PRODUCTION AND COPROCESSING OF REFUSE-DERIVED FUEL: A REVIEW

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ABSTRACT

Objective: To review and synthesize the existing knowledge on the production and co-processing of waste-derived fuel, with a focus on the reality of solid waste management in Brazil.

Method: This is a narrative review of the literature based on scientific articles available in bibliographic databases such as Scopus and ScienceDirect, as well as technical documents prepared by Brazilian governmental agencies.

Results and Conclusion: Studies conducted in the country show that scenarios involving sanitary landfills, along with recycling and composting, have proven more viable in the transition to eco-efficiency. On the other hand, the energy potential of waste-derived fuel produced from urban solid waste has been explored with positive results in replacing fossil fuels and reducing CO₂ emissions. However, it is necessary to ensure strict control of environmental impacts and to carry out comprehensive studies to assess the viability of co-processing in different regions of the country.

Research Implications: The research contributes to the existing literature, emphasizing the performance of waste treatment techniques that can bring significant environmental gains to a country that still faces major problems related to solid waste management.

Keywords: Fuel, Waste, Emissions, Environmental Impacts.

PRODUÇÃO E COPROCESSAMENTO DE CDR: UMA REVISÃO DA LITERATURA

RESUMO

Objetivo: Revisar e sintetizar o conhecimento existente sobre a produção e coprocessamento de combustível derivado de resíduo, com um foco na realidade da gestão de resíduos sólidos no Brasil.

Método: Trata-se de uma revisão narrativa da literatura com base em artigos científicos disponibilizados em bases de dados bibliográficas como a Scopus e ScienceDirect, além de documentos técnicos elaborados pelos órgãos governamentais brasileiros.

Resultados e conclusão: Estudos realizados no país demonstram que cenários que envolvem aterros sanitários, juntamente com reciclagem e compostagem, têm se mostrado mais viáveis na transição para a ecoeficiência. Por outro lado, o potencial energético do combustível derivado de resíduo produzido a partir de resíduos sólidos urbanos tem sido explorado com resultados positivos na substituição de combustíveis fósseis e na redução de emissões de CO₂. No entanto, é necessário garantir um controle rigoroso dos impactos ambientais e realizar estudos abrangentes para avaliar a viabilidade do coprocessamento em diferentes regiões do país.

Implicações da Pesquisa: A pesquisa contribui para a literatura existente, com ênfase no desempenho de técnica de tratamento de resíduos que podem trazer ganhos ambientais significativos para o país que ainda enfrenta grandes problemas relacionados à gestão de resíduos sólidos.

Palavras-chave: Combustível, Resíduo, Emissões, Impactos Ambientais.

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1 INTRODUCTION

The demand for cement in many developing countries increased rapidly due to the continued expansion of the construction industry, driven by rapid urbanization. Cement is among the most used and produced materials in civil construction (Ige, 2022). In 2010, China remained the world's largest producer and consumer of cement, while Brazil ranked 5th in the same year with a total production of 58 million tons (Cimento.org, 2022). However, the cement industry is a major contributor to global carbon dioxide (CO₂) emissions. The total anthropogenic CO₂ emitted by the cement industry corresponds to about 7% of the total emitted into the atmosphere (Chen, 2016). Emissions come from the calcination stages, kiln firing and other plant operations, accounting for 60%, 30% and 10% of CO₂ emissions, respectively (Hashem et al., 2019). Other substances emitted in the cement production process are carbon monoxide (CO), water vapor (H₂O), sulfur dioxide (SO₂), nitrogen oxide (NOₓ), hydrochloric acid (HCl), hydrofluoric acid (HF), dioxins, particulate matter and metals heavy (Moretti et al., 2017).

In general, the production of one ton of Portland cement produces around one ton of greenhouse gases (GHG), and for each ton of Portland cement clinker produced, there is an emission of 1.5 to 10 kg of NOx (Mohamad-GHGet al., 2021).

Some timely strategies for reducing environmental impacts associated with cement manufacturing are co-processing (Fořt et al., 2021), a term used to describe the introduction of alternative fuels and raw materials into the process, replacing conventional materials (Guimarães, 2018). Alternative fuels used in co-processing include a wide variety of materials, among which waste derived fuel - CDR. (Chaves et al., 2021a)

Alternative fuels have a low nitrogen content (0.3% to 0.5%), which implies a reduction in emissions of environmental pollutants (Sobik-szoltysek et al., 2019). In addition, most residues are slightly alkaline, which is favorable for the removal of acid gases generated during kiln operation (Nidheesh et al., 2019). High energy consumption indices and unstable prices of fossil fuels have also contributed to the implementation of co-processing (Guimarães et al., 2018).

It should be noted that urban solid waste with potential for co-processing is still under-exploited in Brazil, which contrasts with the fact that waste disposal is one of the biggest challenges of the country today. Of the total waste accumulated in 2016, only 58.4% was disposed of in landfills. In the same year greenhouse gas (GHG) emissions exceeded 90 million tons of CO₂ where 57.5% of these emissions came from the final disposal of waste. These data demonstrate that final waste disposal methods do not yet meet the efforts of the National Solid Waste Policy (NSRP) which aims to eliminate the landfills and seek suitable alternatives for the treatment of municipal solid waste (Silva, et al., 2019).

It should also be stressed that Brazil has targets for the reduction of greenhouse gases (GHG), as described in the Paris Agreement. To this end, the Brazilian Portland Cement Association has launched a Technological Roadmap to promote the use of energy from urban solid waste (MSW) and sludge waste to achieve 55% fuel replacement in the sector by 2050 in Brazil (Chaves et al., 2021b). It is expected that with this new profile of fuels used in the sector, emissions from fossil fuels in cement production can be reduced by up to 40% (Chaves et al., 2021b).
Thus, the present study aims to review and synthesize the existing knowledge about CDR, production and co-processing in the cement industry, with a specific focus on the reality of solid waste management in Brazil. The literature review aims to understand the technical, environmental, regulatory and sustainability aspects related to these processes.

2 SOLID URBAN WASTE MANAGEMENT IN BRAZIL

In 2020, due to the direct influence of the COVID 19 pandemic, there was an increase in the generation of MSW in Brazil, reaching 82.5 million tons (in 2019, 79 million tons of waste were generated). As a result, each Brazilian generated an average of 1.07 kg of waste per day. The region with the highest waste generation was the Southeast with 460 kg/hab/year, about 113 thousand tons, which corresponds to approximately 50% of the waste generated in Brazil, as shown in Figure 1 (ABELPRE, 2022b).

![Figure 1: Participation of regions in MSW generation](Source: ABELPRE, 2022b)

Most of the collected MSWs went into landfill disposal, with 46 million tons shipped to these locations in 2020. On the other hand, areas of inadequate disposal, such as landfills and controlled landfills, are still in operation in the country and received almost 40% of the total waste collected, corresponding to approximately 30.2 million tons (ABELPRE, 2022b). It should be noted that there is still a great limitation of available data that allow an estimate of the distribution (in%) of each source and sink of the waste streams of some Brazilian municipalities (Chaves et al., 2021a). Figure 2 shows the percentage of municipalities that destined their waste for controlled landfills and landfills in the years 2010 to 2019 (Brazil, 2022).

In 2019, the country also showed a deficit in the coverage of regular collection services, equivalent to 92% coverage (Costa & Ferreira, 2020). In 2020, the number of municipalities that presented some initiative of selective collection was 4,145, representing 74.4% of the total municipalities of the country (ABELPRE, 2022b). The most commonly used selective collection method is voluntary and performed through delivery points, similar to green points and door-to-door. The collection is carried out by service providers (private or public) or by cooperatives of waste pickers (campos et al., 2021). Waste pickers are responsible for up to 90% of the collection of recyclables in the country (Lima et al., 2018). According to (Chaves et al., 2021a) in Brazil recycling has only worked for materials with high market values such as aluminum and paper. For other materials such as glass and plastic, recycling rates are still insignificant and very susceptible to market variation. Figure 3 shows the mean gravimetric...
composition of Brazilian urban solid waste. The most expressive values correspond to organic matter content 45.3%, plastic 16.8% and waste 15.5% (Brazil, 2022).

![Graph showing the percentage of Brazilian municipalities that dispose of municipal solid waste in landfills and controlled landfills/landfills.](source)

**Figure 2:** Percentage of Brazilian municipalities that dispose of municipal solid waste in landfills and controlled landfills/landfills

**Source:** Brazil, 2022.

In this context it should be noted that in Brazil the National Policy of Solid Waste (PNRS - Law No. 12.305/2010) established that landfills should be closed by 2014. However, by 2017, half of the 5,570 Brazilian municipalities did not have an integrated waste management plan (Costa & Ferreira, 2020). When considering maintaining the current scenario, it would take 55 years for controlled landfills and landfills to be closed in Brazil (ABELPRE, 2022a). The deadline was extended in 2015 and in 2020 by the new sanitation regulatory framework (Law No. 14,026) that established 2020 to 2024 as deadlines for closing the landfills, depending on the size of the municipalities and the development of waste management plans (Morita et al., 2021). The closure of landfills is linked to the Sustainable Development Goals (SDGs), besides highlighting the urgency of coordinated responses to mitigate the negative impacts of landfills on global health and the environment (Morita et al., 2021).

![Graph showing the estimate of the mean gravimetric composition of solid urban waste collected in Brazil.](source)

**Figure 3:** Estimate of the mean gravimetric composition of solid urban waste collected in Brazil

**Source:** Brazil, 2022.

These national figures indicate lost environmental, social and economic opportunities and contrast with the fact that Brazil has a comprehensive National Policy on Solid Waste (Santos et al., 2019). Thus, it is observed that there is a physical and structural distance between Brazilian public policies related to urban solid waste management (RSU) and its actual implementation (Costa & Ferreira, 2020).
Through the concept of shared responsibility for the product during its life cycle, PNRS also emphasizes the need for various segments of society (i.e. government, private enterprise, waste pickers) to work together in the proper management of solid waste (Oliveira & Morais, 2021). However, it should be noted that in Brazil the current waste management is almost entirely done by the government. Direct public administration is responsible for 94% of urban cleaning and management activities. However, this scenario may change with the regulatory framework of sanitation (Campos, 2021).

The PNRS lacks comprehensive quantitative targets and transfers responsibility for achieving its objectives to municipal authorities (Maiello et al., 2017). Municipalities can manage waste independently or through consortia between neighboring or nearby cities, they can also hire private companies to carry out waste collection and disposal (Chaves et al., 2021a) however, the consortium management in Brazil is still incipient (Brazil, 2022).

The main reasons that hinder the improvement of the environmental performance of MSW systems in Brazilian municipalities and the achievement of the legislative targets for MSW recovery are the economic limitations, inadequate access to technology and technical training of professionals (Ibáñez-forés et al., 2021). Government, especially at the national and local level, has been identified by some authors as the main reason for the failure of the implementation of the PNRS so far (Lima et al., 2019).

Although PNRS prioritizes reuse, recycling, composting, recovery and energy use, national data indicate that these practices are currently weak. Only 1.9% of Brazilian municipalities have composting plants (Lima et al., 2018). In 2018 the organic fraction corresponded to 37 million tons, but only 127,498 tons were recovered in the composting units, the rest of the organic matter was discarded inappropriately in landfills and dumps (Brazil, 2022). There are also few initiatives of anaerobic digestion projects in the country, especially the power plants installed in the cities Bertioga (São Paulo) and Rio de Janeiro. In 2018 Brazil captured 4.2 billion Nm³ of biogas. If all the organic matter generated that year had been destined for the recovery of biomethane, the country's potential could supply up to 49 million homes (Brazil, 2022).

There is still no activity in the country to burn MSW for electricity generation, with units in the deployment phase in the states of São Paulo and Rio de Janeiro (Brazil, 2022). Therefore, the incineration in the country is still limited to hospital waste, equipment that contains polychlorinated bifelines. Machado (2015) highlights the incinerators of large industries as part of its policy of solid waste reduction and energy cogeneration. These companies are responsible for the incineration of 80,750t/year with an incineration capacity ranging from 7.5 to 50t/day.

According to Lima et al. (2018) the production and use of CDR. in Brazil for the manufacture of cement show better results than its use for electricity generation. Furthermore, this technology is not much stimulated in Brazil, since the country supplies about 45% of its domestic supply of energy and about 83% of its electrical matrix of renewable sources. However, Brazil is improving its legislation for the development of energy recovery from waste.

In 2019, Inter-ministerial Order No. 274 of 30 April 2019 was enacted that deals with the regulation of energy recovery from MSW according to the PNRS, as well as Decree No. 10.117 of 19 November 2019, which describes the qualification of projects for expansion of energy recovery capacity under the Investment Partnership Program for projects that meet technical and environmental requirements. In addition, there is a technical standard developed by the Brazilian Association of Technical Standards (ABNT, 2020) determining the requirements for the MSW to be used for energy purposes (Chaves et al., 2021a).
3 WASTE-DERIVED FUEL (CDR.)

CDR. is obtained from municipal, commercial or industrial solid waste after a treatment to segregate high calorific value material, minimizing environmental risk and lowering moisture content (Chaves, 2021b). In addition to the term CDR., the term Solid Recovered Fuel (SRF) (established in Europe) can be found in the literature. SRF and CDR. are both fuels recovered from waste from the mechanical and biological treatment process (MBT), however, they have heat capacity and other properties that are considerably different, which is mainly related to the process configuration (Casado et al., 2016). The SRF is therefore subject to strict European quality standards. The term CDR. is designated for the process by-product, which does not meet any particular standard composition or specification (Samolada & Zabaniotou, 2014).

CDR. is produced in Mechanical Treatment Plants (MBT) or Mechanical and Biological Treatment (MBT) (Násner et al. 2017; Nasrullah et al. 2014; Ionescu et al. MBT is a generic term used to describe different waste treatment process configurations, leading to the production of materials with variable properties (Samolada & Zabaniotou, 2014).

The advantages of MBT include diversion of biodegradable solid waste from the landfill, extraction of recyclable materials by mechanical sorting (ferrous and non-ferrous materials), stabilization of the organic part before final disposal, through the production of compost, or biogas (depending on the biological treatment method used), and generation of (CDR.) (NG et al. 2021; Russo & Verda 2020). The (TM) facilities do not include any biological phase (Rigamonti et al., 2019). On the other hand, the complexity of mechanical treatment determines the degree of sophistication of BMR. (Passamani et al., 2016).

It should be noted that the composition of the CDR. depends on its source of material and the technology involved in its production (Chaves et al., 2021a). Second (Di Ionardo et al., 2016) regardless of the classification criteria used, the characteristics and quality of the CDR. should be considered as site-specific. In particular, they depend on the MSW management strategies adopted in the area, including the type and percentage of selective collection at source. Thus, in addition to the legal requirements, additional specifications are generally set forth in the contract between the supplier and the CDR. user (Sarc & Lorber, 2013).

The literature contains some studies on the production and use of CDR. as a process for the treatment of urban solid waste in Brazil. Infiesta (2019) presented the project for the construction of a CDR. production unit with the capacity to process 55 tons/day of MSW with a moisture content of up to 50% by weight in the city of Boa Esperança located in the State of Minas Gerais (Brazil). The values for gross calorific value (HHV) and net calorific value (LHV) of the CDR. have been calculated and are in line with the values presented in the scientific literature.

Neto et al. (2021) analyzed the socioeconomic impacts of the implementation of a CDR. production unit in the metropolitan region of São Paulo. The proposed model indicated in addition to environmental benefits with reductions in local energy demand (-0.31%) and carbon emissions (-3.40%) there would be an increase in GDP (+0.21%) and formal jobs (+0.08%) when recyclables are introduced.

Chaves (2021b) presented a reverse logistics network for CDR. production in the state of Espírito Santo, Brazil. This study considered scenarios based on the estimated availability of residues for CDR. production up to 2040. The amount of CO₂ emitted by the reverse logistics network proposed in the baseline and additional demand scenarios was related to the amount of non-recycled waste used for the production of CDR., the fuel supply of waste treatment plants and the substitution of fossil fuels in cement production. The results showed a reduction in greenhouse gas emissions ranging from 2,217.04 tons in 2024, to 15% fuel replacement in the base scenario, to 11,208.69 tons in 2040, to 50% fuel replacement in the additional demand
scenario. Despite the higher cost of the additional demand, this scenario results in less waste discarded in landfills, which contributes to the extension of the life cycle of landfills and a greater reduction of greenhouse gas emissions. Other studies analyzed the comparison of the production of CDR. from MSW (CDRU) with different scenarios for the treatment of urban solid waste in Brazil.

Regarding the analysis of environmental impacts, the vast majority of authors performed Life Cycle Analysis (LCA). LCA is a method to assess the environmental effects related to a product or process, from the raw material acquisition to final disposal, i.e. throughout its life cycle (Coelho & Lange, 2018).

Liikanen et al. (2018) analyzed the management of MSW in different scenarios for the city of São Paulo. The results of the work indicated that the impacts can be effectively diminished with the anaerobic digestion of organic waste separated at the source and waste processed in the mechanical and biological treatment plant, provided that the CDR. is used in the production of cement.

Coelho and Lange (2018) investigated eight waste management scenarios for the city of Rio de Janeiro in Brazil through ACV. All seven hypothetical scenarios have been defined to meet the following prescriptions: reduce recyclables and organic waste sent to landfills by 50% and 55% respectively. The best LCA performances were obtained in scenarios with high selective collection rates, highlighting the scenario based on recyclable recovery and anaerobic digestion.

Paes et al. (2020) assessed different MSW management scenarios in Brazil to determine the best transition to eco-efficiency compared to the current system. The most advanced technologies, such as mechanical and biological treatment and incineration, represented scenarios with better environmental performance (with reductions of 76% and 96%), but not of transition to eco-efficiency, due to the high costs (with an increase of up to 196%) in the Brazilian context. The scenarios involving the use of landfills, coupled with the reuse objectives via recycling and composting, showed lower emission reductions (up to 83%), but also lower increases in operating and investment costs (up to 70% for more populous municipalities and up to 97% for municipalities with lower population), thus showing better results in the transition to eco-efficiency.

Ibáñez-forés et al. (2021) studied fourteen eco-efficient alternatives for solid waste management in the city of João Pessoa. The proposal selected was based on the implementation of a biological and composting mechanical facility capable of handling up to 50% of the mixed municipal solid waste collected by 2023 with a material recovery efficiency of 30%.

Fuss et al. (2020) studied solid waste management scenarios in the city of Belo Horizonte encompassing different conditions of operation of waste pickers and MBT systems. The results show that an integrated commitment by local society can reduce landfills by 70% and global warming emissions by a quarter.

Silva et al. (2021) analyzed the application of life cycle assessment as a basis for better management of MSW in Brasilia, the capital of Brazil. This study compared four MSW management scenarios, the baseline scenario which is the current scenario characterized by sending the waste to the landfill and the other three scenarios are characterized as an expansion of the current practice, incorporating the production of CDR. Compared to the current scenario, all the proposed scenarios resulted in an increase in total emissions of CO₂, CH₄ and N₂ of CO₂. However, avoided GHG emissions by replacing coke in clinker production positively offset the global warming potential.
4 THE FEASIBILITY OF COPROCESSING CDR. IN THE CEMENT INDUSTRY

Co-processing is the use of waste to replace natural mineral resources or fossil fuels in industrial processes. Generally, waste performance depends on its ability to influence the reactivity of the fuel mixture and to reduce the formation of potentially harmful emissions, especially (NOx), (SO$_2$) particulate matter and dibenzo-p-dioxins and dibenzofurans (PCDD/Fs) (Asamany et al., 2017).

In the case of co-processing in cement industries, the ash from the waste is incorporated directly into the product, thus the mixture of raw flour is adapted according to the characteristics of the alternative fuels that will be used (Viczek et al., 2020).

However, there are minimum specifications for these waste materials to be co-processed in the cement industry, of which it can stand out: low alkali, sulfur and chloride content; high heat capacity; minimum water content and organic content; absence of volatile metals such as lead, thallium, mercury, selenium, cadmium and absence of some materials affecting the quality of clinker such as phosphate, chromium, chloride and alkali (Nidheesh et al., 2019). The presence of certain compounds such as chlorine, sulfides and sodium and potassium chlorides causes operational problems, since these compounds volatilize and condense at milder temperatures, and may encrumb into the oven walls, making necessary changes in the process and stops for maintenance (Sobik-szoltysek & Wystalska, 2019).

It was identified that there is a limitation in the number of studies available in the literature regarding the analysis of the viability of CDR. co-processing, taking as a case study the Brazilian industry. Most national papers are based on the co-processing of tires, biomass or industrial waste and published at congress or event annals.

Meystre (2016) analyzed the technical, economic and environmental feasibility of CDRU co-processing in the cement industry. According to the authors, it is possible to replace conventional fuel used in the cement kiln calciner with CDR. by up to 20%, without it posing significant environmental risks in the emission of pollutant gases during combustion.

Piaia (2021) estimated the theoretical net calorific value (NCV) and avoided air emissions of a blend of municipal solid waste for use as fuel derived from municipal waste (UDF) in Brazilian industry. For the three scenarios of replacing the main conventional fuels by UDFs, the sector that showed the greatest reductions in emissions of tons of CO$_2$ equivalent was the cement works, with the possibility of a reduction of up to 64.21%.

However, several international studies have investigated the feasibility of using CDR. as an alternative fuel for cement production. Reza et al. (2013) investigated the environmental and economic viability of the production of CDRU as a partial substitute for coal. Through the LCA, the authors concluded that there are environmental benefits in terms of reducing greenhouse gas emissions, acidification, pollution, nitrification, potential carcinogenic risk and cost reduction for landfills. The use of CDR. as a secondary fuel in cement manufacturing allows a reduction of ± 3.8 tons of CO$_2$-eq per ton of CDR. use compared to conventional fossil fuel (coal) use, and reduction of 863 kg of CO$_2$-eq per ton of clinker produced, based on the estimated composition of MSW in the year 2015.

Rahman et al. (2014) simulated the operating conditions of a preheating tower, and verified the effects of using alternative fuels (tires, meat and bone meal and CDR.) for cement production compared to using coal. The results presented showed that all three alternative fuels are capable of reducing the required energy, and CO$_2$ emissions. The tire can be used (instead of coal) up to 25%, while air-dried CDR. and meat/bone meal can be used up to 15% and 5% respectively, to gain some advantage over using 100% coal.

Güereca et al. (2015) developed the LCA considering two fuel use scenarios: 1) 100% petroleum coke 2) 20% CDR. and 80% petroleum coke. The results indicated that the co-processing scenario had a lower environmental impact than using only petroleum coke as fuel.
for all categories, corresponding to a reduction of 4% in the global warming potential, 10% in photochemical oxidation, 15% in abiotic depletion, 18% in ozone depletion, 30% in acidification, 38% in terrestrial toxicity and 52% in eutrophication.

Georgiopoulou and Lyberatos et al. (2018) conducted the LCA of cement co-processing using alternative fuels, considering seven different scenarios involving the use of CDR (waste-derived fuel), TDF (tire-derived fuel) and BS (organic sludge) as partial substitutes for coal and petroleum coke. The replacement of conventional fuels by alternative fuels was limited to 10% of the net calorific value to meet the thermal needs of the furnace operation. Comparing the scenarios, it appears that alternative fuels reduce the environmental impacts of all the categories considered. The study also indicates that the use of CDR has an advantage when compared to other alternative fuels.

Bourtsala et al. (2018) conducted the (LCA) in four different scenarios to determine carbon dioxide emissions with total and partial substitution of coal for CDR. in the cement production process: 1) 75% of thermal energy comes from CDR. and 25% from coal; 2) 50% of energy is derived from CDR. and 50% from coal; 3) 25% of energy comes from CDR. and 75% from coal; 4) 100% of energy comes from coal. The results indicate that the use of around 17.7 million tons of CDR. from plastic and paper in the cement industry could prevent the emission of around 53 million tons of CO$_2$-eq. The study also found that the use of waste in cement production does not affect factory emissions or product quality. The concentration of mercury and dioxin was below specification.

El-Salamony et al. (2020) analyzed the co-processing of a mixture of rice husk and fuel derived from CDR. residue as substitutes for mineral coal. The use of the mixture in different proportions had no impact on the main operational variables associated with the production of clinker, and the addition of the mixture (5%) reduced the consumption of electrical energy by 13%. In addition, the addition of this alternative fuel decreased the NOx emission concentration, although the amount of SOx gas was not affected, at the calcination temperature tested. The authors further report that the use of this residue is ecologically safe for cement kilns, as the temperature of precalciners is high (> 950 °C) and significantly exceeds the temperatures necessary for the complete incineration of high molecular weight hydrocarbons and the dechlorination of furans and dioxins.

Karpan et al. (2021) produced high heat capacity CDR. 18,652 kJ/kg from five types of hazardous mixed industrial waste and three types of biomass, and analyzed the feasibility of its use as a fuel for cement kilns. The substitution of 5 ton/hour and 8 ton/hour of CDR. in coal resulted in the emission of 356 mg/Nm$^3$ and 301 mg/Nm$^3$ of NOx, respectively, values below the country's regulatory limit. The emission of heavy metals was also within the specifications. The use of CDR has led to a reduction of approximately 2.25 kg of CO$_2$ per kg of cement compared to coal. In general, replacing 15% CDR. for coal at a feed rate of 5 tons per hour in cement production did not cause any problems in the quality of the existing cement production process.

Some authors have specifically studied emissions of persistent organic pollutants and/or heavy metals during the co-processing of waste. Jin et al. (2018) investigated the characteristics and variations of chlorinated polycyclic aromatic hydrocarbons and Cl/Br-HPAs bromates from the co-processing of four cement kilns operating with solid residues such as MSW, sewage sludge, MSW ash and carbides. Cl/Br-HPAs distributions varied with the types of co-processed solid residues, indicating the important influence of the composition of the raw material on congener distributions. Calculations of net emissions of Cl/Br-HPAs within cement kiln systems suggested efficient destruction (87.6% and 98.8%) of Cl/Br-HPAs by cement kilns.

Yang et al. (2019) investigated the levels, profiles and distributions of polybrominated dibenzo-p-dioxins and dibenzofurans (PBDD/Fs) from a cement kiln by co-processing solid waste. The concentration of (PBDD/Fs) in the raw materials was much higher than in particle
samples from different process steps in the cement kiln. The high efficiency of destruction of (PBDD/Fs) in the furnace was verified, since the concentrations of these substances in clinker were 1.40% of the concentrations in the raw materials.

Arfala et al. (2018) Evaluated the emission of heavy metals Hg, Cd, Tl, Co, Sb, As, Pb, Sn, Se, Te, Cr, Cu, Mn, Ni, V and Zn in cement kilns operated with petroleum coke and CDR. Emissions of heavy metals have always remained below the limit values of the National Regulation, including mercury.

5 THE POTENTIAL FOR CO-PROCESSING IN THE BRAZILIAN CEMENT INDUSTRY

The Brazilian cement industry is made up of 24 industrial groups that bring together a total of 100 production units. Of the integrated factories (with rotary kilns for the production of clinker) 37 are licensed for the co-processing of waste, which represents about 70% of the installed capacity in Brazil (Chaves, 2021b). The Brazilian cement industry also has a modern and efficient industrial park, where over 99% of the industrial park operates with a process via drought. The sector is expected to reach thermal consumption values in the order of 3.2 GJ/t clinker and electrical 90 kWh/t cement by 2050 (MME, 2020).

Among the factors considered as triggering the delay in the co-processing of waste in Brazil is the non-compliance with local and federal legislation leading to the restriction of the disposal in landfills or dedicated incineration; the non-compliance with the waste management hierarchy established by PNRS (which prioritizes energy recovery over disposal in landfills); and the difficulty of establishing long-term contracts for the supply of municipal waste with public agents (Visedo & Pecchio, 2019).

The waste most used by Brazilian industry for this purpose so far has been unserviceable tires, hazardous industrial waste, non-hazardous industrial waste and charcoal waste. However, the most promising alternative fuel within Brazilian industry in the medium and long term is the CDRU (Visedo & Pecchio, 2019).

According to ABREN (2022) there are currently four plants in Brazil installed and sending thousands of tons of CDRU, to be co-processed in cement factories. Over the next few decades, the country will have to expand its capacity for producing CDR to attend, besides the cement industry, to other processes, such as the generation of electricity and steam, thus requiring 17 million tons of waste for preparing CDRUs.

From this perspective, the cement industry, through the Brazilian Association of Cement Portland (ABCP) and the National Union of Cement Industry (SNIC), joined entities in the sector of waste, public cleaning and gas, for the creation of the Brazilian Front for Energy Recovery of Waste (FBRER), which had as an initiative to promote with the Ministry of Environment (MMA), under the Zero Garbage Management program, the technical cooperation agreement, aiming to create a favorable business environment for investments in the sector, thus contributing to the closure of all waste dumps in the country by 2024, as established in the Legal Landmark of Sanitation (Visedo & Pseudo ecchio, 2019). This agreement led to the development of the Atlas of Energy Recovery of Solid Waste, a tool that can be used to identify the Brazilian regions with the greatest potential for investments in energy recovery of solid waste (FEBRER, 2021).

According to the Atlas of Energy Recovery 149380.8 t/day of waste are generated, of which only 14129.15 t/day undergoes treatment for energy recovery, while 33674.72 t/day is sent to controlled landfills or landfills, this data is presented in Figure 4. The atlas also contains 9 co-processing plants located in the states of Tocantins, Sergipe, Pará, Ceará, Minas Gerais, Mato Grosso do Sul and Rondônia, with a total co-processing potential of 895.87 t/day and an
energy recovery capacity of 170.5 mW (SINIR, 2022). It should be noted that, 26 states (96.03%) and 2492 municipalities (44.74%) were SINIR declarants in 2020 (SINIR, 2022).

In the literature, there are few studies that address the analysis of the potential for co-processing of CDR. in Brazil. Torres and Lange (2022) analyzed the thermal potential of waste substitution in the Brazilian cement industry considering five hypothetical scenarios. The authors considered the installed capacity of 55.4 million tons of cement per year, the thermal consumption of 2,272 MJ·kg\(^{-1}\) and the thermal substitution ratio of 17%, obtaining the total thermal demand of \(2.14\times10^{10}\) MJ·year, which can be supplied by CDR. from RSU. For the scenario where we would have solid urban waste in natura the consumption potential would be 1,765,000 ton/year of MSW. According to Meystre (2016), according to the analysis of the data on the generation of MSW in Brazil and the energy demand for cement plants, and not counting the material that is already being recycled, there is the possibility of absorbing a thermal energy of 88.5 billion MJ/year, being sufficient to meet the demand of cement plants (40 billion MJ/year) if they replace 20% of their conventional fuel with the alternative CDR.

**Figure 4:** Amount of residue per treatment method


In this way, the data indicates that the co-processing of CDR. in the cement industry emerges as a sustainable and viable alternative for waste management in Brazil. However, it is essential that environmental impacts are rigorously controlled and mitigated to ensure the effectiveness of this practice. In addition, comprehensive technical, economic, environmental and social feasibility studies need to be conducted to evaluate the deployment of CDR. production units in other Brazilian cities. These analyzes are fundamental for guaranteeing the efficiency and adequacy of this approach in the different regions of the country.

6 CONCLUSION

In the light of the data presented, the urgent need to improve the management of solid urban waste in Brazil becomes evident. Although the country has a comprehensive National Solid Waste Policy, effective implementation has been challenging, with many municipalities still facing difficulties in adopting proper waste management and disposal practices. The existence of controlled landfills and landfills in operation, in addition to the limited recycling rate, demonstrates the need for coordinated investments and actions in all spheres of society. It is fundamental to strengthen the shared responsibility between government, private enterprise and waste pickers, besides expanding the infrastructure for selective collection, composting and energy use.

Studies carried out in Brazil have analyzed the production of CDR., its socioeconomic and environmental impacts, as well as comparing different scenarios of urban solid waste.
management. Life Cycle Analysis (LCA) has been widely used to assess the environmental effects of CDR production, with the reduction of greenhouse gas emissions and the transition to eco-efficiency being highlighted as positive results of these studies. Although the most advanced scenarios in terms of technology have shown better environmental performances, the high costs have been a challenge for their implementation in the Brazilian context. Therefore, landfill scenarios, along with recycling and composting, have proven more feasible in the transition to eco-efficiency. Implementing integrated practices and engaging local society are essential to achieving significant reductions in landfill use and global warming gas emissions. While the production of CDRs may result in an increase in total greenhouse gas emissions, emissions avoided by replacing fossil fuels positively offset the global warming potential.

The energy potential of RDF from municipal solid waste has been exploited, with positive results in fossil fuel substitution and CO$_2$ emission reduction. However, it is necessary to ensure strict control of environmental impacts and to carry out comprehensive studies to assess the viability of co-processing in different regions of the country. The creation of the Brazilian Waste Energy Recovery Front and the development of the Energy Recovery Atlas are important initiatives that boost the sector and contribute to the closure of landfills by 2024, as established in the Legal Framework of Sanitation. The continuity of these efforts is fundamental to promote a more sustainable waste management in Brazil and achieve the objectives set for the cement sector.

REFERENCES


