareness campaigns, practical training (Heydari et al., 2021), information publicity, knowledge contests and lectures for the community (Wang et al., 2019). Channels, such as the Internet, television, radio, newspapers, publicity slogans, microblogs and WeChat, are also used (Liu et al., 2019; Meng et al., 2019; Wang et al., 2019).

It is fundamental to emphasize the importance of a detailed analysis to identify the most important information channels for the population. According to a survey by Varotto and Spagnolli (2017), 76.5% of respondents acquire knowledge via television and television media, followed by newspapers and books (58.8%) and the Internet (50.0%). Schools and universities also play a motivating role in source separation and usually are transmitted to the family atmosphere (Hu et al., 2021; Varotto and Spagnolli, 2017). Publicizing information to enlighten the populace about waste-receiving and classification facilities is also crucial to the effectiveness of source separation initiatives (Liu et al., 2019).

In addition, the group's specificities must be observed. For example, the advertisements for young people must be present in places of daily activity for this group (subway, buses, on the university campus) and relevant to the pamphlet's distribution or gifts for older adults. In the workplace, it is essential to strengthen publicity, environmental education and business management with legal instruments (Cui et al., 2021). However, it is frequently challenging to alter engrained environmental values using conventional advertising and teaching strategies (Wang, 2021). In

Table 3. A studies overview that evaluated the policies effect on source separation.

Authors	Policy instruments					Target audience	Country surveyed
	EDU	LEG	ECO	TEC	PLA		
Lishan et al. (2021)	x	–	–	x	–	Urban population and experts	China
Tran and Matsui (2021)	x	–	–	–	–	Urban population	Vietnam
Yang et al. (2021a)	x	–	x	–	–	Rural population	China
Cui et al. (2021)	x	–	–	x	–	Urban population	China
Matiiuk and Liobikienė (2021)	x	–	x	x	–	General population	Lithuania
Yang et al. (2021b)	x	–	x	–	–	Urban population	China
Ma et al. (2020b)	x	–	–	x	–	Rural population	China
Wang and Hao (2020)	x	–	–	–	–	General population	China
Lawrence et al. (2020)	x	–	–	x	–	Low–income population	Trinidad & Tobago
Sadeghi et al. (2020)	x	–	–	–	–	Housewives	Iran
Ma et al. (2020b)	x	–	–	x	–	Rural population	China
Agovino et al. (2020)	x	x	x	x	–	Urban population	Italy
He et al. (2020)	x	–	x	–	–	General population	China
Wang et al. (2019)	x	–	–	–	–	General population	China
Minelgaitė and Liobikienė (2019)	x	–	x	x	–	General population	European Union
Xu et al. (2018b)	x	–	x	–	–	Urban population	China
Xiao et al. (2017)	x	x	x	x	x	Urban population	China
Meng et al. (2018)	x	–	x	–	–	Urban population and experts	China
Tian et al. (2022)	x	x	x	–	x	Urban population	China
Zaikova et al. (2022)	x	–	x	–	–	Urban population	Russia & Finland
Wang et al. (2022)	x	–	–	–	–	Urban population	China
Ma and Jiang (2022)	x	–	x	–	–	Urban population	China
Govindan et al. (2022)	–	–	x	x	–	Urban population	China
Ao et al. (2022)	x	–	–	–	–	Rural population	China
Zhang et al. (2021)	x	–	x	x	–	Urban population	China
Wang et al. (2021a)	x	–	–	–	–	Urban population	China
Zheng et al. (2020)	x	–	–	–	–	Urban population	China
Tian et al. (2019)	x	–	–	–	–	Urban population	China
Fan et al. (2019)	x	–	x	x	–	Urban population	China & Singapore
Meng et al. (2019)	x	x	x	x	–	Urban population	China
Labib et al. (2021)	x	–	–	–	–	Urban population	Saudi Arabia
Zhang et al. (2020)	x	–	–	–	–	General population	China

ECO: Economic; EDU: Educative; LEG: Legal; PLA: Planning; TEC: Technical.

these circumstances, information may be sent through unconventional methods like applications and social networks (Tong et al., 2018).

Environmental education programmes like those listed above have been implemented in various locations. Consequently, the percentages of source separation significantly increased: 20% in Singapore, 59% in South Korea and 40% in Hong Kong (Tong et al., 2018). Additionally, the amount of recycled material collected in Shanghai grew by 432% due to the introduction of obligatory source separation (Wang, 2021). In Vietnam, the population's involvement in segregation programmes grew by around 60%. Concurrently, in the EU, a study conducted by Minelgaitė and Liobikienė (2019) found that only 3% of respondents did not perform source separation.

An environmental education policy may encounter several difficulties during implementation. Information about potential methods of waste separation, for instance, ought to be adequately explicit (where, how and what) (Ma et al., 2020b). Wang et al. (2019) mentioned that low-quality information affects the population's intention towards the source separation. In Brasilia City, for example, a study by Conke (2018) found that 70% of the waste was source-separated poorly, causing losses of US$ 396 million per year.

According to Tong et al. (2018), the first anaerobic digestion project in Singapore failed due to excessive contamination of inorganic waste that was improperly source-separated. The authors mention that the plant has projected to meet an impurity percentage of 15%, but the actual was higher than 30%. In addition, limited awareness and the difficulty of changing the population's habits also prevent the execution of source separation (Wang, 2021). Other aspects are related to lack of interest, and insufficient commitment, besides behavioural barriers related to lack of space at home to recycle, needing to be busier, forgetting to waste disposal and others (Heydari et al., 2021). As noted, environmental education impacts source separation and the waste quality delivered for reuse and recycling (Bertanza et al., 2021; Xiao et al., 2020).

Influence of EPR and policies on the expansion of selective collection in thermal treatments with energy recovery and material recycling

The introduction of selective collection systems and high-productivity sorting units to separate MSW inorganic and organic fractions are the biggest challenges faced by developing countries for energy recovery systems implementation and waste material recovery (Ferronato et al., 2022). In this context, collection stage policies are essential strategies to find lasting solutions for waste management. In addition, define the roles and responsibilities of each actor among the stakeholders (Oluwadipe et al., 2021). These actions include, among others, expanding selective collection (Dutra et al., 2018) through regulations and the deployment of expanded responsibility programmes (Nikiema and Asiedu, 2022).

Extended producer responsibility. The EPR was introduced as a legal instrument in the late 1990s by the International Organization for Economic Co-Operation and Development (Bucknall, 2020; Milios et al., 2018). Subsequently adopted by several countries, it is the responsibility and commitment of the producer to collect and recycle their products, to reduce their impact throughout the life cycle (Xavier et al., 2021). Moreover, the instrument encourages the waste generation prevention strategy, encouraging companies to spend money on projects with more environmentally friendly packaging (Panzone et al., 2021). In California, for example, the Natural Resources Defense Council mandated that producers have to total the volume of their products by 75% over 6 years (Nikiema and Asiedu, 2022). The post-consumer product management can be carried out directly by producers or through an entity responsible for fulfilling the obligations of producers and importers (Bassi et al., 2020). In both cases, the costs are passed on to the polluter, the product's final consumer (Winternitz et al., 2019).

In the EU, member countries have their regulations for extended responsibility, but these must meet the minimum established by the EU directives (Bucknall, 2020). Because of this, its performance and implementation are unequal. In Belgium, for example, 85% of used tyres are recovered, and 15% are sent to energy production, whereas in Italy, only 38% are recovered, and 62% are sent to energy production (Winternitz et al., 2019). In Denmark, Norway and Sweden, the collection percentages and recycling of plastic bottles exceed 85%, whereas the plastic recovery from electrical and electronic equipment is less than 44% (Milios et al., 2018).

The low performance in recycling in developing countries is related to the challenges faced by the industry, such as the supply of materials in quantity and quality inferior to what is needed (Milios et al., 2018), low material densities involving high selective collection costs, materials with varied chemical compositions, deficiencies in classification and recycling information in product design and competition with low-cost virgin alternatives (Bassi et al., 2020) and volatility in recyclable prices (Mehta et al., 2022). Milios et al. (2018) mention that the higher the quality of the recycled material, the greater the willingness of producers to replace their raw material input. However, it is often preferable to incinerate plastics for energy recovery that do not meet homogeneity criteria for recycling and reuse rather than using more costly technologies to sort and materially recycle them (Milios et al., 2018). In Italy, for example, the most economically viable solution for treating tyres is incineration with energy recovery compared to material recycling (Winternitz et al., 2019). It is important to note that incineration can also be used for thermal treatment without energy recovery.

The issue is significantly worse in developing countries since segregation/sorting plants are insufficient, the market for recyclable materials is obscure and undefined, and recycling initiatives are typically more expensive than landfill disposal (Ayeleru et al., 2020; Siman et al., 2020). In many countries, waste is discarded or burned in open-air dumpsites (Aderoju et al., 2019). Additionally, there are many difficulties in monitoring goals and objectives due to the need for more data quality (Nikiema and Asiedu, 2022) and the lack of government policies aimed at recycling, among other factors (Ayeleru et al., 2020; Jalalipour et al., 2021). In response to these difficulties, Jalalipour et al. (2021) and Aderoju et al. (2019) propose that the EPR implementation in these countries could increase material recovery considering that this is the main goal of EPR. Moreover, regarding fractions rejected in recycling, enable the destination for energy use and subsequently reduce their disposal in landfills, as well as in the worst cases reduce waste dumping.

Policies of the expanding selective collection. The selective collection implementation plays a significant part in waste quantity/quality sent for recycling, as it reduces the impurities percentage by more than 20% compared to the conventional collection (Bassi et al., 2020). Italy, for example, increased the selective collection percentage from 27% in 2007 to 52.5% in 2016 (Di Maria et al., 2020) and currently has a recycling rate of over 42% (Eurostat, 2022). Additionally, the selective collection reduces the MSW's biodegradable portion (wet) (Andersson and Stage, 2018), which raises the material's caloric potential and thus makes it easier to employ for thermal recovery (Bengtsen et al., 2020; Yu and Li, 2020). According to ElSaid and Aghezzaf (2020), Egypt's percentage of organic waste decreased from 45% to roughly 25% 6 years after selective collection implementation.

According to several studies, organic waste separation affects LHV set as the amount of heat released by fully combusting a specified quantity less the heat of vapourization of the water in the combustion product (Basu, 2010). Yu and Li (2020) mentioned that separating about 60% of the MSW's organic waste could increase the LHV by 70%, from 8769 MJ t^{-1} to 12275 MJ t^{-1}. Wang et al. (2021d) indicated that the MSW organic residue reduction of 48% could increase the LHV to values greater than 90% (4170–8190 MJ t^{-1}). Gu et al. (2021) highlighted the effect

of waste organic separating along with non-combustible fractions (metals, glass, among others) on energy production and found an increase from 0.439 MWh t^{-1} to 1.114 MWh t^{-1} when 90% has removed of the non-combustible MSW fractions.

Liang et al. (2022) mentioned that increasing the source separation rate by 60% of inorganic waste and 47% of organic waste could increase energy recovery by about 21% in China. Additionally, using biodegradable waste in anaerobic digestion might increase energy production even further. Tong et al. (2018) mentioned the production of 0.032 kWh t^{-1} of biodegradable waste, whereas Leite et al. (2022) described the generation of 5,057,648 MWh $year^{-1}$ from the same material when treated in anaerobic digesters, which would supply the electricity consumption of 3,404,448 households.

In addition to the benefits of energy efficiency, the separation of biodegradable waste has a positive effect on reducing the emission of Greenhouse Gases (GHGs) and other atmospheric pollutants by solid waste management systems. According to Yu and Li (2020), Coelho and Lange (2018) and Zhao et al. (2022), a 60% increase in the rate of biodegradable waste separation results in a more than 40% decrease in carbon emissions. The research by Sun et al. (2018) indicates that the arrangement consisting of source separation of plastics and paper for the RDF production and biodegradable waste for methane generation, as well as the refuse incineration for energy recovery, this scenario had a more significant reduction in emissions (9.44×10^5 tonnes CO_{2eq}). Acidification can be reduced by 4% due to the biodegradable waste source separation of 20% (Yu and Li, 2020). This aspect results from replacing energy products like coal and fossil fuel (Wang et al., 2021d; Yu and Li, 2020) and the high efficiency of WtE technologies (Starostina et al., 2018).

However, although recycling inorganic waste (plastics, paper and cardboard) impacts energy generation, considerable reductions in environmental impacts are achieved (Starostina et al., 2018). Xin et al. (2020) and Leite et al. (2022) mentioned that source separation rates of 60% (plastics, paper and cardboard) might cut GHG emissions by more than 50% (0.0295 tCO_{2eq}) because of avoided emissions with energy generation from fossil fuels. Another factor is related to the electricity production in countries, which has a large part of their renewable electricity matrix. In this case, it would be more environmentally advantageous to replace processes that use fossil fuels as co-processing, such as in the production of heat in the food industry and ovens cement (Coelho and Lange, 2018; Rodrigues and Mondelli, 2021).

Source separation also impacts the economic viability of electricity generation plants in WtE systems. Gu et al. (2021) discovered that the cost has dropped of generating energy from MSW from 480 (an unfeasible condition) to 145 US$ MWh^{-1} with the separation of the non-combustible component and biodegradable waste. However, it must note that source separation, sorting and material diversion of inorganic waste for recycling are expensive compared to thermal processes. Sun et al. (2018), for example, mentioned that up to twice as much revenue when waste is sent directly to incineration with energy recovery compared to that includes segregation/sorting/recycling. In this context, some academics (Bucknall, 2020; Williams and Phillips, 2022) pointed out the possibility that MSW energy usage may not promote material recycling and may, in some cases, hinders the circular economy.

Recycling waste market versus energy market for RDF

As shown in Figure 4, the EU reduced the MSW amount disposed to landfills over the years and has increased recycling rates (organic and inorganic waste) and energy use (Psomopoulos et al., 2022). However, according to Malinauskaite et al. (2017), future trends indicate a progressive decrease in waste delivered for energy generation and a recycling increase. For example, between 2000 and 2018, Italy reduced the amount of waste destined for WtE plants by 29% (Bertanza et al., 2021). Between 2012 and 2020, Denmark, the Netherlands, and Norway reduced the MSW amount destined to WtE by 10, 7 and 8% and increased recycling by 11, 7 and 7%, respectively (Eurostat, 2022). East Asia, on the other hand, continues to utilize a large amount of waste for energy and heat recovery. Countries such as Japan and South Korea send around 50% and 75% of plastic waste for this purpose, whereas 23% and 14% are recycled, respectively (Jang et al., 2020).

The MSW management strategy adopted in these countries generally involves the implementation of material recovery facilities. In these plants occur the separation and processing of MSW recyclable and LHV with the potential to compose RDF and reduce the volume of refuse sent to landfill (Vrancken et al., 2017). In the UK, for example, recycling rates at these plants approach 80%, whereas refuse is sent to RDF production. It must estimate that the country increased RDF exports from zero in 2009 to more than 800 thousand tonnes in 2012 (Malinauskaite et al., 2017). Spain and Portugal also stand out with an annual production of RDF of 112 and 115 thousand tonnes, respectively (Berardi et al., 2020; Malinauskaite et al., 2017).

In contrast to the developed countries, less agreement exists on less expensive and more suitable alternatives for MSW treatment and processing in developing countries (Aleluia and Ferrão, 2017). In Brazil, for example, the National Solid Waste Policy (PNRS) promotes the MSW use as energy through technologies like incineration with energy recovery, so long as its technical, economic and environmental viability is established (Brasil, 2010). However, the public prosecutors forbid this practice, and the National Movement of Waste Pickers vigorously opposes it because it might undermine reuse and recycling efforts (Chaves et al., 2021b).

Moreover, governments still face many difficulties in implementing and developing policies, legislation and strategies aimed at USW management in developing countries, unlike what is observed in the EU (David et al., 2020; Margallo et al., 2019). These aspects reflect in recycling percentages very low, 5% in

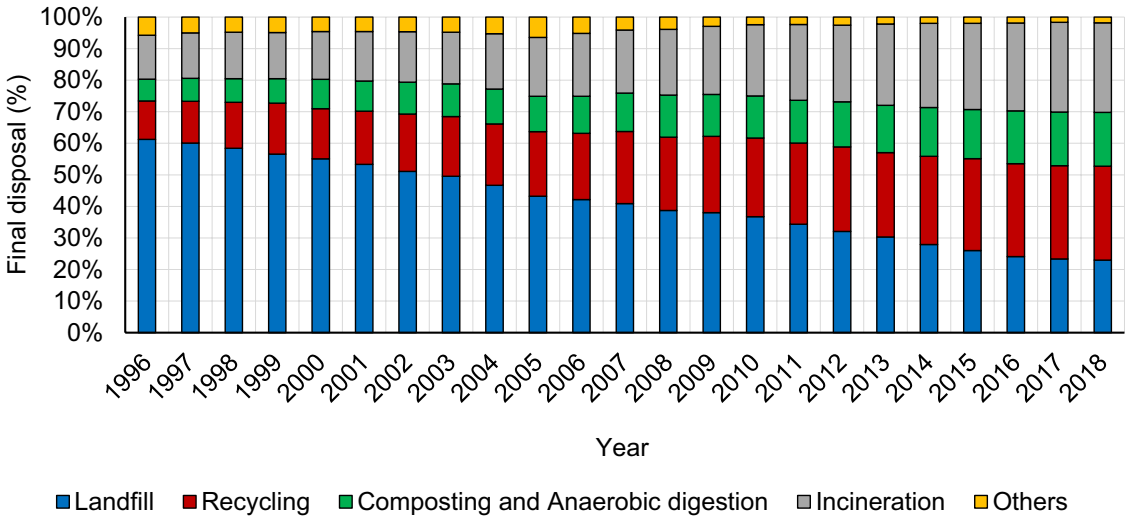

Figure 4. Evolution of treatment alternatives in the EU over the years.
Source: Elaborate from Eurostat (2022).

Latin America, 7% in Sub-Saharan Africa and 5% in South Asia (Kaza et al., 2018). In Brazil, for instance, the National Policy on Solid Waste still presents a lot of uncertainty about the management instruments related to recycling targets (Cetrulo et al., 2018). The reflection of this is that the National Solid Waste Plan (Planares) was only regulated in 2022 (12 years after the enactment of the law), a delay that is reflected in the recycling of recyclable and organic waste of only 0.7% and 0.3%, since 2010 respectively (SNIS, 2023).

Possible causes include lack of information among local inhabitants and uncertainty about which items may be recycled; low spatial coverage of selective collection (Ng and Phan, 2021); lack of adequate infrastructure for waste collection, transport and segregation; poor waste quality for segregation (Jang et al., 2020); weak recycling market; inadequate infrastructure for waste collection, transport and segregation (Dutra et al., 2018; Jang et al., 2020). In addition, aspects related to the fragility and efficiency of sorting (which usually occurs manually in these countries) as fatigue, circulation speed, particle size distribution and large refuse generation, in addition to aspects of the work environment, such as temperature and shed lighting (Vrancken et al., 2017).

These difficulties encountered prevent resources from being recovered to their full potential, which increases the production of mixed/contaminated waste streams and, as a result, refuses (Ng and Phan, 2021). In India, for example, the refuse generation percentage exceeds 33% of MSW sent to sorting facilities (Tyagi et al., 2021). According to Dutra et al. (2018), in Brazil, this percentage can vary between 4% (best performance) and 30% (worst performance) in manual sorting plants. However, the refuse may value as RDF in addition to recyclables selling and generate income for sorting plants (Aleluia and Ferrão, 2017; Ng and Phan, 2021). For example, Suma et al. (2019) and Singhal et al. (2022) evaluated technical elements (MSW production and composition) to suggest potential technologies for India and Thailand, respectively. The results indicated that inorganic (Singhal et al., 2022) and organic (Suma et al., 2019) recycling needs to be implemented alongside the refuse use as RDF. We emphasize, nevertheless, that to deploy the technology, stakeholders must also take economic, environmental and social factors into account (Inglezakis et al., 2018).

Technical, economic, environmental and social assessment of RDF production. The technological, environmental, economic and social viability of various waste treatment solutions, including recycling and RDF production, was assessed by many studies (Table 4).

Among the methods used, the Life Cycle Assessment (LCA), life cycle costing (LCC), multi-criteria decision analysis (MCDA) and system dynamics (SD) stand out. LCA is a method that examines the environmental performance of all MSW handling processes from 'cradle to grave' (Tyagi et al., 2021), whereas LCC assesses economic performance (Braña et al., 2020). These techniques are designed to aid the decision-maker in selecting the optimal management strategy with the least negative environmental impact and expenditure (Hoang and Fogarassy, 2020). MCDA is often used in waste management to assess the sustainability of these systems (Inglezakis et al., 2018). The method allows the application of quantitative and qualitative criteria and cooperation of several stakeholder groups even with contradictory intentions in the indicators determination and the taking of decisions (Hoang and Fogarassy, 2020). SD is a method based on causality and feedback loops that are used to examine and comprehend the behaviour of complex and dynamic systems (Sterman, 2000). It allows an understanding of the future performance of an existing system, considering different scenarios, and also provides decision-makers with a measure of the consequences of their decisions (Chaves et al., 2021b).

Authors such as Chaves et al. (2021a) and Ouda et al. (2017) carried out a technical assessment on the generation of RDF in

Table 4. An overview of studies that examined the viability of recycling and RDF production.

Authors	Viability				Method	Research place
	Technical	Economic	Environmental	Social		
Aleluia and Ferrão (2017)	–	x	–	–	SA	Asia
Joseph and Prasad (2020)	X	x	–	–	MCDA	Pacific Islands
Inglezakis et al. (2018)	X	x	x	x	MCDA	Kazakhstan
Nizami et al. (2017)	X	x	x	–	MM	Saudi Arabia
Juárez-Hernández (2021)	X	x	x	–	MM	Mexico
Lima et al. (2018)	–	–	x	–	LCA	Brazil
Ng and Phan (2021)	X	x			MM	United Kingdom
Ferdan et al. (2018)	–	–	x	–	LCA	Czech Republic
Vinitskaia et al. (2021)	–	–	x	–	LCA	Russia
Silva et al. (2021)	–	–	x	–	LCA	Brazil
Tyagi et al. (2021)	–	x	x	–	LCA	India
Anwar et al. (2018)	X	x	–	–	MM	Egypt
Slomski et al. (2020)	X	x	–	–	MM	Brazil
Chaves et al. (2021b)	X	–	–	–	DS	Brazil
Liikanen et al. (2018)	–	–	x	–	LCA	Brazil
Hoang and Fogarassy (2020)	x	x	x	–	MCDA	Vietnam
Trulli et al. (2018)	–		x	–	MM	Italy
Chaves et al. (2021a)	–	x	x	x	MM	Brazil
Braña et al. (2020)	–	x	x	–	LCA/LCC	Portugal
Bourtsalas et al. (2018)	–	–	x	–	LCA	USA
Ouda et al. (2017)	X	–	–	–	MM	Saudi Arabia
(Talang and Sirivithayapakorn, 2022)	X	x	x	–	MCDA	Thailand
Alam et al. (2022)	X	x	–	–	DS	India
Ak and Braida (2015)	–	x	x	x	MCDA	Turkey

LCA: life cycle assessment; LCC: life cycle costing; MCDA: multi-criteria decision analysis; MM: mathematical models; SA: statistical analysis; SD: system dynamics.

Brazil, Saudi Arabia and India, respectively. Chaves et al. (2021a) studied the effect of policy interventions on the RDF generation in Brazil. According to the authors, the 60% increase in source separation, even combined with the reduction in the rejection rate (to 4%), could generate 200,000 t year^{-1} of recyclable material, 43,000 t year^{-1} of RDF, in addition to reducing about US$ 15.42 million with disposal in landfills. On the other hand, Ouda et al. (2017) assessed three WtE development scenarios: incineration with energy recovery, incineration with material recycling and production of RDF with biomethanization in Saudi Arabia and India. The authors claim that incineration with energy recovery (328 MW), RDF with biomethanization (160 MW) and incineration with material recycling are the options with the highest potential for energy generation (21 MW). However, they demonstrate that it is essential to dynamically analyse economic, social and environmental factors to select the optimal technology.

An economic analysis carried out by Aleluia and Ferrão (2017) observed lower investment costs (CAPEX) in composting plants (21,493 US$ t^{-1}), followed by RDF production (30,056 US$ t^{-1}), anaerobic digestion (34,323 US$ t^{-1}) and incineration with energy recovery (81,880 US$ t^{-1}) for treatment technologies in Asia. Anwar et al. (2018) examined several technical systems for managing MSW in Egypt. They concluded that the system that includes sorting, recycling, composting and RDF production results in a higher net profit. On the other hand, Ng and Phan (2021) contrasted reduction and growth scenarios of refuse. The authors mention that a 1% increase in the refuse fraction (destined for H_2-gasification from the RDF) could generate a revenue of 0.255 million US$ year^{-1}. In comparison, a 1% refuse reduction would increase of 0.027 million US$ year^{-1} in revenue from the sale of recyclable material. The predictive model developed by Alam et al. (2022) identified an increase of around US$ 30 million in revenues (2030) from different treatment centres in India, including RDF plants.

Other studies used the LCA method to assess the environmental performance of scenarios with different technological options (Bourtsalas et al., 2018; Liikanen et al., 2018; Lima et al., 2018; Silva et al., 2021; Uusitalo et al., 2016). Ferdan et al. (2018) found that the scenario with the arrangement consisting of 41% of MSW destined for landfill, 19% for RDF generation and 8% for material recovery could reduce 300 kgCO_2eq t^{-1} in the Czech Republic. According to Vinitskaia et al. (2021), recycling, composting and RDF production would reduce 500 kgCO_2eq t^{-1} MSW in Russia. On the other hand, Bourtsalas et al. (2018) evaluated four scenarios for replacing coal with RDF in cement production. According to the authors, replacing 75% of coal with RDF could reduce GHG emissions by 351.1 kgCO_2eq t^{-1} compared to the baseline scenario (0% RDF).

In Brazil, Lima et al. (2018), Liikanen et al. (2018) and Silva et al. (2021) found that the best option (in terms of reducing

Table 5. Amount of waste received and refuse generated in WPOs in some locations.

Research place	Waste received by WPOs (thousand tonnes year^{-1})	Percentage of the rejects generated in WPOs (%)	Rejects disposal	Authors
Brazil	690.0	20	Landfill and dumping	Pincelli et al. (2021)
Espírito Santo (Brazilian state)	46.0	4–30	Landfill	Dutra et al. (2018)
João Pessoa (Brazilian city)	78.8	95		Forés et al. (2021)
Belo Horizonte (Brazilian city)	11.3	40		Fuss et al. (2021)
Blumenau (Brazilian city)	1.1	31		Moura et al. (2018)
Buenos Aires (Argentine city)	293.3	20		Munain et al. (2021)

WPOs: Waste Picker Organisations.

environmental impacts) is to use RDF in cement production as a substitute for coal compared to electricity generation. According to Liikanen et al. (2018), this occurs because the highest percentage of Brazil's electrical matrix comes from renewable sources (hydroelectric, wind and solar, among others).

Joseph and Prasad (2020), Inglezakis et al. (2018), Braña et al. (2020), Juárez-Hernández (2021) and Talang and Sirivithayapakorn (2022) evaluated the ranking of scenarios with different technological arrangements considering economic and environmental aspects. Joseph and Prasad (2020) concluded that the second-best alternative for the Pacific Islands is a combination of anaerobic digestion, energy production from RDF and materials recycling. Inglezakis et al. (2018) and Juárez-Hernández (2021) indicate composting, generating energy from RDF and recovering materials as the best option for Kazakhstan and Mexico, respectively. Hoang and Fogarassy (2020) and Ak and Braida (2015) pointed to the same conclusion, but the authors evaluated social, in addition to economic and environmental aspects. Braña et al. (2020) mention the recycling of materials combined with anaerobic digestion and the introduction of RDF to Portugal. For Thailand, Talang and Sirivithayapakorn (2022) suggest a combination of recycling, composting and energy recovery from RDF.

Nizami et al. (2017) compared a variety of technologies as anaerobic digestion, RDF, pyrolysis and recycling of materials. They verified that the generation of RDF had the third-best performance concerning the potential of GHG reduction, gross revenue and capital and operating costs. Another study by Tyagi et al. (2021) identified that the RDF introduction for power generation in a MBT plant in India could increase revenues by 266,815 US$ year^{-1} and reduce emissions by 8.36 kgCO_2 t^{-1} of MSW.

Production of RDF and inclusion of waste picker organizations. The European Commission has stated that WtE thermal treatment processes, such as the production of RDF, can play an essential role in the transition to the circular economy, provided that the waste management hierarchy is respected (Malinauskaite et al., 2017). The hierarchy prioritizes non-generation, reuse, recycling, treatment and landfill (Brasil, 2010; Costa and Dias, 2020). In addition, it is also a guiding principle for MSW management in developing countries such as Brazil (Mannarino et al., 2016).

Given that the primary executors of MSW sorting in much of Latin America (Brazil, Uruguay, Argentina, Chile, Bolivia, Peru, Ecuador, Colombia, Venezuela, Panama and Nicaragua), South Africa, Italy, Serbia, India, Bangladesh and Indonesia are the waste pickers of recyclables and reusable materials, organized in Waste Picker Organisations (WPOs) (The Global Alliance of Waste Pickers, 2022), the generation of RDF in these plants (from the refuse) could generate significant benefits (Chaves et al., 2021b). A study realized by Slomski et al. (2020) evaluated the economic potential of household waste in São Paulo, Brazil. The authors concluded that RDF sales (US$ 24 million) would increase revenues from WPO (US$ 269 million) by about 9%. Additionally, these initiatives brought in more than US$ 290 million in additional revenue from the sale of carbon credits. In this regard, the refuse disposed of in landfills can become a resource with a high value. Table 5, for example, presents the amount of rejects generated in WPOs in different locations and sent from landfills. However, most of this refuse is composed of plastic materials (Forés et al., 2021; Fuss et al., 2021; Moura et al., 2018), materials of LHV, which could be used for energy recovery of RDF production.

The increase in waste to be processed and the demand for RDF will require WPOs restructuring. However, WPOs currently face adversities that compromise their productivity, such as problems monitoring operations, organizing human resources management (Conke, 2018) and controlling the material collected and sold; poor infrastructure with small and structurally precarious sheds (Fuss et al., 2021); lack of equipment; limited knowledge about the recycling market; the need for technical/financial support and lack of confidence on the part of companies in these associations (Dutra et al., 2018). To solve some of these problems, Chaves et al. (2021b) suggested the WPO network meeting to carry out the functions assigned to these organizations in the mandatory reverse logistics systems and the RDF production in Brazil, mentioning that political interventions are essential to promote these advances.

Given this, WPO's productivity can be enhanced through some initiatives. Rebehy et al. (2017) indicated the implementation of subsidy policies for equipment acquisition and

technological improvement. The supply of tools/machinery, for example, increases the recycling rate by 2.38 kg h^{-1} worked, the granting of access to credit increases collection by 6.48 kg $worker^{-1}$, the waste pikers institutionalization by 15.96 kg h^{-1} and daycare access by 6.89 kg h^{-1} (Hernandez and Hernandez, 2018). Fuss et al. (2021) suggested expert support to enhance WPO management. Siman et al. (2020) recommend using corporate governance instruments to improve WPO's self-management and organizational and economic efficiency, support structured work as commercial networks, eliminate/reduce identified dysfunctions and other actions.

Future studies possibilities based on the literature

Although many studies have investigated the effects of individual psychology on source separation, there are still many gaps to be filled. The driving forces behind the behaviour of waste source separation, for example, have yet to be discussed, particularly in developing countries (Wang et al., 2021b). This aspect is relevant because developing countries still need more public participation and an understanding of the importance of source separation by the population (Forés et al., 2018; Sukholthaman and Sharp, 2016). In addition, it is necessary to evaluate the social cost internalization effects on individual costs to increase the individual's willingness to source separation (Shen et al., 2019).

Furthermore, many authors recommend aspects yet to be addressed about the effect of public policies on source separation. Meng et al. (2019) advise examining the impact of various policies of source separation to guide the formulation of new policies more comprehensively. Matiiuk and Liobikienė (2021) recommend jointly analysing the implementation of informational, social, and convenience tools. According to Setiawan et al. (2021), a thorough investigation is required to evaluate the mechanisms and circumstances linked to the impact of information publicity on the source separation behaviour of people. These instruments are relevant tools for training and awareness. However, one should also note the delays in the effect of these instruments on source separation (Xu et al., 2018a), the costs of their implementation (Sidique et al., 2010), and the different separation modes' combinations (Fei et al., 2022).

Authors like Panzone et al. (2021) and Ma and Jiang (2022) recommended exploring various economic and behavioural policy possibilities in the source separation of MSW. PAYT plans (Bonelli et al., 2016) and reward strategies (Hettiarachchi et al., 2018; Xu et al., 2018a), for example, might be applied in this situation. On the other hand, the tax collection system could be more effective for source separation since it does not encourage individuals to change their behaviour (Chung and Yeung, 2019). Pivetti et al. (2020) indicated the concept of perceived fairness exploration in supporting social policies and civic engagement. In this context, people will encourage a policy that does not offer personal benefits if it is fair.

The literature also points out several gaps aimed at optimizing selective collection routes and the location of collection points. In this context, new studies should also consider the perishability of biodegradable waste in storage and transport, besides resizing the collection routes to minimize the environmental impacts (Marques et al., 2021; Yang et al., 2021c). Unlike recyclables, the collection of biodegradable waste can cause discomfort to people with the release of odours due to storage for longer periods (Beltrán et al., 2014; Fei et al., 2022). From this perspective, mixed modalities of the selective collection could be considered, with a combination of door-to-door systems and delivery points. Regarding delivery points, it is crucial to assess the environmental impact considering the attitude of residents and the environment around the stations. In addition, environmental impact assessment of changes in the production and composition of waste collected at the stations (Yang et al., 2021c).

Another significant factor to be evaluated is related to the dynamic changes in the MSW composition over time to quantify the impurity presence (ElSaid and Aghezzaf, 2020); the impacts assessment of source separation considering environmental, economic and social aspects (Yu and Li, 2020); assess the impacts of different separation methods and increased recycling rates on comprehensive waste disposal strategies (Xin et al., 2020), such as energy recovery from refuse (Istrate et al., 2021). Furthermore, future studies should evaluate the various technologies combinations for energy generation, considering geographic characteristics, future trends and technical-environmental performance (Sun et al., 2018). These detailed studies are essential to avoid interruptions in the operation of energy plants or unnecessary investments (Altan, 2015; Yilmaz and Abdulvahitoğlu, 2019).

Regarding the refuse use as RDF, Lima et al. (2018), Ng and Phan (2021), Slomski et al. (2020), and Çankaya and Pekey (2020) mentioned that many studies are limited to recovery paths for rejected materials. However, none of these studies included a comprehensive techno-economic and environmental assessment to support the viability and potential of these recovery paths (Sakri et al., 2021). These studies are crucial because it is in cement companies' best interests to determine whether the used RDF is more advantageous than fossil fuels from an economic and environmental standpoint. In addition, it has to recommend the possibility of financial incentives for possible social sustainability and expansion of their demand (Ng and Phan, 2021). In this context, research about social impact should be realized, considering the stakeholders involved (workers, society, consumers and actors in the value chain) (Talang and Sirivithayapakorn, 2022).

Another significant aspect is the evaluation of the interrelationships between the systems involved and their changes over time (Longo et al., 2020). In this context, it assesses waste composition changes triggered by waste management strategies and the associated impact on the RDF use for energy production (Juárez-Hernández, 2021; Ng and Phan, 2021). Another important factor is an analysis of the consequences of the cement industry's (Chaves et al., 2021a) rising need for high-quality alternative fuels (Świechowski et al., 2020). Additionally, assessing the LHV of RDF decreasing because of recycling efforts should also be researched in future studies. In this context, variables related to aspects of MSW management should be

considered, such as classification efficiency, source separation, collecting technique and others (Rezaei et al., 2020; Vershinina et al., 2021).

Future studies can also consider the technical aspects of the RDF production process. To prevent RDF production is outside of specifications, Karpan et al. (2021), for instance, advised precise quantification of each input material and enhanced drying and de-moisture procedures. The RDF moisture reduction is a significant factor in the heating value increase (Białowiec et al., 2017; Infiesta et al., 2019), as well as the removal of inert materials (stones, sand, and construction debris, among others) (Gajewska et al., 2019; Tyagi et al., 2021).

Finally, future research should also assess the impact of Brazilian specificities on RDF logistics networks (Chaves et al., 2021a). Marques et al. (2021) suggested studies of transport costs involved in the logistics network in Brazil to determine the ideal location that optimizes benefits. This factor is crucial to lowering transportation costs and making it possible to install RDF plants (Mohanta and Goel, 2021; Tyagi et al., 2021).

Final considerations

According to the literature, source separation reduces the losses percentage in the recycling process and influences the MSW quality and quantity sent for energy recovery and biological compost production. Source separation, in turn, is induced by internal factors related to individual psychology and external factors related to political instruments. Many studies, mainly in Asian countries, point out that environmental education and advertising are the intervention methods for internal factors such as attitude, SN and control of perceived behaviour. In addition, environmental education and publicity play an essential role in increasing the perceived policy effectiveness of other policy instruments (economic, technical, legal and planning).

The EPR and initiatives to increase selective collection have impacted in quantity and quality of refuse supplied for thermal treatment with energy recovery. EPR implementation, for example, increases recycling rates, enables the destination of non-recyclable waste (refuse) for energy use and reduces their disposal in landfills. The selective collection of biodegradable waste increases the calorific value of the waste sent for thermal treatment, thus increasing energy generation. However, several studies note that the recyclables' selective collection decreases the potential for gross energy recovery since materials with a LHV are diverted (landfill) for recycling (paper, plastic and others).

The literature also points to future trends towards a gradual reduction of waste sent for energy generation and a recycling increase in Europe. Although developing countries, such as Brazil, have resistance lot about the implementation of thermal treatments with energy recovery, even with low recycling rates and a large flow of improperly discarded and disposed of in a landfill. However, the utilization of this significant quantity of refuse produced as RDF in developing countries could reduce inappropriate disposal, since this refuse would be valued for energy generation in thermal technologies. Additionally, it may decrease the quantity of refuse dumped in landfills, lengthen the life of landfills and benefit WPOs in economic and social terms. In this context, many studies mention the technical, economic, environmental and social feasibility of using these wastes as RDF (mainly in developing countries), even when combined with other forms of treatment such as waste recycling, composting and anaerobic digestion.

It should be noted that the systematic review revealed certain additional gaps that need to be investigated in future studies, as described below.

- For the proper direction of public policies, it is critical to identify internal factors that promote source separation in some regions. This point is crucial, particularly in developing countries, where there is less source separation. To our best knowledge, just a study was conducted in Latin American countries that have significant differences (economic, social, cultural and others) from Asia countries.
- Policy instruments are also relevant driving forces to encourage source separation, but few studies have comprehensively evaluated the implementation of educational, economic and technical instruments. Aspects related to advertising and education, rewards for recycling and expansion of the selective collection, among others, might be considered in this context.
- The EPR is a crucial tool for promoting higher recycling rates. However, future studies should be assessed EPR implementation effects on the quantity and quality of refuse sent for energy use in developing countries.
- Future studies involving RDF use for energy generation should consider the long-term effects of implementing policies to encourage the recycling of inorganic and organic waste on the quantity and quality of refuse. This assessment is crucial to avoid interruption in the operation of energy recovery plants or unnecessary investments.
- Only two studies included the social dimension in the evaluation of RDF production. However, only one research focused specifically on the production of RDF. As a result, future studies on the energy use of the RDF should also consider the social dimension, especially the manual sorting units of the WPOs.

Future research should also consider the complexity of implementing public policies by the municipalities, administrative microregions and national authorities in developing countries. These stakeholders often confront several issues that jeopardise the efficacy of public policies, including a lack of resources – both financial and human – for planning and execution, as well as shortcomings in the regulatory institutions' use of punitive measures. In addition, the implementation of programmes like environmental education and reward and collection schemes may be impacted by the fact that a significant portion of the population still has poor levels of education.

Regarding the refuse use as RDF, consideration should be given mainly to replacing fossil fuels to effectively reduce GHG emissions. In Brazil, for example, a large part of the electricity matrix comes from renewable sources such as wind, solar and hydroelectricity, which limits the possible environmental benefits of waste energy strategies. However, using RDF to partially replace traditional fossil fuels like coal in the cement industry, for instance, will significantly lower GHG emissions.

Co-processing with RDF combines circular economy principles, adheres to the waste management hierarchy and gives refuse that would otherwise be disposed of in a landfill additional value. Therefore, efforts for improving the governance structure and regulations must be directed in developing countries to encourage and ensure the production of RDF. It is important to consider the technical requirements for RDF in these countries as well as the impact of long-term economic incentives to encourage the construction of RDF facilities.

Finally, this article aims to contribute to the literature by identifying gaps that need to be filled in future studies on the use of refuse as RDF and on the political instruments implemented to divert MSW from landfill to achieve appropriate governance of MSW in developing countries.

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