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Life Cycle Environmental Assessment of Three Excavated Soil and Rock (ESR) Treatment Methods: A Case Study in Shenzhen City

Jing Bai [1,*], Yi Ma [2], Qingbin Song [3], Zhijun Hu [4,*], Yanqiu Li [4] and Huabo Duan [5]

[1] The Institute for Sustainable Development, Macau University of Science and Technology, Macao SAR 999078, China
[2] Guangzhou Greenstone Carbon Technology Co., Ltd., Guangzhou 510000, China; my@gscarbon.cn
[3] Faculty of Innovation Engineering, Macau University of Science and Technology, Macao SAR 999078, China; qbsong@must.edu.mo
[4] Construction First Group, The Fifth Construction Co., Ltd., Beijing 100024, China; liyanqiu@cscec.com
[5] School of Environmental Science & Engineering, Huazhong University of Science and Technology, Wuhan 430074, China; huabo@hust.edu.cn
* Correspondence: 2109853gtu30003@student.must.edu.mo (J.B.); huzhijun@cscec.com (Z.H.)

Abstract: This study aimed to quantitatively assess the environmental impacts of different methods used for treating excavated soil and rock (ESR) in Shenzhen, namely landfilling, sintering, and non-sintering, using the life cycle assessment (LCA) method. The findings indicate that recycling ESR through sintering or non-sintering processes offers more sustainable alternatives than landfilling. The recycled products derived from ESR can effectively replace traditional building materials, thereby reducing their environmental impacts. However, when comparing the environmental impacts of sintering and non-sintering processes, the latter demonstrated more significant impacts, particularly in terms of global warming potential (GWP), acidification potential (AP), and eutrophication potential (EP). Furthermore, it is worth noting that the environmental impacts of the sintering processes are influenced by fuel type and exhaust gas emissions, with natural gas combustion yielding more substantial overall environmental benefits. Moreover, ESR landfilling poses constraints on sustainable development and land resource occupation. This study contributes to a better understanding of the environmental impacts associated with ESR landfilling and recycling, provides management departments with optimal ESR management suggestions, and alleviates environmental pressure from urban development.

Keywords: excavated soil and rock; life cycle assessment; landfilling; sintering; non-sintering

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1. Introduction

The construction industry plays a crucial role in China's economic and social development, contributing to a total output value of 29.3 trillion yuan in 2021 [1]. Large-scale urban construction projects also generated significant construction and demolition waste (CDW), including urban regeneration, underground space development, and the demolition of different buildings and infrastructures [2]. The improper management of CDW poses significant environmental impacts [3] and urban management challenges [4]. Globally, the annual generation of CDW exceeds 10 billion tons [5], with China, the United States, and the European Union being the top three contributors [6]. Between 2003 and 2013, China generated approximately 2.3 billion tons of CDW annually [7]. However, the resource utilization rate of CDW in China is relatively low compared to other developed countries, ranging from 70% to 95% [8]. Improper CDW treatment practices in urban areas may lead to land occupation [4], soil contamination [9], and water body destruction [10], as well as a series of safety issues [11].

Excavated soil and rock (ESR) is referred to as engineering sediment or slurry. According to the "Technical Standard for Construction And Demolition Waste Treatment (CJJ/T 134-2019)", engineering sediment is generated from foundation excavation works such as various structures and pipe networks, while engineering mud is generated from the pile construction and shield construction processes [12]. ESR accounts for over 70% of the total volume of CDW [13]. In Shenzhen, approximately 74 million m^3 of ESR is generated from various construction projects annually, posing significant challenges [14]. A landslide occurred at an ESR landfill site in Guangming District, Shenzhen, resulting in 77 deaths and 33 houses being destroyed on 20 December 2015 [15]. An in-depth analysis of this landslide event in Shenzhen has suggested that the volume of ESR dumped in landfills should be reduced to minimize the risk of landslides [16,17]. Common ESR recycling technologies in China include the conversion of ESR into building products, sediment separation, and backfilling fillers. However, compared with developed countries, the rate of ESR recycling or backfilling in China is relatively low [18], mainly due to the lower value and higher costs of ESR recycling compared to other types of CDW [19].

Shenzhen, a leading "Zero waste city" in China [20], is actively working towards improving the resource utilization of ESR. Although remarkable progress has been made in recycling CDW in Shenzhen compared to traditional landfill practices [21], only 15% of recycling enterprises in Shenzhen are involved in ESR recycling, with an average processing capacity of less than 50,000 m^3 per year. Consequently, most of Shenzhen's ESR (65%) is transported to other cities for further treatment, such as land reclamation and engineering backfilling [22]. Experiences in Europe indicate that regulatory frameworks, logistical challenges, and material quality are the main factors for reusing ESR effectively [23]. To address these challenges, Shenzhen is seeking new strategies to enhance ESR utilization and reduce the environmental impacts associated with landfilling. "Shenzhen Construction and Demolition Waste Management Measures (revised version in 2020)" emphasizes the control and management of CDW at the source, transportation, and final disposal to prevent improper disposal of CDW. The measures also mandate that ESR with a water content of over 40% should be taken to undergo sedimentation, drying, or curing measures before being transported to landfill sites or other factories. Shenzhen is conducting sediment separation pilot projects to promote ESR on-site treatment [14]. The ESR sediment separation process involves sedimentation, flocculation, and pressure filtration techniques [22,24]. These methods yield coarse and fine aggregates that can be mixed with cement and other additives for diverse applications in concrete products, including building materials, road surface materials, and drainage pipes. However, the resulting sludge cakes still require further disposal at landfills.

The successful application of both sintering and non-sintering techniques has been demonstrated in ESR recycling [25], while some brick and tile plants are actively exploring the development of high-value recycled products like large-size wall panels and lightweight partition walls [22]. Even though sintering facilities have yet to be introduced in Shenzhen, the feasibility of utilizing clay-rich ESR as a sintering material has been evaluated from the perspectives of composition, sintering techniques, and environmental regulations [26]. However, is the application of sintering or non-sintering methods sufficient to reduce the volume of ESR, and, thus, the environmental impacts in Shenzhen? The purpose of this study is to evaluate the environmental impacts of different ESR treatment methods, including landfilling, sintering, and non-sintering.

Previous ESR-relevant studies employed various assessment methods. Ma et al. [27] qualitatively analyzed the environmental impacts of ESR in the transportation stage and the classification methods of ESR. Zhu et al. [28] and Guo et al. [29] explored the possible environmental impacts of ESR related to shield construction during transportation and landfill processes. These studies revealed the generation of ESR in different countries or regions, indicating that the transportation and landfill processes have negative impacts on the environment. However, the existing qualitative studies only focus on the environmental impact of individual stages or some specific recycled technologies. In contrast, the quantitative analysis focuses on several aspects, such as production estimation [18], disposal methods [22,23], and recycling potential [30].

To address these limitations, further quantitative research is required to assess the environmental impacts of specific ESR treatment techniques throughout their life cycles. Life cycle assessment (LCA) can be utilized to assess the environmental impacts of CDW treatment technologies [31] and different recycling scenarios [32] during demolition, transportation, and recycling stages. Therefore, this study employs the LCA approach to evaluate the environmental impacts of three ESR disposal methods and supplement the results with sensitivity and scenario analysis. Subsequently, based on the generation and disposal scenarios of ESR in Shenzhen, the potential for reducing the environmental impacts of future ESR disposal is predicted, and recommendations for optimizing disposal are proposed. To realize the low-carbon development in Shenzhen's construction industry and "Zero waste city" pilot, it is necessary to fully understand the environmental impacts and the critical factors for ESR treatment. Such an assessment can effectively inform future management strategies to reduce the environmental impacts of ESR treatment and support the large-scale implementation of ESR recycling technologies.

2. Methodology

The LCA research in this study is conducted according to the framework of ISO 14040 and 14044. LCA should include the following four parts: (1) goal and scope, (2) life cycle inventory analysis, (3) life cycle assessment, (4) interpretation [33,34].

2.1. Goal and Scope

The first step in conducting an LCA study is to define the goal and scope, focusing on the goal definition, system boundaries, and functional units [31,34]. The goal of this study is to assess and compare the whole life cycle environmental impacts of three ESR disposal methods, landfilling, sintering, and non-sintering, complement existing ESR resource utilization practices in Shenzhen, and finally provide insights into improving resource utilization technologies for the CDW treatment industry.

This assessment considers different raw materials, energy sources, and disposal processes, evaluating them under three scenarios derived from ESR disposal field case studies. The system boundary of this study (Figure 1) illustrates the process of ESR collection and subsequent transportation by dump trucks to either a landfill or a resource utilization plant for further treatment. The landfilling process encompasses both the transportation process and the landfilling process. At the same time, ESR resource utilization focuses on the transportation and manufacturing process of recycled products, excluding the use and disposal processes of these products. It is worth noting that, according to various studies on recycled construction materials, including ESR, the recycled products exhibit nearly identical physical and mechanical properties to traditional building materials, indicating the potential for substituting traditional materials and achieving significant environmental benefits [35]. Therefore, the scope of research on ESR resource utilization also includes the environmental benefits of replacing traditional building materials with recycled products. In addition, due to limited research work, on-site ESR turnover or stockpiling, storage, employee transportation, fixed equipment installation, maintenance, and operation processes are outside of the system boundaries of this study. The LCA study is based on average survey data from 2019 and 2021. Similarly to previous CDW research, the functional unit is defined as "1 ton of ESR" [36], allowing for the quantification of material and energy inputs and outputs for all three ESR treatment processes, including raw material inputs, energy consumption, transportation, solid waste, exhaust emissions, and wastewater discharge per functional unit.

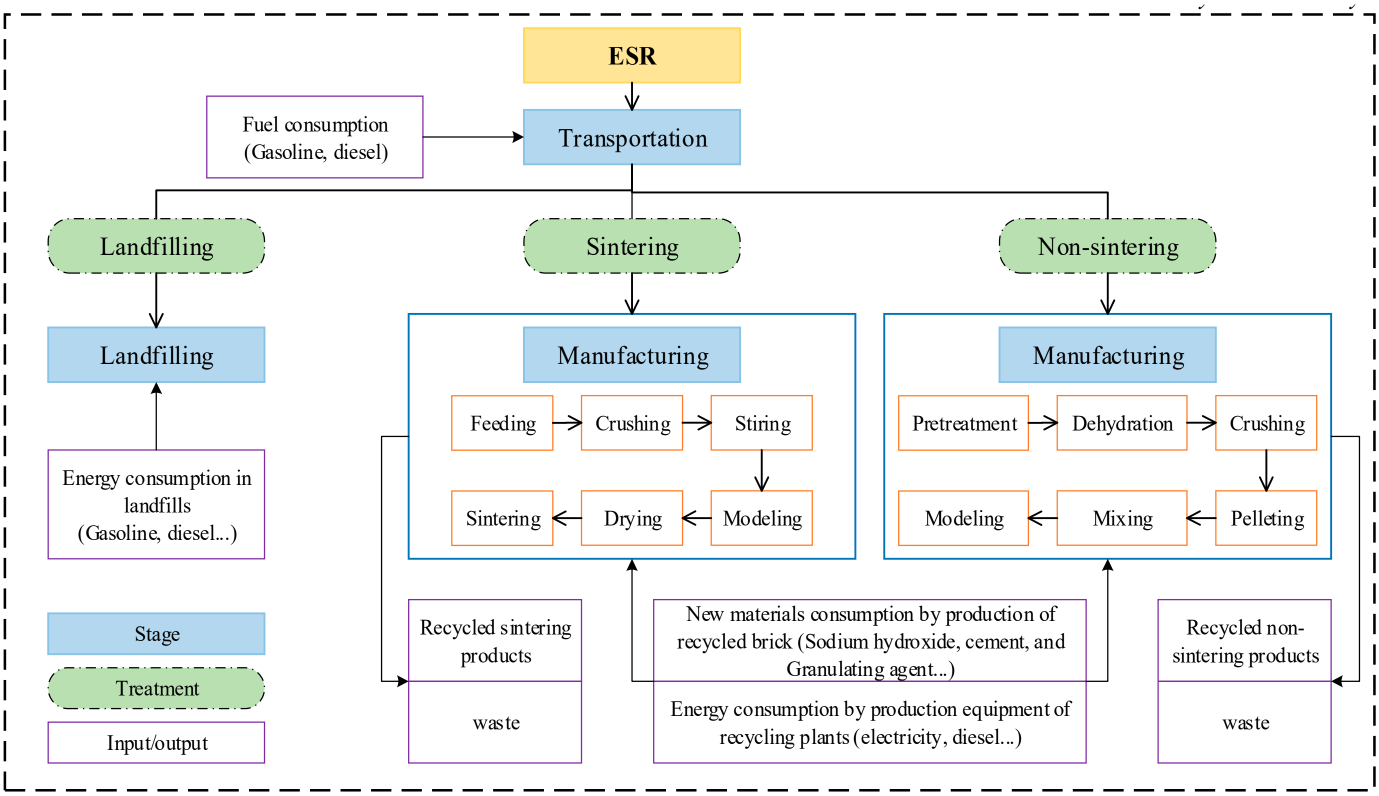


Figure 1. The system boundary of life cycle assessment of three ESR treatment methods.

2.2. Life Cycle Inventory Analysis

Life cycle inventory (LCI) analysis is a crucial tool for quantifying the environmental inputs (such as materials and energies) and outputs (such as gas emission, wastewater, and solid waste) associated with a specific process or product, which helps to assess the environmental impacts within the system boundary [37].

In the case of ESR disposal in Shenzhen, it is essential to use as much local data as possible to ensure the accuracy and representativeness of the LCI analysis. These primary data, including materials and energy consumption, are mainly obtained through field surveys and relevant environmental impact assessment (EIA) reports. However, due to the absence of sintering facilities for large-scale production in Shenzhen, process information from sintered brick plants in other provinces and cities in China, such as Dongguan City and Huzhou City, where advanced technologies and mature processes are available, has been collected to supplement the local data. Table 1 displays the original inventory data of 1 ton of sintered and non-sintered ESR, respectively. Meanwhile, secondary data, mainly from commercial databases, such as GaBi 9.2 and Balance 3.0, have also been utilized (detailed data sources in Table 1). Furthermore, based on the distribution of ongoing construction projects and ESR resource utilization facilities in Shenzhen, the estimated average transportation distances of ESR landfilling, sintering, and non-sintering are 16 km, 37 km, and 32 km, respectively.

Table 1. Summary of the inventory data for ESR sintering and non-sintering treatment. All quantities are based on 1 ton of ESR.

Treatment Methods	Type	Project	Unit	Amount	Data Sources
Sintering	Input	ESR	t	1	Field investigation and EIA reports outside Shenzhen city
		Slag	kg	220	
		Fly ash	kg	110	
		Sodium hydroxide	kg	0.8	
		Calcium hydroxide	kg	0.64	
		Water	kg	150	
		Electricity	kWh	17.07	
	Output	Recycled bricks *	Pcs.	400	
		PM	kg	0.003	
		SO_2	kg	0.06	
		NOx	kg	0.07	
		Unqualified products	kg	2	
		Waste brick	kg	5	
Non-sintering	Input	ESR	t	1	Field investigation and EIA reports in Shenzhen city
		Cement	kg	93.75	
		Granulating agent (Polyacrylamide mixtures)	kg	5	
		Additive (lime)	kg	6.25	
		Water	kg	104	
		Diesel	kg	0.35	
		Electricity	kWh	9	
	Output	Non-sintered bricks	t	1.19	
		Dust	kg	0.04	
		Unqualified products	kg	3	
		Waste brick	kg	22	

Note: * convert to standard size brick count (240 mm × 115 mm × 53 mm); unit pieces.

2.3. Life Cycle Impact Assessment

This study quantitatively assesses the environmental impacts of various options in ESR treatment methods following ISO 14040 and ISO 14044. GaBi software (version 9.2) and CML 2001 (January 2016 version) are utilized to calculate the midpoint indicators in the environmental impact assessment. Three key evaluation metrics were selected: 100-year global warming potential (GWP), acidification potential (AP), and eutrophication potential (EP). GWP is a widely used indicator to measure the impact of environmental emissions on climate change, making it particularly important in studies related to CDW. Within the current global warming context, a study has found that recycling may release higher levels of NO_x and SO_2 compared to landfilling [38]. AP and EP indicators provide a method to evaluate the environmental burdens associated with regulated emissions such as NO_x and SO_2. These indicators are of significant concern to Shenzhen's ecological environment supervision department.

To calculate the environmental impact of landfilling, Equation (1) is employed, incorporating the impacts of both transportation and landfilling processes:

$$E_{L,i} = E_{LT,i} + E_{L1,i} \tag{1}$$

Here, i represents the three environmental impact indicators (GWP, AP, and EP), $E_{L,i}$ represents the environmental impact of landfilling, $E_{LT,i}$ signifies the environmental impact specifically associated with transportation for landfilling, and $E_{L1,i}$ represents the environmental impact resulting from the landfilling process.

In terms of recycling, this study focuses on two types of recycled products: sintered brick (produced by firing in a kiln) and non-sintered brick (produced by mechanical pressing). These recycled products serve as substitutes for traditional materials, providing comparable functionalities. Recycled sintered bricks have a wide range of uses, whereas recycled non-sintered brick has more limited applications due to its lower strength and heavier weight, making it suitable primarily for non-load-bearing walls in low-rise buildings and pavement structures [39].

The recycling of CDW not only provides significant environmental benefits but also reduces the consumption of natural resources [40]. Therefore, the life cycle environmental impact assessment for ESR recycling incorporates the evaluation of process impacts, including transportation, as well as the credit assigned to recycled construction materials, which eliminates the environmental burden associated with the production of similar products. Equations (2) and (3) express the calculation methodology for the total environmental impact of sintered and non-sintered brick production, respectively:

$$E_{s,\,i} = E_{ST,\,i} + E_{SM,i} + E_{SA,\,i} \tag{2}$$

$$E_{Ns,\,i} = E_{NST,\,i} + E_{NSM,i} + E_{NSA,\,i} \tag{3}$$

In these equations, $E_{s,\,i}$ and $E_{Ns,\,i}$ represent the total environmental impact of sintered and non-sintered brick production, respectively. $E_{ST,\,i}$ and $E_{NST,\,i}$ denote the impacts associated with transportation for sintered and non-sintered brick production. $E_{SM,\,i}$ and $E_{NSM,\,i}$ capture the environmental impact of the respective manufacturing stages. Lastly $E_{SA,\,i}$ and $E_{NSA,\,i}$ represent the environmental impact that is avoided through the utilization of recycled materials, encompassing transportation and manufacturing stages, as compared to the production of traditional brick alternatives.

2.4. Sensitivity Analysis

Sensitivity analysis in the LCA is a method used to assess the robustness of LCA results by evaluating how variation in input parameters influences the total outcomes [41]. In this study, each key parameter varies positively by 10%, and then the corresponding variations in the three life cycle impact indicators are evaluated. That is, the sensitivity of these contributing parameter variations to the results is identified. Specifically, the variable parameters of sintering include electricity consumption and exhaust gas emissions. For non-sintering, the variable parameters include materials and energy consumption, such as cement, granulating agents, admixture, and electricity. By conducting sensitivity analysis, decision-makers can gain insights into the reliability and validity of LCA findings and make more informed choices in terms of ESR management.

2.5. Scenario Analysis

The production technologies of sintered bricks can be classified into two methods: internal combustion and external combustion. The internal combustion method entails incorporating a certain amount of finely ground fuel or combustible industrial waste, such as coal slag and fly ash, into the clay raw material. This mixture undergoes processes such as billet making, drying, loading, and sintering. During the heating phase inside the kiln, the fuel within the billet body is burned to ultimately form bricks. Conversely, the external combustion method relies on conventional thermal sources like hard coal and natural gas for sintering in the kiln, with no fuel added to the billet body itself. However, this method exhibits lower thermal efficiency due to the large size of brick billets and their inherently low thermal conductivity [42]. Sintered brick production has significant environmental implications, primarily due to the extensive consumption of high-quality clay as a raw material, leading to ecological degradation and loss of arable land. Furthermore, the combustion of fossil fuels in the sintering process releases particular matter and harmful gases, such as NO_x and SO_2 [43].

The increasingly stringent environmental regulations have necessitated the closure of traditional brick and tile plants in several provinces and cities in China. These plants are characterized by high resource consumption, significant pollution levels, and low energy efficiency. Their shutdown is partly due to the significant expenses and difficulty associated with exhaust treatment. Therefore, the selection of appropriate sintering methods and fuel types is crucial for the brick and tile industry to achieve cleaner production goals and promote a circular economy.

To further minimize the potential environmental impact of utilizing ESR as a raw material in sintered brick production, this study aims to quantify the environmental implications associated with different fuel choices. Specifically, using 1 ton of ESR as a benchmark, three scenarios are examined:

1. For scenario I (S1), in the sintering process, thermal energy is generated from an internal fuel such as fly ash and slag, which is mixed with the raw materials. This scenario serves as the baseline comparison;
2. For scenario II (S2), in the sintering process, thermal energy is generated from hard coal, which is independent of the raw material mixture;
3. For scenario III (S3), in the sintering process, thermal energy is generated from natural gas.

3. Results

3.1. Comparison of LCA Results between ESR Landfilling and Recycling

3.1.1. LCA Results of ESR Landfilling and Recycling

Figure 2 presents a comprehensive analysis of these environmental impacts of 1 ton of ESR throughout its life cycle between landfilling and recycling, using three key indicators. Negative values within the framework of these analyses denote environmental benefits or credits, while positive values denote environmental burdens [44]. The findings indicate that landfilling imposes considerable burdens across all environmental indicators, with the total environmental impacts from landfilling 1 ton of ESR being 17 kg CO_2 eq, 10 g PO_4^{3-} eq, and 90 g SO_2 eq, as shown in Figure 2. However, recycling (including both sintering and non-sintering methods) demonstrates significant environmental benefits, and the life cycle results of three ESR treatment methods are shown in Table A2. Although the process of recycling ESR itself generally results in a higher environmental burden compared to landfilling, the total results of ESR recycling remain highly favorable due to the reduction in raw building material consumption through resource utilization. Notably, the environmental credits generated by replacing traditional bricks with recycled alternatives can effectively offset the burdens associated with recycling operations. Recycling significantly reduces the GWP impact by more than three times, highlighting its substantial advantage over landfilling. Furthermore, recycling ESR resources reduces the impacts on AP and EP by more than two times compared to other disposal methods.

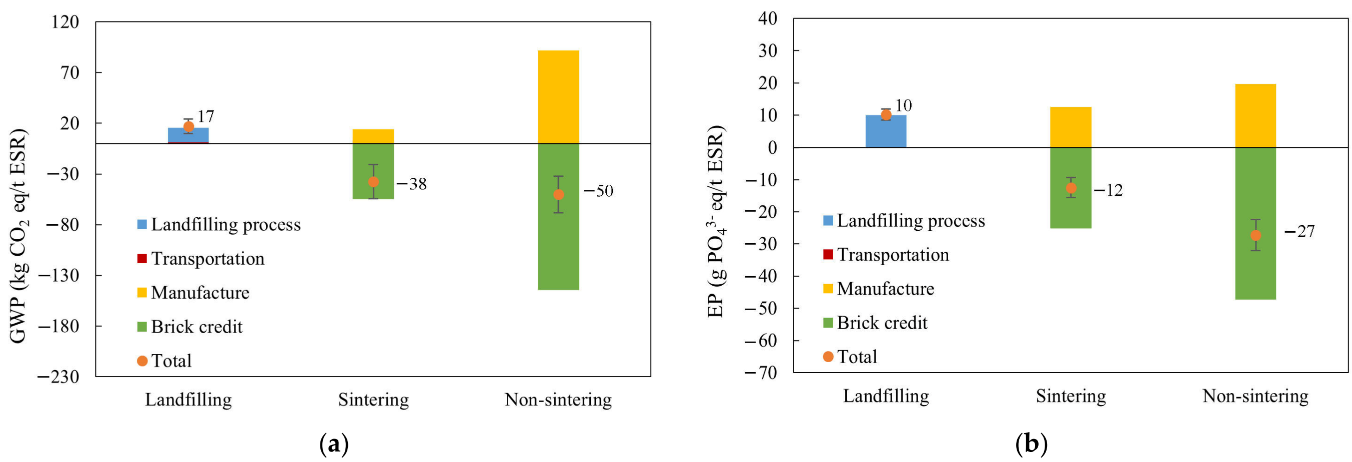
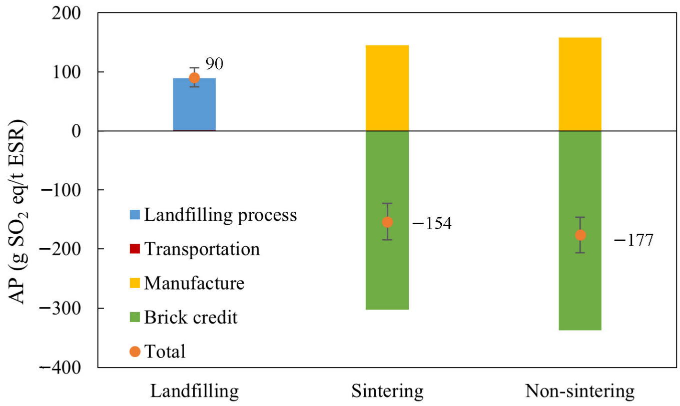


Figure 2. *Cont.*



(c)

Figure 2. The total environmental impact results from 1 ton of ESR landfilling and recycling. (**a**) GWP; (**b**) EP; (**c**) AP. Note: "Landfilling process" represents the operation in the landfill site; "Manufacture" refers to the operation of recycled brick in brick and tile plants; "Brick credit" represents the environmental burden of replacing traditional bricks (including the impact of transportation and manufacture stage); "Total" refers to the sum of all contributions in the life cycle.

3.1.2. Comparison of LCA Results between ESR Sintering and Non-Sintering

It is crucial to recognize that the adoption of different ESR recycling approaches introduces discernible variations in environmental burdens and benefits. Non-sintering methods have higher environmental burdens, including transportation and manufacturing processes, as well as lower environmental benefits compared to sintering methods. This is consistent with the trends observed in GWP, AP, and EP. Specifically, GWP generated from non-sintering is approximately 5.5 times higher than that of sintering, while EP is 1.5 times higher, and the difference in AP is relatively small. In terms of environmental benefits, there is a significant difference between sintering and non-sintering methods of ESR recycling. Sintering techniques primarily rely on ESR as the main material, with fewer auxiliary materials.

On the other hand, non-sintering uses additional natural materials like cement, granulating agents, and admixtures, in addition to ESR. Moreover, most materials used in non-sintering have high emission levels, resulting in a higher environmental burden compared to sintering. The difference in the emission factors of the traditional building materials being replaced also contributes to the disparity in environmental benefits between the two methods. The emission factor of ordinary sintered bricks replaced by ESR bricks is generally lower than that of concrete bricks replaced by non-sintered bricks, leading to a substantial difference in the benefits of recycled bricks between the two methods (Figure 2). In order to mitigate the uncertainties arising from various factors, the Monte Carlo simulation was carried out using Oracle Crystal Ball software (version 11.3). The number of iterations is an important factor in obtaining reliable results using the Monte Carlo simulation [45]. The materials and energy consumption during the ESR disposal process are influenced by the production levels of the selected cases. The maximum and minimum values of material consumption were determined based on field surveys conducted in different cities, and the simulation was performed 10,000 times, with a confidence level of 95%. The uncertainty of the results is depicted through error bars in Figure 2.

In summary, it is unequivocally evident that both sintering and non-sintering methods offer significant advantages over landfilling from the life cycle perspective. Non-sintering methods demonstrate higher environmental impacts compared to sintering for 1 ton ESR of in the manufacturing process. However, the selection and implementation of recycling methods should also comprehensively consider the mechanical properties and market potential of the recycled products.

3.1.3. Contributing Factors Analysis in Environmental Impacts of ESR Recycling

In Figure 3a, the analysis of the environmental impact attributed to sintering reveals that electricity consumption (75.1%), transportation (16.8%), and auxiliary material consumption (8.1%) are the main contributors to GWP. The sintering plant's high electricity consumption, as well as China relying heavily on thermal power generation, results in a higher GWP factor. Exhaust emissions and electricity are the major contributors to AP and EP. Transportation and auxiliary material consumption have relatively minor effects on AP and EP. Notably, exhaust emissions, mainly from SO_2 and NO_x, have a significant influence on AP and EP during the sintered brick manufacturing process. Despite the introduction of desulfurization devices, the combustion of fly ash and slag still releases high levels of SO_2, contributing to AP. Moreover, the absence of a denitrification device at the time of data collection led to higher NO_x emissions.

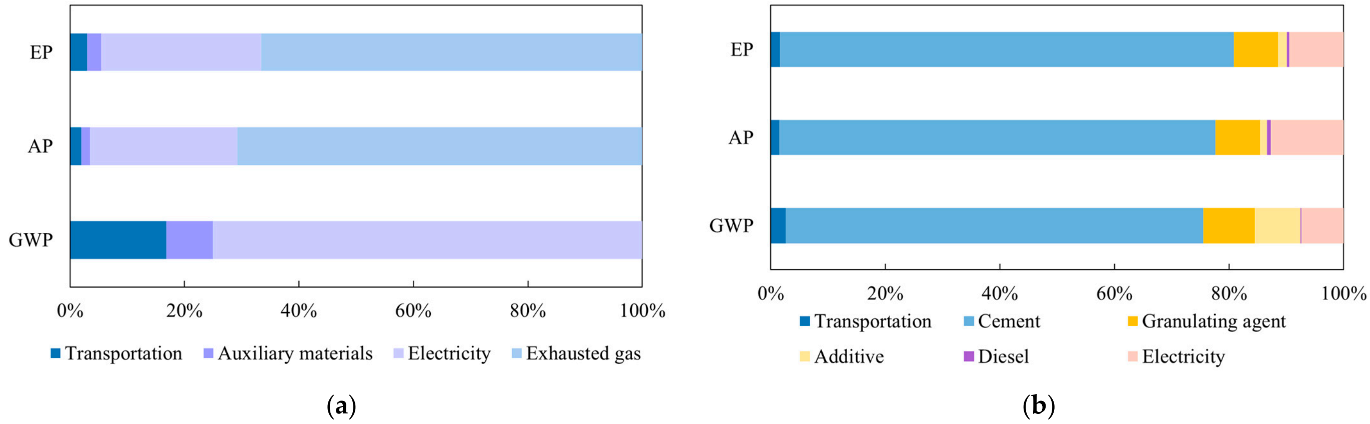


Figure 3. Contribution analysis of process environmental impacts for ESR recycling (avoided burden not included). (**a**) Sintering method; (**b**) non-sintering method.

In Figure 3b, for GWP generated from ESR non-sintering treatment, the environmental burden mainly arises from cement (72.8%), granulator agent (9.0%), and electricity consumption (7.4%). Cement, as a high-emission construction material, represents the largest proportion of raw material consumption in non-sintered brick production (excluding ESR). Consequently, it contributes substantially to the environmental burden during the recycling process. Lime, the main component of the admixture, has minimal effects on AP and EP but accounts for 8.1% of GWP. Compared to other factors, emissions from transportation and diesel consumption during non-sintered brick production contribute relatively less to the environmental burden.

3.2. Contributing Parameters Analysis of ESR Recycling Environmental Impacts in Shenzhen

Based on the sensitivity analysis results presented in Figures 4 and 5, it can be observed that specific parameters have a significant influence on the environmental indicators for both the sintering and non-sintering methods of ESR treatment. Understanding these key contributing parameters and their degree of contribution is essential for optimizing the environmental impacts of both processes.

In the case of sintering, electricity consumption emerges as a crucial factor that strongly influences all environmental indicators, particularly GWP. It is important to note that negative values indicate an opposite effect on the results. Conversely, variations in transportation distance have an insignificant effect on the three indicators. Thus, reducing electricity consumption and exploring alternative energy sources could be effective strategies for minimizing the environmental impact of sintering. Moreover, the emission of SO_2 exhibits strong sensitivity for AP, while NO_x greatly influences AP and EP, with the highest sensitivity observed for EP. These findings emphasize the importance of exhaust gas generation and control technology in reducing the emissions of SO_2 and NO_x, which are critical air pollutants in the sintering process. Implementing measures to control these emissions can significantly mitigate the environmental footprint of ESR sintering. It should be noted that if the emissions of SO_2 and NO_x exceed 317% and 244%, respectively, compared to the current state, sintering may no longer be an environmentally desirable treatment method compared to landfilling.

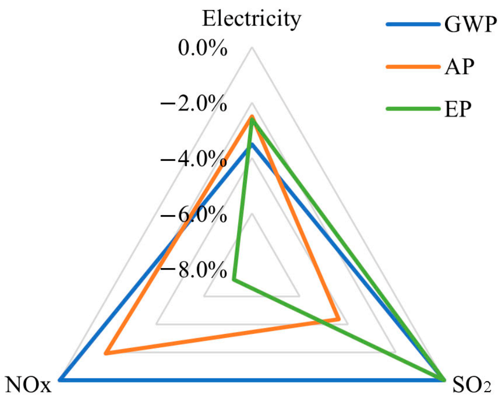


Figure 4. Sensitivity analysis of the environmental impacts of sintering.

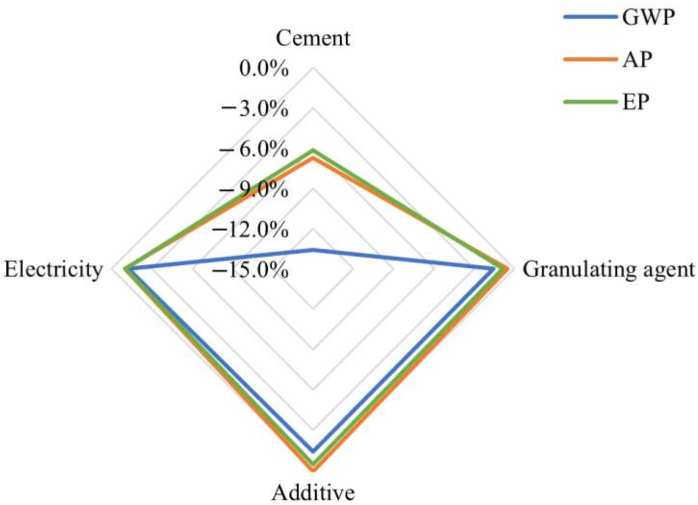


Figure 5. Sensitivity analysis of the environmental impacts of non-sintering.

For the non-sintering method, the results demonstrate that the three environmental indicators are most sensitive to variations in cement consumption, especially in terms of GWP. On the other hand, the dosage of granulating agent and admixture has a minimal effect on AP and EP. Similar to sintering, variations in transportation distance do not significantly affect the three indicators. Therefore, reducing cement consumption or mitigating the environmental impact of cement production is critical to decrease the environmental footprint of non-sintering. To ensure that non-sintering is more environmentally beneficial than landfilling, cement consumption should remain below 173%, based on the sensitivity analysis results presented in Figures 4 and 5. In the case of sintering, electricity consumption is a crucial factor that strongly influences all environmental indicators, especially GWP. Conversely, changes in transportation distance have an insignificant effect on the three indicators.

3.3. Further Environmental Impacts Reduction Potential of ESR in Shenzhen

Based on the above results in Section 3.2, three scenarios were formulated to reduce the environmental impacts of ESR sintering in the sintered brick industry. These scenarios mainly focus on the selection of primary fuel type and combustion technology. The scenario analysis results indicate that all three scenarios lead to environmental benefits, as reflected by negative values for all indicators, as shown in Figure 6. In comparison with Scenario I (internal fuel) and Scenario III (natural gas), Scenario II (hard coal) demonstrates the least life cycle environmental benefits, and similar conclusions are observed for GWP, AP, and EP.

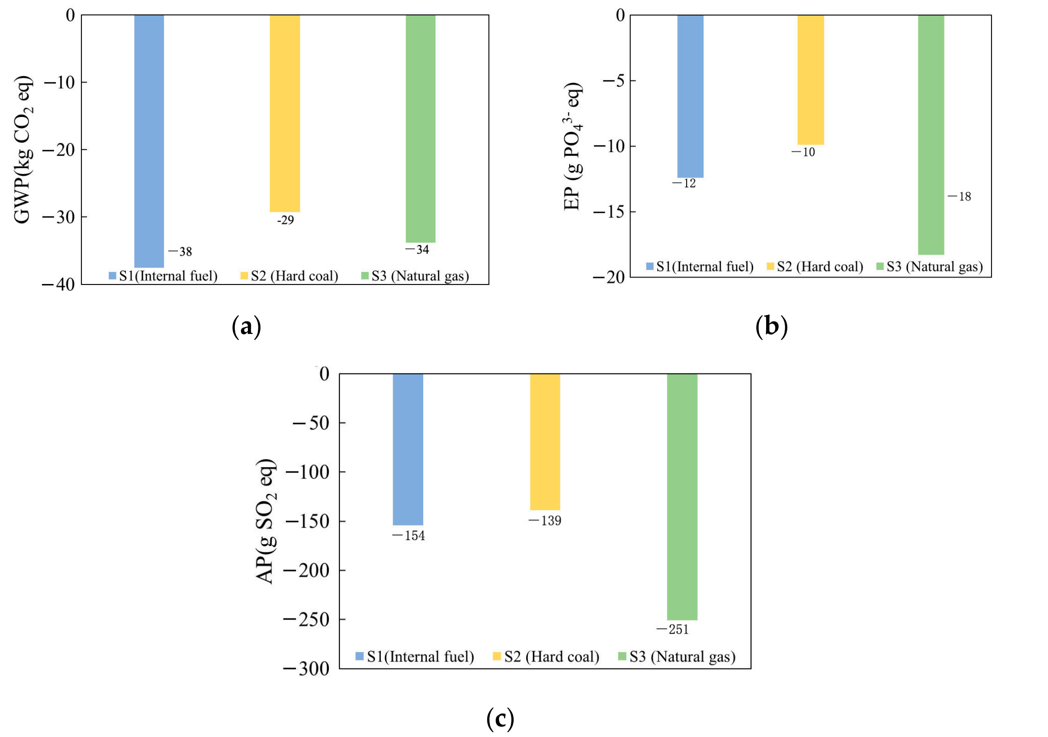


Figure 6. Analysis results of sintering total impact in the whole life cycle stage (− benefit/credit, + burden) (**a**) GWP; (**b**) EP; (**c**) AP.

In terms of GWP, Scenario I (−38 kg CO_2 eq) which uses internal fuel shows a slightly higher benefit than Scenario III (−34 kg CO_2 eq) using natural gas. However, this difference is not statistically significant. When considering AP and EP benefits, Scenario III outperforms Scenarios I and II.

Internal fuel, used in Scenario I, primarily consists of industrial wastes generated during or after coal production, such as fly ash, slag, and coal gangue. Unlike hard coal and natural gas, internal fuel does not cause additional environmental burden associated with its production. Hence, Scenario I showed better GWP reduction compared to the other two scenarios. Other things being equal, the use of coal as a sintering heat source incurs a higher environmental burden during the production stage. Combustion of coal generates significantly higher levels of SO_2 and NO_x, thereby intensifying the impact of AP and EP. The key distinguishing factors among different fuels lie in their sulfur content and nitrogen oxide production, with coal exhibiting higher levels of both. Internal fuel primarily consists of residues from high-temperature combustion in boilers, which typically contain fewer volatile compounds.

Natural gas, on the other hand, as a clean energy source, has lower sulfur content compared to internal fuel and hard coal. Furthermore, natural gas supplied by municipalities undergoes comprehensive desulfurization and denitrification treatments before utilization. Consequently, both internal fuel and natural gas offer more evident environmental benefits compared to hard coal. Additionally, in terms of AP and EP benefits, natural gas surpasses internal fuel. Thus, it is crucial to consider the sulfur content of internal fuel during sintered brick production.

3.4. Estimation of Environmental Impact Based on the Total Volume of ESR in Shenzhen

Figure A1 in the Appendix A illustrates the projected generation volume of ESR in Shenzhen from 2020 to 2035, as provided by the Shenzhen Municipal Housing and Construction Bureau (SMHCB). Analysis of SMHCB statistics reveals that about 74% of the ESR generated within Shenzhen yearly was transported to other cities for further disposal between 2016 and 2019. On the other hand, the recycling rate of ESR during the timeframe stood at a mere 5%. Considering the composition of ESR in Shenzhen (Figure A2) and the CDW disposal plans outlined by regulatory authorities, predictions about the environmental impacts and benefits of both landfilling and recycling scenarios were formulated.

The current study analyzed the potential environmental impacts and land occupation resulting from the practice of landfilling 74% of ESR in Shenzhen from 2020 to 2035. Additionally, two recycling assumptions were considered, including sintering and non-sintering methods: (1) the business-as-usual (BAU) scenario, where the current recycling rate remains at 5%; (2) the high scenario, where the future recycling rate of ESR increases to 38%.

Considering the composition of ESR in Shenzhen, clay-rich soil assumes a prominent role as the primary raw material employed in both sintering and non-sintering processes. The environmental impacts and land occupation associated with ESR landfilling in Shenzhen are summarized in Figures 7 and A3 (Appendix A). The emissions with GWP, AP, and EP resulting from ESR landfilling are expected to be the highest in 2020 and cumulatively reach 22.45 million tons of CO_2 eq between 2020 and 2035.

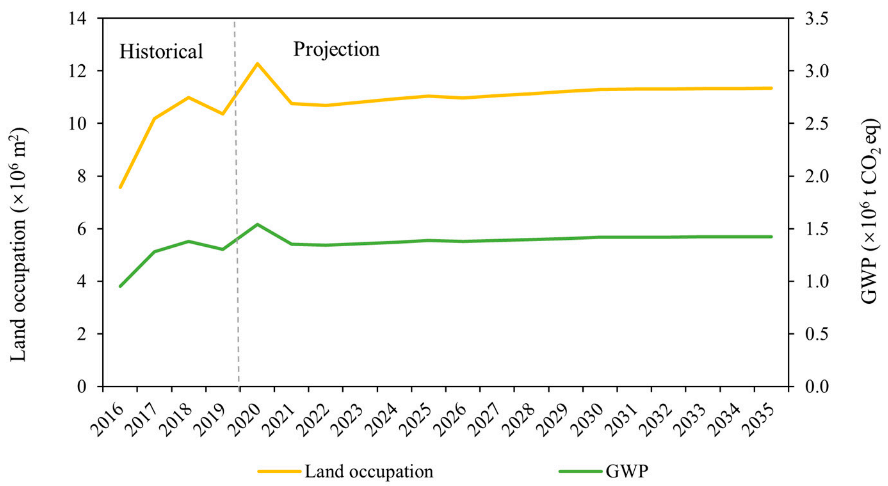


Figure 7. GWP and land occupation potential of ESR landfilling in Shenzhen.

The extensive landfilling of ESR in Shenzhen has detrimental environmental impacts and leads to the inefficient use of land resources. The need for land allocation for ESR disposal is projected to reach its peak in 2020 and continue to rise until 2035, resulting in a total land area requirement of 179 million m^2, equivalent to the entire Longhua District of Shenzhen. Moreover, as neighboring cities like Zhongshan and Zhuhai undergo development, their capacity to accommodate ESR will diminish, posing significant challenges to the region's land resources, urban planning, and construction.

In contrast, recycling ESR presents a promising solution with the potential for substantial emission reductions and positive environmental outcomes, as seen in Figures 8, A4 and A5. Even with the current recycling rate of only 5% (business-as-usual scenario), there are considerable environmental benefits that can be achieved. For instance, between 2020 and 2035, recycling ESR could result in a saving of approximately 3.3–4.5 million tons of CO_2 eq. In the high scenario, with a recycling rate of 38%, non-sintering techniques demonstrate even greater environmental benefits compared to sintering methods. Over the same time frame, sintering is projected to save around 25.5 million tons of CO_2 eq, 105 thousand tons of SO_2 eq, and 8.4 thousand tons of PO_4^{3-} eq. Meanwhile, non-sintering is expected to achieve savings of approximately 34.1 million tons of CO_2 eq, 120 thousand tons of SO_2 eq, and 18.6 thousand tons of PO_4^{3-} eq. These findings indicate that a recycling rate of 38% can significantly reduce environmental emissions. Whether employing sintering or non-sintering approaches, the cumulative environmental benefits are nearly equivalent to or exceed those resulting from ESR landfilling between 2020 and 2035.

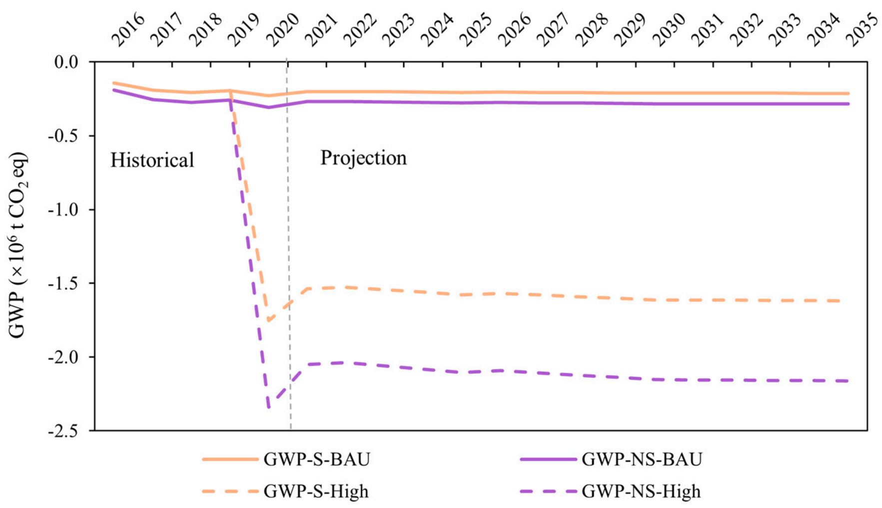


Figure 8. GWP saving of ESR recycling in Shenzhen. Note: S = sintering; NS = non-sintering; BAU = business-as-usual scenario (5% of ESR for recycling); high = high scenario (38% of ESR for recycling).

4. Discussion

4.1. Management Implications

Despite the advanced ESR disposal regulations established in Shenzhen, the utilization rate of ESR resources still needs to improve, with landfilling persisting as the primary disposal method. Therefore, there is a pressing need for management authorities to improve the current ESR disposal methods and enhance the efficient utilization of ESR resources. The following management implications are proposed:

1. ESR reduction at the source: During the engineering design stage, designers should consider the site's topography and implement appropriate solutions, such as vertical elevation adjustments and foundation pit support solutions, to minimize the volume of excavation required. To effectively utilize ESR generated at the construction site, it should be prioritized to backfill low-lying plots or areas where the ground elevation does not meet usage requirements. Furthermore, surplus materials generated from earthworks can be utilized to increase the thickness of green covering soil and incorporate rock landscapes into the construction project, thus reducing the need for transporting ESR off site;
2. Classification: ESR should be classified and treated according to resource utilization requirements and composition, with dedicated classification facilities established at suitable construction sites. ESR conforming to performance technical standards for filling purposes, such as plain fill or miscellaneous fill on the surface, should be prioritized for use as filler for backfilling. ESR rich in clay content can be used as raw materials for sintered or non-sintered bricks, which can replace traditional brick products. ESR with a high sand content can be used to produce aggregates through sedimentation separation, with these aggregates being sold to the public or used in cement mortars, while filter cakes generated from pressure filtration can serve as raw materials for sintering or non-sintering treatment and produce recycled products. For

ESR with complex compositions that are difficult to treat, harmless treatment followed by landfilling is recommended;

3. Recycle process improvements: Compared to landfilling, ESR sintering and non-sintering present significant potential to reduce carbon emissions. Particularly, ESR rich in clay content can be effectively recycled into high-quality building materials, including common sintered bricks, perforated bricks, thermal-insulation blocks, etc., which find important applications in newly constructed buildings. However, it is important to note that the manufacturing process of ESR-recycled building materials involves considerable energy and material consumption, such as the electricity consumption of the brick-making machinery, the natural gas consumption in the brick kilns, and the use of cementing materials. Therefore, further improvements can be made in key aspects during the production process. During sintering, effective control of the generation and emission of exhaust gases from the production process is necessary. Brick and tile plants can consider cleaner energy sources, such as natural gas, as external fuel for kilns. Additionally, tunnel kilns equipped with automatic temperature control systems, efficient desulfurization (limestone–gypsum wet process), and denitrification facilities may prove beneficial. Moreover, in non-sintering processes, future work will focus on process improvement to enhance the durability of products and reduce the consumption of additional materials such as cement.

4.2. Limitations and Future Work

To extend the research's impact and address the limitations of this study, future studies could delve into the following points:

1. ESR composition variations: This study focuses only on clay-rich ESR that can be used as raw materials for sintering or non-sintering processes, but not all types of ESR can directly replace original clay materials due to variations in geological conditions and sources. Therefore, future ESR management strategies should prioritize graded disposal methods and explore the potential reuse of non-clay-rich ESR;
2. Environmental impact assessment indicators: This study discusses three normalization indicators (GWP, AP, EP) under the LCI, while other indicators, such as EC (energy consumption) and HTP (human health potential), were not included. These additional indicators should be considered in future assessments to provide a more comprehensive evaluation. Additionally, it is important to acknowledge that due to the unavailability of specific Chinese local background data (emission factors), the study relies on the adoption of the best alternative background data from existing databases. Efforts should be paid to improve the availability and accuracy of local data, enhancing the accuracy of future assessments;
3. Low-carbon transportation: Although the environmental impacts of the ESR transportation process in this study are relatively small compared to the overall life cycle impacts of the three ESR treatment methods, it is important to consider the potential introduction of electric heavy goods vehicles (HGVs) as an alternative to diesel HGVs in future research, due to the large-scale promotion of electric vehicles in Shenzhen city;
4. The economic evaluation and recycling process improvements: Since large-scale sintering facilities have not been introduced in Shenzhen, this study does not address the economic evaluation and market potential of ESR recycled products. Considering the potential high economic costs associated with implementing these disposal schemes, it is necessary to explore strategies that can promote ESR recycling technologies and the use of recycled building materials in new construction projects in China while ensuring economic feasibility. In addition, future studies could focus on recycling process improvements, such as optimizing sintering processes by exploring variations in natural gas combustion and exhaust gas treatment methods within the sintering process and reducing additives in non-sintering processes.

5. Conclusions

This study aims to conduct a quantitative assessment of the environmental impacts associated with ESR recycling (sintering and non-sintering) or landfilling under the guidance of LCA methodology. These findings can provide valuable insights for policymakers to better understand the environmental benefits of ESR recycling, as well as support the development of CDW management policies and the implementation of Zero Waste Cities initiatives, particularly in cities like Shenzhen.

The key findings found that recycling ESR through sintering or non-sintering processes seems to be a more sustainable option than landfilling in terms of environmental impacts and land resource occupation. The recycled products derived from ESR can be effectively utilized to replace traditional building materials, further offsetting the environ-mental impacts associated with their production processes.

When comparing the environmental impacts of sintering and non-sintering processes for 1 ton of ESR disposal, the latter demonstrated greater impacts (specifically in terms of GWP, AP, and EP) based on the LCA approach. This result is primarily due to the large amounts of cement as a cementitious material required in the non-sintering process. Therefore, reducing cement consumption becomes a crucial area for future process improvement.

Consequently, it may be concluded that the sintering method is a more suitable option for large-scale ESR disposal compared to non-sintering. In addition, the environmental impact arising from ESR sintering process is profoundly influenced by energy consumption and exhaust gas emissions. Results from scenario analysis reveal that fuel type significantly affects the total assessment results, regardless of other factors. Specifically, using natural gas as the combustion fuel yields more substantial environmental benefits.

Author Contributions: Conceptualization: J.B. and H.D.; model analysis, investigation, and data curation for the LCA of ESR treatment: J.B. and Y.M.; formal analysis and investigation: J.B. and Y.M.; data curation: J.B. and Y.M.; writing—original draft preparation: J.B. and Y.M.; writing—review and editing: Q.S. and Y.L.; supervision: H.D. and Z.H. All authors have read and agreed to the published version of the manuscript.

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Appendix A

Table A1. Summary of nomenclature used in this research.

Terms	Acronyms
Construction and demolition waste	CDW
Excavated soil and rock	ESR
Life cycle assessment	LCA
Global warming potential	GWP
Acidification potential	AP
Eutrophication potential	EP
Life cycle inventory	LCI
Environmental impact assessment	EIA

Table A2. Life cycle results of three ESR treatment methods.

Environmental Indicators	Treatment Methods	Landfilling Process	Transportation	Manufacture	Brick Credit	Total
GWP ($kg\ CO_2$ eq)	Landfilling	15.7	1.248			17
	Sintering		2.886	14.3	−55	−38
	Non-sintering		2.496	91.8	−144	−50
AP ($g\ SO_2$ eq)	Landfilling	89	1.239			90
	Sintering		2.865	145	−302	−154
	Non-sintering		2.478	158	−337	−177
EP ($g\ PO_4^{3-}$ eq)	Landfilling	10	0.164			10
	Sintering		0.380	13	−25	−12
	Non-sintering		0.329	20	−47	−27

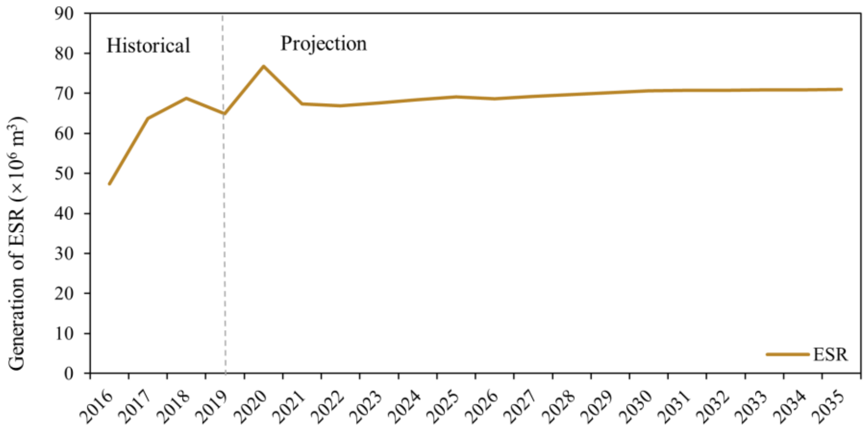

Figure A1. Projection of ESR generation volume in Shenzhen (2020–2035). Note: the data sources are from statistical reports of Shenzhen Municipal Ecological Environment Bureau (SMEEB) and Shenzhen Municipal Housing and Construction Bureau (SMHCB).

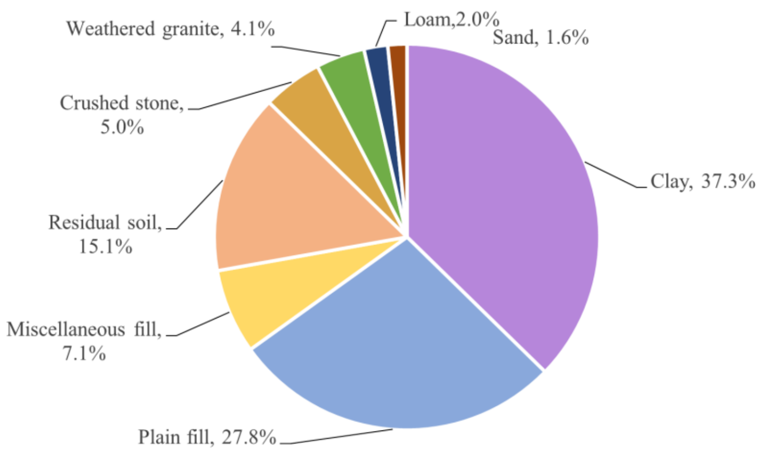

Figure A2. Composition of ESR in Shenzhen. Note: the data are available from filed engineering geological prospective reports.

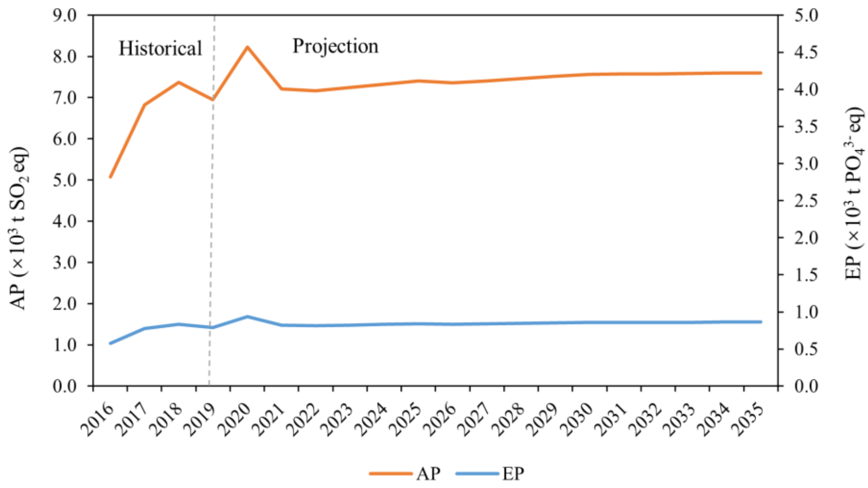

Figure A3. Projection of environmental impact (AP and EP) of ESR landfilling in Shenzhen.

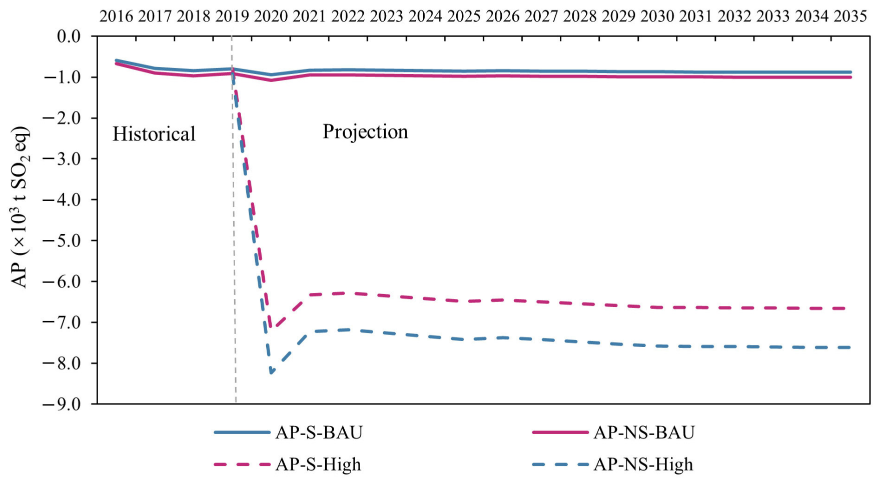

Figure A4. Projection of AP saving potential of ESR recycling in Shenzhen. Note: S = sintering; NS = non-sintering; BAU = business-as-usual scenario (5% of ESR recycling); high = high scenario (38% of ESR recycling).

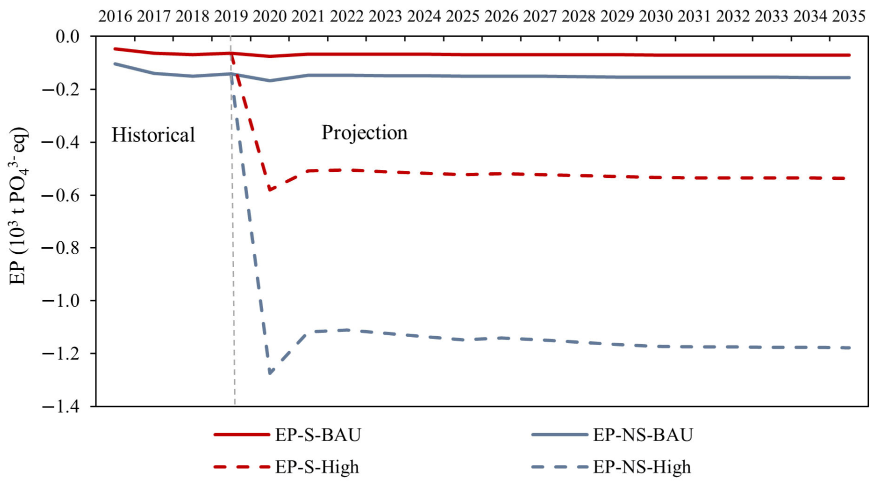

Figure A5. Projection of EP saving potential of ESR recycling in Shenzhen. Note: S = sintering; NS = non-sintering; BAU = business-as-usual scenario (5% of ESR recycling); high = high scenario (38% of ESR recycling).

References

1. NBS. Total Output Value of Construction. 2022. Available online: https://data.stats.gov.cn/english/easyquery.htm?cn=C01 (accessed on 30 December 2023).
2. Yu, B.; Wang, J.; Wu, H.; Wong, A.B.; Liao, Y.; Zuo, J. Self-fulfillment degree of construction and demolition waste management capability based on the Triple-balance theory: A case study of Guangdong-Hong Kong-Macao Greater Bay Area. *Waste Manag.* **2021**, *133*, 99–109. [CrossRef]
3. Menegaki, M.; Damigos, D. A review on current situation and challenges of construction and demolition waste management. *Curr. Opin. Green Sustain. Chem.* **2018**, *13*, 8–15. [CrossRef]
4. Duan, H.; Miller, T.R.; Liu, G.; Tam, V.W. Construction debris becomes growing concern of growing cities. *Waste Manag.* **2019**, *83*, 1–5. [CrossRef] [PubMed]
5. Wu, H.; Zuo, J.; Zillante, G. Status quo and future directions of construction and demolition waste research: A critical review. *J. Clean. Prod.* **2019**, *240*, 118163. [CrossRef]
6. Kabirifar, K.; Mojhatedi, M.; Wang, C.; Tam, V.W.Y. Construction and demolition waste management contributing factors coupled with reduce, reuse, and recycle strategies for effective waste management: A review. *J. Clean. Prod.* **2020**, *263*, 121265. [CrossRef]
7. Zheng, L.; Wu, H.; Zhang, H.; Duan, H.; Wang, J.; Jiang, W.; Dong, B.; Liu, G.; Zuo, J.; Song, Q. Characterizing the generation and flows of construction and demolition waste in China. *Constr. Build. Mater.* **2017**, *136*, 405–413. [CrossRef]
8. Huang, B.; Wang, X.; Kua, H.; Geng, Y.; Bleischwitz, R.; Ren, J. Construction and demolition waste management in China through the 3R principle. *Resour. Conserv. Recycl.* **2018**, *129*, 36–44. [CrossRef]
9. Ye, G.; Yuan, H.; Shen, L.; Wang, H. Simulating effects of management measures on the improvement of the environmental performance of construction waste management. *Resour. Conserv. Recycl.* **2012**, *62*, 56–63. [CrossRef]
10. Ferronato, N.; Moresco, L.; Lizarazu, G.E.G.; Portillo, M.A.G.; Conti, F.; Torretta, V. Comparison of environmental impacts related to municipal solid waste and construction and demolition waste management and recycling in a Latin American developing city. *Environ. Sci. Pollut. Res.* **2021**, *30*, 8548–8562. [CrossRef]
11. Duan, H.; Wang, J.; Huang, Q. Encouraging the environmentally sound management of C&D waste in China: An integrative review and research agenda. *Renew. Sustain. Energy Rev.* **2015**, *43*, 611–620.
12. *CJJ/T 134-2019*; Technical Standard for Construction and Demolition Waste Treatment 2019. Ministry of Housing and Urban-Rural Development of the People's Republic of China: Beijing, China, 2019.
13. Zhou, W. *Construction and Demolition Waste Resource Utilization*; Ministry of Ecology and Environment the People's Republic of China: Beijing, China, 2020; p. 8.
14. MEEBSZ. *Shenzhen Solid Waste Pollution Prevention and Control Information Bulletin (2014–2021)*; Shenzhen Municipal Ecological Environment Bureau (SMEEB), Ed.; Shenzhen Ecology and Environment Bureau: Shenzhen, China, 2022.
15. Yin, Y.; Li, B.; Wang, W.; Zhan, L.; Xue, Q.; Gao, Y.; Zhang, N.; Chen, H.; Liu, T.; Li, A. Mechanism of the December 2015 catastrophic landslide at the Shenzhen landfill and controlling geotechnical risks of urbanization. *Engineering* **2016**, *2*, 230–249. [CrossRef]
16. Yang, H.; Xia, J.; Thompson, J.R.; Flower, R.J. Urban construction and demolition waste and landfill failure in Shenzhen, China. *Waste Manag.* **2017**, *63*, 393–396. [CrossRef]
17. Gao, Y.; Yin, Y.; Li, B.; He, K.; Wang, X. Post-failure behavior analysis of the Shenzhen "12.20" CDW landfill landslide. *Waste Manag.* **2019**, *83*, 171–183. [CrossRef]
18. Zhang, N.; Duan, H.; Sun, P.; Li, J.; Zuo, J.; Mao, R.; Liu, G.; Niu, Y. Characterizing the generation and environmental impacts of subway-related excavated soil and rock in China. *J. Clean. Prod.* **2020**, *248*, 119242. [CrossRef]
19. Zhang, N.; Zhang, H.; Schiller, G.; Feng, H.; Gao, X.; Li, E.; Li, X. Unraveling the Global Warming Mitigation Potential from Recycling Subway-Related Excavated Soil and Rock in China Via Life Cycle Assessment. *Integr. Environ. Assess. Manag.* **2021**, *17*, 639–650. [CrossRef]
20. Ma, W.; de Jong, M.; Zisopoulos, F.; Hoppe, T. Introducing a classification framework to urban waste policy: Analysis of sixteen zero-waste cities in China. *Waste Manag.* **2023**, *165*, 94–107. [CrossRef]
21. Tong, Y. Study on Planning Strategy of Construction Waste Resource Utilization-Taking Chaoyang District of Beijing as an Example. Master's Thesis, Beijing University of Civil Engineering and Architecture, Beijing, China, 2021.
22. Bai, J.; Zhang, Y.; Liu, H. Study on the Generation Characteristics and Optimistic Management Characteristics of the Engineering Excavated Soil and Rock in Shenzhen. *Environ. Sanit. Eng.* **2021**, *29*, 16–21.
23. Hale, S.E.; Roque, A.J.; Okkenhaug, G.; Sørmo, E.; Lenoir, T.; Carlsson, C.; Kupryianchyk, D.; Flyhammar, P.; Žlender, B. The reuse of excavated soils from construction and demolition projects: Limitations and possibilities. *Sustainability* **2021**, *13*, 6083. [CrossRef]
24. Lin, Y.; Fang, Y.; He, C. Investigations of filter-clog mechanism and prediction model of slurry penetration during slurry pressure transfer. *Acta Geotech.* **2023**, *18*, 5251–5272. [CrossRef]
25. Xiao, J.Z.; Shen, J.Y.; Gao, Q.; Ma, Z.M.; Li, F.A. Current situation and innovative technology for recycling of engineering waste soil. *J. Archit. Civ. Eng.* **2020**, *37*, 1–13.
26. Bai, J.; Kang, P.; Zhang, W.; Chen, K.; Zhang, Y.; Zhou, D.; Duan, H. Feasibility study on using excavated soil and rock to sintering utilization. *Circ. Econ.* **2022**, *1*, 100007. [CrossRef]

27. Ma, Z.H.; Wang, W.J.; Zhang, G.Z. Study on City Engineering Waste Resources Classification and Comprehensive Utilization. *Jiangsu Architec.* **2015**, *6*, 100–103.
28. Zhu, K.; Zhang, Y.; Xue, Z.; Hu, D.; Zhang, K. Environmental issues and green treatment of shield residues. *Urban. Archit.* **2018**, *29*, 108–110. (In Chinese)
29. Guo, W.S.; Wang, B.Q.; Li, Y.Z.; Mo, S. Status quo and prospect of harmless disposal and reclamation of shield muck in China. *Tunn. Constr.* **2020**, *40*, 1101. (In Chinese)
30. Magnusson, S.; Lundberg, K.; Svedberg, B.; Knutsson, S. Sustainable management of excavated soil and rock in urban areas—A literature review. *J. Clean. Prod.* **2015**, *93*, 18–25. [CrossRef]
31. Jain, S.; Singhal, S.; Pandey, S. Environmental life cycle assessment of construction and demolition waste recycling: A case of urban India. *Resour. Conserv. Recycl.* **2020**, *155*, 104642. [CrossRef]
32. Borghi, G.; Pantini, S.; Rigamonti, L. Life cycle assessment of non-hazardous Construction and Demolition Waste (CDW) management in Lombardy Region (Italy). *J. Clean. Prod.* **2018**, *184*, 815–825. [CrossRef]
33. *ISO 14040*; Environmental Management: Life Cycle Assessment; Principles and Framework. ISO: Geneva, Switzerland, 2006.
34. *ISO14044*; Environmental Management—Life Cycle Assessment: Requirements and Guidelines. ISO: Geneva, Switzerland, 2006.
35. Ginga, C.P.; Ongpeng, J.M.C.; Daly, M.K.M. Circular economy on construction and demolition waste: A literature review on material recovery and production. *Materials* **2020**, *13*, 2970. [CrossRef]
36. Qiao, L.; Tang, Y.; Li, Y.; Liu, M.; Yuan, X.; Wang, Q.; Ma, Q. Life cycle assessment of three typical recycled products from construction and demolition waste. *J. Clean. Prod.* **2022**, *376*, 134139. [CrossRef]
37. Quina, M.J.; Garcia, R.; Simões, A.S.; Quinta-Ferreira, R.M. Life cycle assessment of lightweight aggregates produced with ashes from municipal solid waste incineration. *J. Mater. Cycles Waste Manag.* **2020**, *22*, 1922–1931. [CrossRef]
38. Kvočka, D.; Lešek, A.; Knez, F.; Ducman, V.; Panizza, M.; Tsoutis, C.; Bernardi, A. Life cycle assessment of prefabricated geopolymeric façade cladding panels made from large fractions of recycled construction and demolition waste. *Materials* **2020**, *13*, 3931. [CrossRef]
39. Seco, A.; Omer, J.; Marcelino, S.; Espuelas, S.; Prieto, E. Sustainable unfired bricks manufacturing from construction and demolition wastes. *Constr. Build. Mater.* **2018**, *167*, 154–165. [CrossRef]
40. Bovea, M.D.; Powell, J.C. Developments in life cycle assessment applied to evaluate the environmental performance of construction and demolition wastes. *Waste Manag.* **2016**, *50*, 151–172. [CrossRef] [PubMed]
41. Cellura, M.; Longo, S.; Mistretta, M. Sensitivity analysis to quantify uncertainty in life cycle assessment: The case study of an Italian tile. *Renew. Sustain. Energy Rev.* **2011**, *15*, 4697–4705. [CrossRef]
42. Mei, C. The effect of fuel blending on the production and quality of internal combustion bricks. *Brick Tile World* **2012**, *6*, 24–25+44.
43. Shubbar, A.A.; Sadique, M.; Kot, P.; Atherton, W. Future of clay-based construction materials—A review. *Constr. Build. Mater.* **2019**, *210*, 172–187. [CrossRef]
44. Moazzem, S.; Wang, L.; Daver, F.; Crossin, E. Environmental impact of discarded apparel landfilling and recycling. *Resour. Conserv. Recycl.* **2021**, *166*, 105338. [CrossRef]
45. Hung, M.-L.; Ma, H.-W. Quantifying system uncertainty of life cycle assessment based on Monte Carlo simulation. *Int. J. Life Cycle Assess.* **2009**, *14*, 19–27. [CrossRef]