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Review

Municipal Solid Waste as a Substitute for Virgin Materials in the Construction Industry: A Review

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Abstract: Municipal solid waste (MSW) requires adequate management to mitigate the negative impacts caused by its poor disposal in the environment. It is composed of several fractions, such as organic waste, paper, cardboard, metals, plastic, and glass, among other valuable materials. An area of opportunity for its recovery is the construction industry, which currently consumes around 3000 million tons of natural resources annually and is responsible for 34% of greenhouse gas emissions into the atmosphere. There are examples of the worldwide reuse of MSW in construction materials: plastics have been incorporated as substitutes for sand in the production of concrete and pavements; paper as a hygrothermal and lighting regulator in buildings; and glass has been reused as fine aggregate in concrete mixtures, among others. In this paper, we revised how these MSW fractions have been used for designing and producing sustainable construction materials, thereby favoring a circular economy approach and reducing their landfilling. Opportunity areas for these materials to be developed and applied were also identified focusing on Latin America and the Caribbean.

Keywords: green economy; construction materials; environmental impacts; aggregate mining

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Citation: Lizárraga-Mendiola, L.; López-León, L.D.; Vázquez-Rodríguez, G.A. Municipal Solid Waste as a Substitute for Virgin Materials in the Construction Industry: A Review. *Sustainability* **2022**, *14*, 16343. https://doi.org/10.3390/su142416343

Academic Editor: Jonathan Oti

Received: 16 October 2022
Accepted: 5 December 2022
Published: 7 December 2022

1. Introduction

Municipal solid waste (MSW) comprises household waste, commercial waste, and institutional waste, as well as residues collected from street cleaning services, public areas, and private sectors [1]. Worldwide, 2.01 billion tons of MSW were produced in 2016 [2], which has environmental impacts on local, regional, and global scales. These impacts are exacerbated if MSW is not managed in an environmentally sound manner, and this is the case for at least a third of the MSW produced in the world [2]. Conventionally, MSW has been used as an energy source through incineration; however, this process generates acid gases, polychlorinated dioxins, and other persistent organic pollutants [3], for which it faces strong public opposition. The European Environment Agency, among others, has proposed preventing the generation of waste through a circular economy approach, promoting the adoption of technologies and solutions that lead to greener and healthier cities, such as the generation of hydrogen gas, bioethanol, or fertilizers from MSW [4]. Thus, a sustainable approach consists of comprehensive waste management, prioritizing value chains that recycle or reuse it.

In 2018, with more than 80% of its population living in cities, the Latin America and the Caribbean (LAC) region was the most urbanized in the world and, from this fact, their cities are key players in the circular economy transition [5]. MSW generated daily in the region was 541,000 tons in 2014, and this amount could increase to 670,000 tons per day by 2050 [5]. In 2016, 0.99 kg of MSW per inhabitant and per day were produced in LAC countries, with the following composition: organic waste (52%); paper and cardboard (13%); plastics (12%); glass (4%); metals (3%), and others (17%) [2]. However, the MSW composition, as well as its generation per inhabitant, are strongly dependent on the income level of each country [6].

As all throughout the Global South, open-air burning and uncontrolled landfilling are common practices in LAC countries, leading to public health, environmental, and economic problems, particularly for those living in marginal areas. This mismanagement occurs along with financial deficiencies, weak institutional functioning, and the presence of an informal recycling sector, among others [6].

The construction industry deeply influences the three pillars of sustainability: economy, society, and environment [7]. Concerning the latter, the construction sector consumes around 40% of primary energy use [8] and contributes to 34% of greenhouse emissions [9], both at the global level. These emissions derive from the energy used directly in buildings (for heating, cooling, ventilating, or water heating) and the energy embodied in on-site construction operations and in the products and services required for construction operations [8]. As far as material flows are concerned, this sector is responsible for 50% of resource consumption and 15% of freshwater use worldwide [10]. Thanks to these material flows, in 2020, the mass of anthropogenically constructed or modified matter exceeded that of living biomass, reaching about 1154 Tt [11]. This corresponds to a rate of 30 Gt per year [11]. Of this amount, at least 94% corresponds to materials directly associated with the construction industry, such as concrete, bricks, and asphalt [11]. Obviously, such intense use of materials leads to enormous waste flows, which are primarily generated as construction and demolition waste (CDW) at the end of the life of buildings and built infrastructure. Global CDW generation was estimated at 3 billion tons in 2012 by considering only 40 countries [12]. Other estimations consider that CDW accounts for 30% to 40% of total solid waste produced in the world [7,10].

Consequently, waste reuse or recycling in this sector represents a great opportunity to diminish the massive extraction of raw materials made today, and an abundant bibliography shows this. Several MSW materials have great potential to be used for this purpose, and therefore the objective of this research was to analyze examples of the incorporation of MSW fractions into construction materials, which could contribute to implementing a circular economy approach in a key sector while at the same time alleviating the problem represented by MSW. Although CDW could also be used for the same purpose [7,12], it was not included in this review. First, we developed a theoretical framework around two main concepts, namely, the waste management hierarchy and the circular economy. We focused this review on the LAC countries, and some circular economy initiatives developed in the region are also presented in the theoretical framework. Second, we presented examples of reusing or recycling MSW fractions in construction materials, for which we compiled their effects on the materials' properties and other considerations to be taken into account. Likewise, the need to reduce the extraction of natural stone materials that the world construction industry carries out at the present time was deepened, as well as the barriers limiting MSW reuse in construction and some strategies developed internationally to overcome them. Finally, the opportunity areas for the reuse of waste materials in the LAC construction industry were identified.

2. Theoretical Framework

2.1. The Waste Management Hierarchy and the Circular Economy

Since the early 1980s, the waste hierarchy principle has emerged as the predominant paradigm of solid waste management. One of the earliest precedents of this principle is the "ladder of Lansink", which was proposed in the Dutch parliament as a preferential order for waste management options: landfill, incineration, energy recovery, recycling, reuse, and reduce, with "landfill" and "reduce" as the least and the most acceptable practices, respectively [13]. One important distinction was made between reuse and recycling, which refer, respectively, to the new use or application of waste in its original form, and to the practice that converts waste into new products with some physicochemical reprocessing. As recycling requires more energy than reuse, and potentially new material inputs, the former option is lower in hierarchy than the latter. This scheme was embodied in the U.S. Pollution Prevention Act of 1990 and is now in most of the world's regulations. The waste hierarchy is almost always presented in pyramidal form, as in the Waste Framework Directive 2008/98/EC of the European Union or in the Waste and Climate Change Strategy Framework of the United Nations Environmental Programme [14] (Figure 1a). However, waste hierarchy is not fixed, and the positions of some options (i.e., incineration) in the hierarchy do not have a general consensus and remain contentious [1].

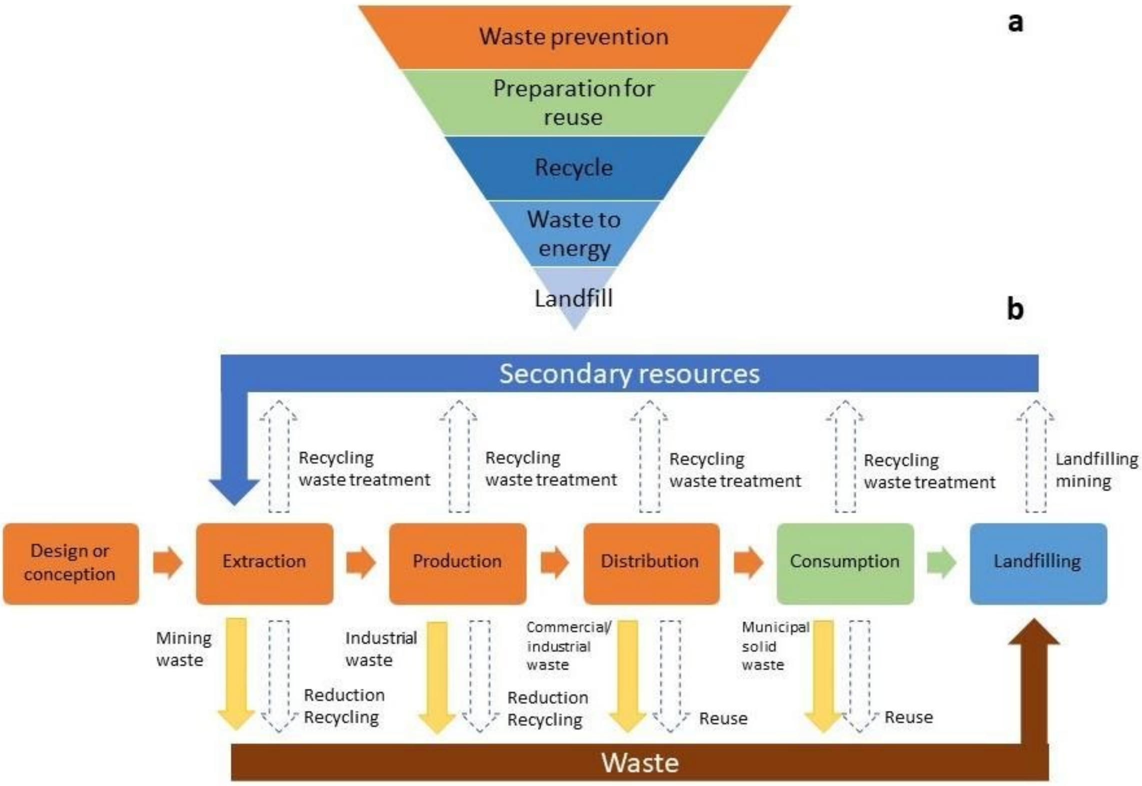

Figure 1. (**a**) Waste hierarchy principle according to the Waste and Climate Change Strategy Framework of the United Nations Environmental Programme [14]; (**b**) waste as a secondary resource (adapted from Chang and Pires [1]). In both diagrams, pre-use, use, and post-use phases appear in orange, green, and blue, respectively.

This paradigm relies on the conception of waste as a resource rather than as a public health problem. Waste becomes a secondary material derived from each life cycle stage of products, which can be redirected to the same production process or to others, used for energy production or new applications increasingly enabled by technological advances (Figure 1b) [1]. As in the pyramidal hierarchy, landfilling is only a marginal option for the waste fraction that cannot be reintroduced in this "circularized" system, and is not the main waste destination as it occurs today.

The circular economy approach emerged through the 3Rs rule, involving three main actions: namely, reduce, reuse and recycle, which were already present in the ladder of Lansink [13]. These actions are also hierarchized because the "reduce" option has priority over the others. Reducing waste mostly relies on the pre-use stages of products, that is, on their smarter conception and design, which is at the core of waste policymaking in China, the European Union, Japan, the Republic of Korea, and the U.S.A. [13], among many other countries.

The ultimate goal of the circular economy is to optimize resource use towards closed material loops inspired by natural biogeochemical cycles. This slows down material circulation and produces less waste, pollution, and emissions while using less energy. Over time, the waste-managing options were enlarged with additional "Rs"; for instance, Reike et al. [15] recognize 10 Rs (Refuse, Reduce, Resell/Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover energy, and Re-mine).

2.2. Circular Economy Initiatives in Latin America and the Caribbean

The concept of circular economy is gaining momentum in LAC countries, which are designing or even implementing policies, public initiatives, and roadmaps [5]. Additionally, schemes of shared producer responsibility are being increasingly incorporated, either in the general waste law or in specific regulations for a particular waste stream **[6]**. In 2021, a Circular Economy Coalition from Latin America and the Caribbean was launched, with the aim of developing a common regional vision with a holistic approach, and being a platform for sharing knowledge and tools and supporting the transition to the circular economy [16]. For this, the mining and extractive sector, waste recycling and management, and bioeconomy have been identified as priorities [5]. The circular economy is also increasingly considered a strategy to increase environmental and economic resilience in the context of post-COVID-19 recovery [5].

By virtue of the burden that MSW represents for the cities in LAC, several of them have designed their own circular economy plans. For instance, in Buenos Aires, Argentina, the Green City Plan was launched in 2012 to reduce MSW [5], and, in 2021, a Circular Economy Network was launched to foster responsible consumption, recycling, and reuse of resources in the industry [17]. Mexico City has recently banned single-use plastics and announced its Action Plan for a Circular Economy, which couples environmental goals with green job creation. This plan contemplates proper waste management infrastructure, the creation of cooperatives specialized in waste management, and education campaigns [18].

One of the distinctive features of these initiatives in the LAC countries, while also being their main challenge, is the relation between circular economy and inclusive recycling. Inclusive recycling situates within the larger scope of environmental justice, which stands against the neoliberal extractivist model, supports a justice-oriented approach to solving environmental degradation, and recognizes the right to resources for historically marginalized groups, among other crucial socioeconomic aspects. Inclusive recycling considers the urban poor more than just consumers and has been defined as waste management systems that prioritize recovery and recycling while recognizing and formalizing the role of recyclers as key actors in such systems [19]. Around 3.8 million of urban inhabitants of the LAC countries make their living from informal recycling, most of them in unsanitary conditions [20]. Chile and Brazil have made progress in the inclusion of informal recyclers (or "waste pickers") in new waste management systems [5], but Bolivia, Colombia, and Ecuador stand out in this process, mainly due to the actions undertaken by national organizations of informal recyclers. Because of this, around 1500 of them are formally paid by the city of Bogotá, Colombia, for their services in collecting and transporting recyclable materials [20]. Informal recyclers are considered a major driver for more sustainable waste management [21], and key to building just and livable cities in the LAC region [5].

3. Methodology

MSW includes several fractions such as organic waste, plastics, glass, paper and cardboard, metals, textiles, and other materials present in minor quantities. The organic fraction (including food waste, yard trimmings, and wood residues) is the most prominent in MSW produced in the LAC region [2], and its biodegradable nature enables its use in various clean processes, such as composting, or even for waste-to-energy purposes through anaerobic digestion. It is our view that such applications, rather in the scope of circular bioeconomy [22], should be preferred for the recycling of the organic fraction, which was not considered in this review as a result. After organic waste, paper and cardboard, plastics, and glass are the most abundant MSW fractions produced in LAC [2] and were also retained for this review by considering them to have the greatest potential for being reused in the construction sector from a technical perspective. Ashes produced by MSW incineration were also considered because their reuse for construction purposes may broaden the range of available options for this material, which is problematic from an environmental point of view [23].

We performed a search for articles in the Google Scholar, Scopus, and ScienceDirect databases using several combinations of the keywords "construction materials", "recycling", "reuse", and the MSW fractions retained for the review ("plastics", "glass", "paper and cardboard") along with "MSW incineration products" or "MSW incineration ashes". The articles were selected according to their relevance to the subject matter herein and analyzed. Our search period included the year 2000 to 2022; that is, from the proposal of the Millennium Development Goals [24], which are precursors of the Sustainable Development Goals. These constitute an internationally recognized roadmap to target many of the world's most pressing socio-ecological issues, including waste generation. Papers within the following search contexts were included in the review sample: (a) MSW reuse or recycling in construction; (b) aggregates substitution in construction; and (c) ecological building materials.

For each paper, it was determined if using any of the MSW fractions in a building material modified its physical or mechanical characteristics, and how sustainability was enhanced, mainly concerning the diminution in CO_2 emissions or the extraction of virgin aggregates. Attention was paid to the waste conditioning before their introduction in the construction materials (i.e., if they were cut, ground, or chemically treated), and if they were used as aggregate substitutes, additives, binding agents, or reinforcing fibers. The limitations or recommendations made by the authors of each study were also gathered. Figure 2 summarizes the methodology followed.

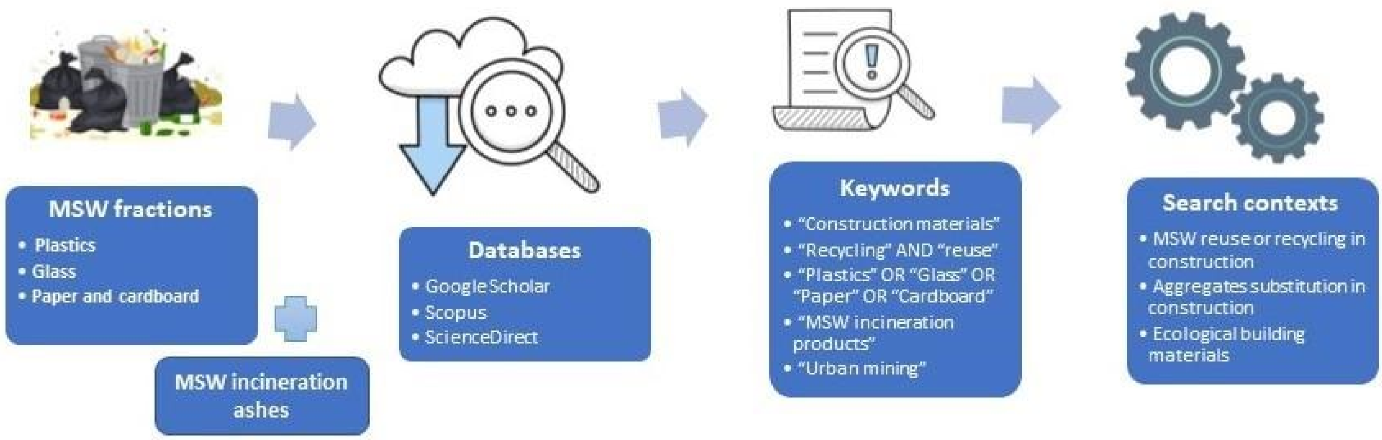

Figure 2. Diagram of the methodological process followed.

4. Municipal Solid Waste and Its Use in Construction

4.1. Plastics

Plastics are polymeric materials with numerous applications due to their malleability, lightness, stability, and thermal and electrical insulation capacity, among other properties. For this reason, their annual world production increased from 2 to 460 million tons between 1950 and 2019 [25]. The most produced plastics are polypropylene (PP, 16%), fibers (13%), low-density polyethylene (LDPE, 12%), high-density polyethylene (HDPE, 12%), polyvinyl (PVC, 11%), and polyethylene terephthalate (PET, 5%). More than 60% of world production is destined for packaging, construction, and transport [25].

The generation of plastic waste (PW) was estimated at 353 million tons in 2019, of which 50% went to landfills, 19% was incinerated, and only 9% was effectively recycled; the rest represents plastics that were open-air burned, ended up in uncontrolled dumps, or were dispersed in the environment [25]. The recycling rate of plastics is much lower than that of metals, paper, cardboard, or glass, partly because the heterogeneity of their composition, color, and transparency imposes restrictions on this practice [26].

Recycling and reuse of PW in construction allow for reducing the environmental problems that it causes and improving certain properties of conventional materials. The applications of plastics to construction materials can be classified into three categories:

(i) addition to concrete, as substitutes for aggregates or reinforcing fibers; (ii) incorporation into asphalt; and (iii) emerging applications, whether to build the base and sub-base of highways and roads, manufacture new composites that replace conventional materials (such as wood), or replace construction elements (such as bricks). Table 1 presents a summary of studies about construction materials modified by PW addition and the properties of the materials that were modified or affected. In the table, it is specified if the PW was recycled or reused, according to the waste hierarchy definitions presented above.

PW can be incorporated into concrete as aggregates or as fibers, although the first case is the most frequent; likewise, most of the reports refer to the use of PET [27]. An obvious advantage of the replacement of conventional materials by PW is that its low weight reduces the density of the concrete and therefore the dead weight of the work, which can be beneficial in certain cases [28]. As a general trend, the replacement of natural aggregates (up to 30–40%) by PW coarse aggregates increases the slump in the concrete [27,29,30], which is commonly used to indicate workability. An opposite trend is found when natural aggregates are replaced by fine PW [27].

Plastics can also be used as reinforcing fibers to improve the tensile strength of concrete. In practice, these fibers are mostly virgin PP (PET or LDPE are used to a lesser extent), have a length of 30 to 60 mm and a cross-section of 0.6 to 1 mm^2, and allow control of the plastic shrinkage and drying shrinkage [31]. However, the use of recycled plastic fibers, with their associated impurities and their different degrees of degradation, has not been generalized due to the variability of the mechanical properties of the resulting concrete, as well as the lack of data regarding its durability [28]. Yin et al. [32] produced fibers from recycled PP pellets and compared them with virgin PP fibers. They found that the addition of recycled PP fibers in low proportion (4 or 6 kg/m^3) did not affect the compressive strength of the concrete, and significantly improved its flexural tensile strength. In addition, they concluded that the post-cracking behavior of concrete reinforced with recycled PP fiber is similar to that of concrete reinforced with virgin PP fibers [32].

In general, the addition of fibers (natural or from recycled PW) improves the performance of concrete, increasing toughness, ductility, and impact resistance while reducing its weight and density, thus improving the strength-to-weight ratio of concrete [33]. Recycled fibers have the characteristic of controlling cracking due to plastic shrinkage and drying uniformity [34]. The presence of recycled fibers in the concrete does not affect the appearance of cracks, in addition to delaying their propagation compared to natural fibers [35]. The addition of fibers also reduces the permeability of concrete, which positively affects its durability; additionally, fibers reduce free water in the mix when it rises to the surface and forms a cement paste on the surface, known as laitance [36]. The main drawbacks of this concrete modification are the possibility of reducing workability and the higher costs associated with natural fibers compared to fibers derived from PW [37].

Another application of PW is its incorporation in asphalt mixtures. For this, either the dry or wet process is used. In the former, PW is added directly to the asphalt mix, either as an aggregate replacement or a mix modifier. In contrast, in the wet method, PW is added to the binder, which requires high temperatures and homogeneous mechanical mixing, and then to the rest of the aggregates [38]. The dry process can be applied in any asphalt plant without major modifications; on the other hand, in the wet process, specific mixing and storage facilities are required. Although this last aspect could be considered a limitation, the wet method is currently the most common since it allows better control of asphalt properties. The binder produced by the wet process has a high viscosity, which results in an adequate coating of the aggregates that excludes drainage problems, while the asphalt produced by the dry process has poor stability against water [38].

Table 1. Examples of construction materials modified with plastic waste.

Plastic Waste (PW) Description	Replaced or Added Amount	Effects of the Modification	Recycling/ Reuse	Reference
PET aggregates [1] (5–12 mm)	20%, 30%, 40%	The compressive strength of concrete with 20% PET replacement (30.3 MPa) was only 9% less than in the controls and had higher workability. This concrete can be used for structural purposes.	Recycling	[29]
LDPE fibers and/or PW aggregates [2] (4.75–20 mm)	1% fibers, 6–30% aggregates	Concrete with 1% of fibers had higher compressive and tensile strengths than the control. Replacement of natural materials by up to 30% of PW aggregates led to materials suitable for structural uses.	Reuse	[30]
PP fibers [3] (1.5 mm width, 0.7 mm thickness, 47 mm length)	4–6 kg/m^3	PP fibers had good resistance in concrete and other alkaline media. Concrete modified with PP fibers showed excellent post-cracking performance and ductility.	Recycling	[32]
HDPE [4] (0.125–4 mm) or EVA PW[4] (diameter < 4 mm)	5% PW in the binder	Asphalt mix (AC 14 SURF, prepared with aggregates and 70/100 pen-grade bitumen) was modified with PW through the wet process. The PW-modified binders were stiffer and more elastic when compared with the unmodified bitumen.	Recycling	[38]
PW [5] strips (12 mm width, 0.4 mm thickness, 12–36 mm length)	0.25–4% (ratio of PW weight to subbase weight)	Reinforcement with PW strips increased the strength and secant modulus of pavement sub-bases. The maximum improvement was obtained with a 4% addition of 36 mm length PW strips.	Reuse	[39]

[1] Aggregates were prepared by shredding, melting, and crushing PET bottles from drinks and food containers. [2] Fibers were made by cutting low-density polyethylene packaging waste (plastic bags, cling film, plastic wrapping) in laminar strips (0.15–1 mm width). Aggregates were prepared by melting and crushing mixed plastic waste. [3] Fibers were made by extruding, spinning, and stretching polypropylene waste, mainly from food and pharmaceutical bottles and kitchenware, among others. The stabilized material was indented, winded, poly-wrapped, and cut. [4] PW consisted of high-density polyethylene (HDPE) and ethylene vinyl acetate (EVA), mainly from milk jars, detergent bottles, and toiletries containers. [5] PW consisted of high-density polyethylene (HDPE), mainly from butter tubs, auto parts, and juice bottles.

LDPE and HDPE are the most promising plastics as asphalt modifiers [28]. However, a recent study concluded that incorporating LDPE, PE, and PP into the asphalt with the wet method resulted in an earlier release of microplastics compared to the substitution of stone aggregates by PET and acrylonitrile butadiene styrene particles through the dry method [40]. In addition, low temperatures and weathering at low pH values favored the detachment of microplastics from the modified asphalts. This study is an example of the research needed to ensure the sustainability of PW employment in construction, demonstrating that it is not enough to evaluate the properties (resistance or durability, for example) of the modified material. Still, it is also necessary to know the eventual release of hazardous materials, the economic benefit, and the implications on CO_2 emissions through a life-cycle analysis [26].

As far as emerging applications are concerned, PW has replaced a fraction of aggregates in the base and sub-base construction of pavements, for which improvements in deformation resistance and load-bearing capacity have been determined [28,39]. Increasingly, constructive elements made with remolded PW are available commercially or in street furniture, either alone or in composites with other materials such as wood. Additionally, plastic bottles can be arranged in various ways to build walls; bottles are often held together with ropes or inside wire structures or lined with masonry. For instance, in a study, masonry wall blocks were built with waste PET bottles filled with either dry sand, saturated sand, or air, and bound by cement mortar [41]. The blocks made of air-filled bottles showed slightly higher compressive strength than the other plastic-modified blocks and had structural stability. The gross strength of these plastic-modified blocks (670 kN/m^2) was significantly lower than the traditional blocks' strength (3670 kN/m^2). However, the authors suggested that the blocks modified with air-filled bottles still can be used as well-suited construction units for partition walls or as bearing walls for one roof slab. Additionally, blocks built with air-filled bottles could act as thermal insulation material because they had better thermal insulation performance than the traditional blocks tested [41].

These structures can only withstand low loads but can be used to build complete houses. The great diversity of applications available on the internet indicates the creativity with which many people in the world are reusing this abundant waste.

4.2. Glass

Glass is a very versatile and inert material. However, it is not biodegradable, so once it is disposed of, it can remain in nature as waste for at least a million years before it decomposes naturally [42]. If one ton of glass is reused in the cement industry, 560 kg of sand, 190 kg of soda ash, 176 kg of limestone, and 64 kg of feldspar can be preserved [43]. Its reuse as a ground powder in clinker production process helps reduce air pollution [44]. This makes it an attractive reusable material because concrete is the most used construction input worldwide. Currently, traditional glass production leads to negative environmental impacts during the aggregate extraction and manufacturing processes, such as high energy consumption and CO_2 emissions [44]. Among its main applications in the construction industry are the production of concrete, mortar, and asphalt pavement; additionally, they are an alternative for the non-chemical treatment of clay soils. There is a variety of glass types (soda lime glass, lead glass, crystal glass, borosilicate glass, and electric glass), but these should not be mixed for reuse [43]. Each type of glass is manufactured at different melting temperatures, which currently makes their use in combination unfeasible [45]. It has been pointed out that only 5 g of non-recyclable glass could contaminate one ton of recyclable glass [45].

When glass is crushed and sieved, it acquires engineering properties similar to sand and other fine materials [46]. For example, substituting natural aggregates with glass improved the workability of concrete thanks to its non-absorbent properties. This improvement may depend on the particle size of the replaced aggregates, so it is important to determine their ideal granulometry [46]. It has been found that adequate glass amounts for the replacement of fine aggregates vary between 20–30% and between 10–20% for replacing coarse aggregates [44]. Equally, substituting 20% of fine aggregates with glass improved the concrete workability compared to conventional concrete [43]. Another study partially replaced cement with ground glass and improved the resistivity of the concrete surface, as well as its resistance to sulfate attack; in addition, chloride ion penetrability and drying shrinkage were reduced [46].

Table 2 summarizes some applications of glass waste on construction materials. Glass was only ground before being incorporated into these construction materials, and consequently they are examples of waste reuse. The compressive strength of the modified materials changes according to the glass fineness and substitution ratio; in this way, compressive strength can decrease along with a glass dosage increase from 20% to 40% [47]. However, the pozzolanic reactivity of the glass after 28 days compensates for the loss of strength, because the pozzolanic reaction improves drastically due to the reduction of the particle size, showing significant increases in compressive strength in stages after 28 days [48]. For a glass content greater than 10%, the effect of fineness on strength behavior was limited, as nearly all glass particle sizes resulted in a comparable compressive strength decrease with respect to conventional concrete [49]. In other words, aggregates can be replaced up to 10% with glass waste of any size without significantly affecting the material's strength.

Table 2. Examples of construction materials reusing glass waste.

Particle Size	Substitution Ratio	Effects of the Substitution	Reference
75 µm	20% and 40%	Glass powder was added as a potential enhancer of the permanent deformation resistance of paving materials (asphalt mortars).	[42]
0.3 mm	20%	Fine aggregates increased concrete workability data.	[43]
<0.60 mm	20–30%, 10–20% [1]	Both combinations were appropriate for concrete manufacturing.	[44]
4.75 mm	30%	Glass was added to expansive clay as a non-chemical soil treatment approach (113% increase in resilient modulus of clay).	[50]
<45 µm	20%	Direct replacement of cement by waste glass powder increased the compressive strength of foam concrete.	[51]

[1] Fine aggregates and coarse aggregates, respectively.

However, a decrease in the concrete workability could result from the aggregate substitution with glass, because these artificial aggregates have smooth surfaces, sharp edges, and rough textures that affect the fluidity of the concrete [43]. Another disadvantage is that reused glass has about 70% amorphous silica [44]. Hence, an alkali–silica reaction occurs [46] that can cause microcracks or swelling in concrete and affect its mechanical properties [43]. This can be mitigated by using glass particles smaller than 0.3 mm, modifying their chemical composition, or sealing the concrete to prevent moisture from entering [43].

The use of glass as fill material in roads is another sustainable alternative, since among its proven advantages are the improvement in the thermal susceptibility of its surfaces, its fatigue performance, the increase in its resistance to plastic deformation, and rutting at high temperatures [42]. When there are expansive clay soils in the subgrade layer, replacing the natural material with low percentages of glass (of the same size as sand) acts as a non-chemical treatment that improves its mechanical properties by reducing vertical and horizontal deformations in this layer's matrix [50].

This waste has also been used in the production of cellular concrete, which has low weight, low density, high fluidity and is self-compacting. In addition, it contains little aggregates and is a thermal and acoustic insulator [51]. A total of 10% crushed glass smaller than 38–45 µm mixed with cement and superplasticizers has been used to produce this type of concrete. It was found that the finer the glass, the less alkali–silica reaction occurred, thanks to its significant pozzolanic activity [51]. Although there are some disadvantages to incorporating waste glass into building materials, as already mentioned, its advantages are a starting point to explore more efficient reuse and recycling techniques.

4.3. Paper and Cardboard

Worldwide, around 4 billion trees are felled each year to produce 450 million tons of paper and cardboard [52]. Once disposed of, they represent the largest volume accumulated in landfills after glass and plastic. Fortunately, their recycling capacity is very wide and there are examples of their use in construction materials, such as mortar and cement, due to its non-hazardous nature [53]. For example, this waste was used as cardboard pulp to partially replace the cement content in boardcrete, which is a material that can replace bricks in buildings thanks to its cellulose content, which acts as a fibrous material [52]. The authors concluded that this waste can be used in non-load-bearing or non-structural walls. Its main advantage is that it is a permeable, solid, and heterogeneous material that facilitates heat transfer by conduction [52]. One disadvantage is that there are no regulations suitable for the manufacture and testing of this material, so future studies must be based on adapting procedures established for other construction materials.

The use of fibers obtained from these residues was very common in the works consulted in this review. For example, Haigh et al. [54] used kraft fibers to improve the mechanical properties of concrete. This type of fiber comes from the cellulose of the plants and trees from which the paper or cardboard was initially obtained. Utilizing a complex chemical treatment (chemical sulfate method), the authors eliminated the lignin adhered to the fibers to increase their dispersion and random size. It was mentioned that to improve the mechanical and durability properties of these fibers, it is necessary to modify their matrix and give a pretreatment to reduce their degradation [53]. An advantage of recycling this waste as fibers is that they are non-abrasive, high-strength, low-density, and inexpensive. As a disadvantage, its degradation can weaken the fiber and make it brittle, reducing the useful life of the material in which it is used [54]. Therefore, the authors recommend including cement-based compounds to reduce calcium hydroxide, which causes this degradation.

Another limitation found in the bibliography is that composites reinforced with natural fibers, such as those obtained from paper and cardboard, tend to absorb more water due to their high porosity and hydrophilic nature [55]. To counteract this absorption effect, calcium carbonate has been used with good results [52]. It has been emphasized that, when used as cardboard tubes and honeycomb sheets in the construction of architectural elements, they have sufficient compressive and tensile strength for light structures. A case in point is the contemporary architecture exhibited since the 1980s by the Japanese architect Shigeru Ban through houses, public buildings, and temples [56].

In another study, corrugated cardboard was used in the core of sandwich beams in conjunction with a polymer [57]. This type of structure tends to have low density, which can reduce the structure's weight and increase its resistance and rigidity. The authors found that beams using corrugated cardboard cores had a thirteen-times-higher shear modulus than a polypropylene honeycomb material of the same thickness. Likewise, they had 40% less apparent density, which makes them a suitable substitute ecological material. A disadvantage that was mentioned is that its thermal conductivity, although encouraging, is still low (λ~0.05 W/mK) [58]. Despite not reaching optimal values as a thermal or acoustic insulator, recycled cardboard, unlike traditional insulation materials, can be easily treated and reused, thus reducing the consumption of virgin raw materials [59]. Table 3 presents some examples of construction materials modified with waste paper and cardboard.

Table 3. Examples of construction materials reusing waste paper and cardboard.

Waste Description	Enhanced Property	Observations	Reference
Cardboard pulp	Density: 0.8 g/cm^3	Boardcrete (a mix of cardboard pulp, cement, and sand) was employed as lightweight building construction blocks.	[52]
Kraft fibers	-	A total 1–15% of natural fibers were used as reinforcement agents in cement-based composites.	[53]
Kraft fibers modified with silica fume	-	A total 5% of modified Kraft fibers were added to the concrete mix, reducing its alkaline level.	[54]
Cork and paper waste fibers	-	A total 60% (v/v) of fibers were added to gypsum (40%, v/v). The composites provided low thermal insulation.	[55]
Corrugated paper	Bulk densities: 170, 127, and 138 kg/m^3	Sandwich beams elaborated with corrugated paper had high shear modulus and low density.	[57]
Paper	Thermal conductivity: 0.038 W/mK	Authors employed different layers of paper, compressed by steel bars and coated with gypsum plaster, in a refugee construction.	[58]
Cardboard	Thermal conductivity: ~0.05 W/mK	Insulating cardboard panels from the packaging industry can be considered a promising recycled insulation material.	[59]

4.4. Ashes from the MSW Incineration

One of the procedures used to reduce the waste volume is incineration, which allows MSW mass reduction by up to 70–90% while producing energy [60]. However, dangerous pollutants produced by incineration, namely particulates (PM_{10}), acid gases (as NOx and SO_2), heavy metals, polychlorinated dibenzo-p-dioxins and furans, polycyclic aromatic hydrocarbons and polychlorinated biphenyls, generate widespread concern about their impact on the population exposed [3,61]. Several adverse health effects, such as some neoplasia, congenital anomalies, infant deaths, and miscarriage have been associated with waste incineration, particularly in old facilities [62]. However, these risks appear to be minimized in modern MSW incinerators, as indicated by a national-scale study that found no evidence for increased risk of a range of birth outcomes, including birth weight, preterm delivery, and infant mortality, in relation to exposure to PM_{10} from incinerators operating under current European standards [63].

In an incinerator, the solid product is recovered as bottom ash (BA) and fly ash (FA). BA is a mixture of particles with a heterogeneous composition that varies from silt and clay to gravel. BA also contains metals and various contaminants (mainly chlorides). If metals are recovered through vitrification and physical separation, BA can be transformed into a safe material suitable for reuse [64]. These ashes represent about 80% of the incinerated raw material. Hence, their recovery is a very important area of opportunity [65].

In contrast, FA is formed in the incineration system and transported with combustion gases; it can be recovered through filters or other air pollution control devices [66]. These ashes are considered hazardous waste since they contain heavy metals (Cr, Cd, Pb, and Zn) [60] and dioxins [66]. As an alternative to their immobilization, geopolymer compounds have been used through a stabilization–solidification system to fix the metals in the polymer network [60]. Bottom ash, due to its amorphous fraction and high content of silica and other oxides (CaO, Al_2O_3, and Fe_2O_3), can be used as a precursor for these geopolymers that transform fly ash into a non-hazardous material [60]. However, it is recommended to use less than 5% by weight of this residue to achieve such efficiency [67]. Through this transformation process, positive environmental effects were also achieved, since lower energy consumption (75.7%) and lower CO_2 emissions (75.9%) were obtained [67]. Likewise, since its chemical composition is similar to Portland cement, the ashes have been used to make other associated materials, such as clinker, combined cement, ecological cement, aggregates, ceramic tiles, and pavers, as well as road bases [68].

Although there are many studies on using these residues in the construction industry, there are still certain restrictions that are worth exploring. For example, the aluminum in the ashes used as fine aggregate in mortars produced cracks due to the aluminum hydroxide that makes the material extra-porous [69]. It was also determined that if the necessary amount of water is used in the paste and its workability is controlled, a mortar with properties similar to a conventional one can be obtained [70]. Another factor that can affect the strength of ash-mixed concrete is that it contains little SiO_2, which produces a porous texture [65]. This porosity can be reduced using lower proportions of ashes as fine aggregate or cement (less than 30% substitution). Furthermore, if vitrification is used to solidify the heavy metals present in these residues, it is possible to reduce their leaching over time [71]. Table 4 includes some applications of MSW incineration ashes to construction materials.

Table 4. Examples of construction materials reusing MSW incineration ashes.

Ash Description	Addition Ratio	Observations	Reference
BA composed of sand and gravel (60–90%), and silt and clay (5–15%)	-	If it is finely ground, BA might show pozzolanic or hydraulic behavior and be employed as an alternative light aggregate.	[65]
FA consisting of light fine-grained particles	5–20%	FA could be used as a source of lime in the cement industry.	[65]

Table 4. *Cont.*

Ash Description	Addition Ratio	Observations	Reference
FA (soluble salts content below 10 wt%)	-	The presence of soluble salts in FA was detrimental to physical–mechanical properties. For the production of fired clay brick, FA can be used only after desalination.	[66]
FA	<5 wt%	Employment of construction and demolition waste-based geopolymer for the solidification/stabilization of FA. The compressive strength of the geopolymer was improved.	[67]
FA	5 wt%	A strong alkaline activator and a compaction pressure as a thermodynamic process were employed. FA contributed to forming strong solids with relatively high flexural and compressive strengths.	[68]
Ash	25%	Ash was used as a cement replacement in mortar production. A pretreatment assured mitigating expansion, hydration, and strength development.	[69]
BA	40%	BA was used as a cement replacement in paste and mortar. Water demand on paste and workability on mortar were similar to the values presented by common concrete mixtures.	[70]
FA	30 wt%	FA was used to prepare foam ceramic, whose thermal insulation performance was adequate.	[71]

5. Waste Reuse and Recycling in Sustainable Construction

In Global South countries, the construction industry accounts for 80% of the total capital asset, 10% of their gross domestic product, and more than 50% of the investments in fixed assets [72]. However, as previously mentioned, direct or embodied energy use in the sector is highly unsustainable. The manufacture of concrete alone generates 8% of the total CO_2 emissions associated with buildings and construction [73], mainly due to the calcination process during cement production [74]. Since this energy is currently mostly provided by nonrenewable sources, its use constitutes a key unsustainability factor.

To effectively solve this problem, as already pointed out, any material modification with MSW should be accompanied by a life-cycle analysis that determines its real environmental implications. For example, Akbar and Liew [75] determined, after an analysis of this type, that it was possible to reduce CO_2 emissions from cement composites by 13.7% by adding 1% recycled carbon fiber. This was achieved due to the recycled carbon fiber improving the mechanical properties of the material (elastic modulus, tensile strength, fracture toughness, for example) compared to a conventional paste (without fibers). However, the authors pointed out that these percentages could not be exceeded to ensure that the properties of the concrete were not negatively modified. In another similar study, ground bottom ash was used as a substitute for sand to produce alkali-activated mortars [76]. Although rapid carbonation occurred, the strength of the mortar increased considerably. This process allowed CO_2 emission reduction by 55–75% compared to materials obtained from cement [76]. From the foregoing, it is inferred that MSW is an alternative method of producing supplies and construction materials that are friendly to nature.

5.1. Towards a Crisis of Aggregates?

Aggregates have become the most extracted and consumed material in the world. For sand alone, a conservative estimate of the amount mined is 40 Gt per year [77], making it the second most-used natural material after water and the most mined material globally [78]. Furthermore, aggregates are not only involved in the construction of buildings and infrastructure; they are also immersed in screens and cell phones, among other technological products, and their demand is growing in the energy sector for hydraulic fracturing (or fracking) of hydrocarbons [79].

This huge extraction of aggregates cannot occur without environmental and social costs. In their original ores, aggregates provide innumerable ecosystem services, such as the support of agricultural and fishing activities, the treatment and purification of water, protection against floods and natural disasters, and the assurance of aesthetic and cultural values through access to clean beaches and water bodies [80]. On the one hand, the exploitation of material banks for their extraction reduces green areas in an unsustainable way; this causes potential threats to life support systems, such as recharging water sources, and prevents their environmental role as carbon sinks [81]. On the other hand, aggregate mining is relatively simple compared to the extraction of other mineral resources (such as metallic ore), and therefore it is often accompanied by black markets, illegal extraction, and violence against local communities opposed to this practice [78,80]. In some places, such as Malaysia, there have been crises in the supply of aggregates, which have highlighted the importance of guaranteeing mineral security for the country's development [82]. Likewise, about 25 Indonesian islands have disappeared due to the constant extraction of sand to fill the coastlines of tourist destinations affected by erosion, and in the Canary Islands, sand from the Sahara is continuously imported for the regeneration of beaches and the construction of buildings [83].

The LAC region is characterized by a large contribution to the world's social metabolism. Material flow analyses have shown that extraction of materials (metal ores and industrial minerals, fossil fuels, biomass, and construction materials) in LAC surpassed 8 billion tons in 2008, which corresponds to 13.6 tons per capita (approximately 30% higher than the global average per capita) [84]. Furthermore, given that its exports largely exceed its imports, the region is a net supplier of materials to the rest of the world. Net supplies from the region were 4 million tons in 1900, and 610 million in 2016 [85]. This material deficit has increased inexorably, making the LAC region (along with Central Asia) the highest net supplier of materials per inhabitant in the world (one ton per capita per year) [85]. As the export profile of the region is quite diverse, the range of environmental impacts derived from these exports is also wide [85]. Likewise, this material extraction intensity is linked to the displacement of commodity frontiers to new territories, leading to local resistance and conflicts [85]. For instance, in 2019, 43 Mt of cement were produced in Mexico, and 3.14 Gt of stone aggregates, gravel, and sand were extracted [86] to satisfy the country's high urbanization rate. As demand grows, aggregates are extracted from surface deposits in rural or peri-urban areas. This mining increasingly competes for space with other land uses, such as agriculture, and affects greatly the way of life of the communities involved [79]. Finally, although aggregate operators often claim to rehabilitate the quarries once the exploitation is over, in truth they simply abandon old sites or fail to remediate the damages caused [87].

Therefore, circular economy adoption in the construction industry might slow down the intense exploitation of aggregates in the LAC region and worldwide. In particular, the recycling and reusing of waste in concrete represent a great opportunity to mitigate some of these environmental and social impacts, since this material is produced in enormous quantities (10,000 million cubic meters in 2012) [88]. If 17,518 Mt of aggregates were used to produce the aforementioned amount [88], even the substitution of a small percentage of these by residues can represent a great opportunity to reuse them, as well as to reduce the extraction of natural aggregates and reduce their socio-environmental impacts.

5.2. Barriers Limiting MSW Employment in Construction

The reuse and recycling of MSW in construction materials such as concrete present a wide variety of options; however, it is important to keep in mind that the partial substitution of natural aggregates with residues can reduce some of their properties, such as workability or cohesive strength [43]. By crushing the glass, irregular shapes can be obtained that alter the internal friction in pavements and decrease their slip resistance [42]. The presence of silica in glass is another characteristic that requires detailed analysis. Since glass and cement are chemically incompatible, an alkali–silica reaction occurs that expands the concrete and produces cracks [51], affecting the material strength [46].

The use of plastic in the production of construction materials also has challenges to overcome. Hama and Hilal [89] found that the shape and the added proportion of plastics affect the workability of fresh concrete, and that a higher proportion of PW (PET and fragments, primarily polycarbonate and PP) with an angular shape decreases the concrete settlement. These authors also determined that round-cut HDPE residues slightly improve the flowability (and workability) of fresh concrete relative to controls to which no PW was added. The substitution of aggregates with 20% ground PW decreased the settlement of fresh concrete by 25%, although to a value still considered acceptable [90]. Given that a 72% decrease in compressive strength was also determined for the modified concrete with 20% PW, the authors recommended that the substitution with PW be carried out in a controlled manner and depending on the structural element to be built [90]. Similarly, it has been mentioned that PW reduces the flexural and tensile strength of concrete due to insufficient bonding between the former and the concrete paste, as well as to a higher air content [27,28], and that surface treatment with sodium hypochlorite or sodium hydroxide improves the properties of PW-modified concrete [27].

There are restrictions regarding the addition of cardboard and paper since they alter the water absorption capacity of the cement, so their use in concrete production increases the proportion of water needed and reduces its resistance [52]. If proper treatment methods are not applied, cardboard and paper fibers can degrade in the material and reduce their useful life. Likewise, if they absorb moisture, they can produce holes around their fibers and affect their durability [54].

Finally, these barriers highlight the need for standardized procedures for the reuse and recycling of MSW in the construction sector, because researchers currently rely on regulations designed for conventional construction materials.

5.3. Strategies of Some Countries to Promote Waste Reuse and Recycling in Construction

The management of the MSW reflects particular interests in each region of the planet. For example, the countries of the European Union have a waste prevention program whose main interest is to minimize the volume deposited in landfills through reduction, recycling, and reuse [4]. Once the MSW reaches these sites, it is incinerated for electrical power and other purposes. In addition, they have economic and fiscal incentives that they apply to their citizens and to different productive activities [4]. In Great Britain, up to 29% of natural aggregates have been replaced with recycled aggregates. CDW production has been reduced in this country thanks to its environmental policies, which include taxes on the generation and disposal of waste in landfills [91]. Meanwhile, in Australia, considerable volumes of CDW have been recycled thanks to the very well-defined specifications by the authorities. Likewise, they have rates applicable to companies that deposit their CDW in sanitary landfills to encourage separation and reuse in construction [92].

In the United States, the Environmental Protection Agency promotes the reuse and recycling of CDW as an alternative to reducing the extraction and processing of materials [93]. In the same way, the Resource Conservation and Recovery Law considers the life cycle of construction materials until their disposal, reuse, and recycling. However, it does not consider the reduction of virgin materials through their substitution with other sources of inputs, such as MSW [94,95]. The Organization for Economic Cooperation and Development (OECD) also measures the management and reduction of waste in its member countries through environmental performance reviews. These reviews include incentive programs implemented by member governments to regulate the generation, management, and reduction of waste, including the consumption of materials [96].

In Mexico, actions are taken so that producers, exporters, importers, and distributors of products take advantage of and value waste through the General Law for the Prevention and Comprehensive Management of Waste (LGPGIR). This law promotes the technical, environmental, and economic management of waste through management plans at the state level aimed at reducing its volume and its adverse effects on the environment and society. However, in a diagnosis carried out in 2020 by Mexico's Secretariat of Environment and Natural Resources, it was determined that this management is inefficient since the waste is not incorporated into the production chain, with the exception of PET and tires [97]. In this same diagnostic study, it was highlighted that some MSW fractions, such as paper, cardboard, and glass, among others, are not well classified by the LGPGIR, which causes ambiguity in their management and use [97].

In several regions of Mexico, measures have been taken to reduce the volume of waste. For example, in July 2021, the NACDMX-007-RNAT-2019 standard, which refers to the management of CDW, came into force for Mexico City. It establishes that this waste (considered a "special handling waste" by the LGPGIR) must be selected at the source and delivered for recovery at sites authorized for this purpose [98]. Additionally, regarding CDW, measures have been taken to manage those produced due to natural disasters, such as earthquakes [99]. In short, even though waste management is on the Mexican legislative agenda, it is notorious that there is no efficient action plan that reincorporates other options besides incineration and the recovery of CDW and MSW for reuse and recycling in the construction sector.

6. Areas of Opportunity in Latin America and the Caribbean Construction Industry

For the last two decades, favorable commodity export prices have supported natural resource extraction as a development strategy in LAC, resulting in the commodification of most of the region's national economies [100]. Commodification results in ongoing dynamics of land dispossession, over-exploitation of non-renewable resources, expansion of commodity frontiers (to lands once considered 'unproductive') and, in general, new forms of dependency [100]. At the same time, the reliance on commodity exports makes the region vulnerable to commodity price cycles, which has not been addressed through appropriate countercyclical macroeconomic policies [5]. LAC countries have been unable to take advantage of the surpluses produced by natural resource exports, but circular economy initiatives could constitute opportunities to generate added value domestically.

From this review, it follows that it is necessary to expand the options available to the construction sector through the reuse and recycling of waste. One of the most successful examples in LAC is "Construye 2025", a Chilean program promoting a circular approach in the construction sector. This program includes deconstruction initiatives (i.e., aiming to substitute conventional demolition by thorough and optimal removal of as many of the materials that make up a building), reuse of steelmaking slag for construction, and a start-up that recycles expanded polystyrene from CDW in paint resin, among many others [101].

Mexico has invested in MSW recycling plants whose main purpose is to reduce the volume that is deposited in landfills, especially those that are almost at their capacity limit; such is the case of the Azcapotzalco Selection Plant, inaugurated in 2021 in Mexico City [102]. There, the waste is separated and recycled to obtain compost used in the city's green areas, while other waste goes to local cement companies to generate electricity. The volume that is not recovered is sent to the different sanitary landfills that serve the urban area. Additionally, the industrial sector has invested in MSW recycling and treatment plants in different states to obtain energy, reduce CO_2 emissions and use them in the cement industry [103]. Regarding CDW, in 2020 a call was issued in Mexico City to build six treatment plants that will serve at least 1000 tons daily [104]; one of them has already started operations.

The combination of a circular economy with Industry 4.0 technologies such as 3D printing expands further the opportunities for the construction industry. Concrete mortar layers hardening as they are 3D-printed have been used to build low-cost houses in El Salvador, Haiti, Bolivia, and Mexico [5]. Likewise, 3D printing can eliminate waste in the building's design by minimizing material inputs through prototyping and enable disassembling for the later reuse or recycling of constructive elements. In 2016, for the Rio

Olympic Games, some of the venues were equipped with modularly designed structures that could be removed and repurposed [5].

7. Conclusions

Proper disposal of MSW is one of the main challenges for society, since the biosphere has a limited capacity to absorb this waste without negatively impacting natural resources. The rapid urban growth in Latin America and the Caribbean represents a great challenge for governments, society, and the environment, notably concerning the resulting MSW volumes. At the same time, the construction industry has a major boom in infrastructure development in the region, and large projects from both the government and private sectors are underway. In addition to reducing their own waste generation, cities should consider options that favor the incorporation of MSW into value chains that benefit other sectors, such as construction.

In this review, we made a general analysis of the areas of opportunity in this region of the Global South. We propose a synergy in the manufacture of materials that incorporate MSW in substitution of natural resources such as aggregates and cement, mainly. MSW can represent part of the necessary inputs for their production and commercialization, which requires investing in research to improve their properties and environmental benefits.

We also highlight the limitations of this synergy because, although it is feasible to partially replace fine and coarse aggregates with residues such as plastic, glass, or incineration ashes, various chemical treatments must be used to reduce the risk of pollutant release. The grinding of these residues to obtain the desired particle size is another challenge to be investigated; irregularities in the glass, for example, can have adverse effects on the mechanical properties of the concrete. The variety of colors and manufacturing processes of the various products turned into waste require a selective separation to avoid deterioration in the development of new construction materials.

It is important to accompany performance evaluations of MSW-modified materials with evaluations of the leachate produced (especially in the case of the addition of plastics), economic benefits, and life-cycle analyses. The options presented in this work describe opportunities worth exploring to contribute to an environmentally responsible national construction industry. However, by virtue of poverty and inequality prevailing in the LAC region, circular economy actions must be inclusive and compatible with the specific social needs of each location and country, in order to ensure a justice-oriented transition.

We consider it relevant to measure the additional benefits that this approach would mean for the LAC region. On the one hand, the economic benefit of waste collectors must be measured by incorporating them into a productive value chain with the construction sector. Their participation is fundamental in the selective separation of the different types and varieties of MSW to obtain the appropriate raw material to replace natural resources of stone origin. Afterward, it is advisable to propose policies and laws that motivate builders to incorporate more ecological practices in their production processes. The environmental assessment of such practices could help quantify the recovery of natural resources currently being overexploited in the Global South.

Author Contributions: Conceptualization, L.L.-M.; methodology, L.L.-M. and G.A.V.-R.; data curation and original draft preparation, L.L.-M. and G.A.V.-R.; visualization and copyediting, L.D.L.-L. All authors have read and agreed to the published version of the manuscript.

Funding: Open access publishing costs were covered by the 2022 Annual Operating Plan of the Academic Area of Engineering and Architecture, Autonomous University of the State of Hidalgo, Mexico (PAO-2022-0152).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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