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Eco-effective Sustainable Risk Assessment Model for homogeneous solid waste mortars based on the *Cradle to Cradle* paradigm

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Introduction: The unrestricted use of non-renewable natural resources in masonry mortars and the rapid increase in solid waste contribute to the deterioration of the environment. It is a priority for the United Nations to promote growth without compromising the ability of new generations to attend to their own; for this purpose, 17 Sustainable Development Goals for all countries have been formulated. The present work arises from the need to propose a model to evaluate, in the design phase, homogeneous solid waste and total or partial substitutes for some of the components of the mortars used in the construction sector, based on the Cradle to Cradle paradigm, which has the objective of including improved materials for the health of living beings and the environment by establishing a circular system in the manufacture of mortars including only safe and healthy materials that can be reused with a guarantee of not affecting the health of living beings and the environment and contributing to sustainability.

Methods: Based on the positivist epistemological current, projective documentary research begins by analyzing scientific publications that recommend the use of solid waste only to verify its rheological properties, ignoring how the inclusion of this material can affect living beings and the environment; it is contrasted with the results of published public access research regarding the chemical substances that make up said material.

Results: The eco-effective model is designed and its application is validated in identifying potential risks to the health of living beings and the environment in the waste of the selected cases; recommending the avoidance of recycling those materials that cause concern; contributing improved mortar designs for living beings and the planet, which minimize the use of natural resources and increase productivity in the field of construction; and implementing this vision through continuous development and improvement.

Conclusions: The eco-effective model facilitates doing the right things from the design stage, promoting growth with opportunities, diversity, and abundance for the present generation as well as future generations.

KEYWORDS

natural resources, eco-effective model, eco-effectiveness, masonry mortars, homogeneous solid waste, paradigm, Cradle to Cradle, sustainable

Introduction

Natural resources are limited and their use in the production of goods and services must be regulated to avoid problems related to their scarcity (Rodríguez, 2018). Therefore, in order to live in a world that is increasingly safe, healthy, and equitable and to preserve it for future generations, it is necessary to formulate strategies to ensure the conservation, restoration, and sustainable use of natural resources.

Humanity generates 1.9 billion tons of solid waste annually, and ∼30% remains uncollected. As for the portion collected, only 70, 19, and 11% go to landfills, recycling, and energy generation, respectively, according to Atlas Waste (2020). Efforts are being made at the municipal level for the proper management of solid waste (Ahangar et al., 2021) and, significantly, medical waste (Maihami and Ghalehkhondabi, 2022; Tseng et al., 2022), to reduce its environmental impact.

Based on this reality, scientific research has produced several proposals for mortars with Homogeneous Solid Waste (HSW); some of which, referred to in Table 1, were conceived to reduce the use of non-renewable natural resources and their recommended use is based on the evaluation of their rheological properties and proven similarity to traditional mortar.

In the mixtures proposed in Table 1, the uncertainty surrounding the effect on the health of living beings and the environment is evident. It is essential that research work on this subject prioritizes providing mixtures that mainly do not present risks to living beings and the environment.

This procedure facilitates doing the right things from the design stage, as proposed by Braungart and McDonough (2005) with their change strategy called eco-effectiveness, based on the Cradle to Cradle (C2C) paradigm, which focuses on improving the positive footprint, applying continuous improvement in product development, industry, and economy, without limiting technological innovation (Toxopeus et al., 2015; Fiel, 2022; Tamoor et al., 2022).

According to the United Nations (UN, 2020a), certain sectors alter the availability of natural resources, which affects their sustainability. One of these sectors involves the housing construction process, which uses mortars that exponentially deteriorate the environment, despite ensuring the welfare of its inhabitants.

The UN (2020b) recommends making efficient use of resources and adopting clean and environmentally sound technologies and industrial processes. According to Rangel-Abril (2019), "the fundamental basis of sustainable constructions, *[sic]* lies in energy efficiency, optimizing energy consumption in proper waste management and responsible consumption of resources and materials" (p. 10).

Mortars are a product in regular use in the construction area and their basic composition consists of non-renewable natural resources (a mixture of one or more inorganic binders, aggregates, and water, with additions or admixtures).

Abbreviations: HSW, Homogeneous Solid Waste; C2C, Cradle to Cradle; BRQ, Chemical Risk Flags.

TABLE 1 Homogeneous solid waste (HSW) mortar investigations.

Homogeneous solid waste			
No.	Source	Residue (chemical substance)	Purpose
1	Pradena et al., 2019	Slag (Cu)	Partial sand replacement
2	Kherbache et al., 2019	Metallic fibers (Cu and Zn)	Partial cement replacement
3	Medina, 2019	Pigment (TiO_2)	Optimize physical-mechanical properties
4	Palacios, 2013	Sulfur and rice ash (S)	Optimize cooling capacity
5	Correa, 2020	Plastic and rubber bottles in disuse (PET and recycled rubber)	Optimize costs
6	Pérez et al., 2019	Crushed clear bottles (glass)	Partial sand replacement
7	Gómez et al., 2020	Crushed *Manihot esculenta* shell (cassava shell)	Optimize compressive strength

A recent UN report (2019) exposed that 18 kg of sand and gravel are extracted daily for each inhabitant of the planet for the manufacture of concrete, asphalt, and glass. Furthermore, it states that sand is becoming a scarce resource, considering that it is the second most consumed natural resource after water.

Based on this premise, it is necessary to endorse the design of eco-effective mortars with HSW, prioritizing knowledge of the associated environmental impacts, from the formulation of the proposal, to obtain products with similar utility, without harming living beings and the environment in any of the phases of their life cycle and maximizing the quality of the materials for future recycling (Cadenas, 2021).

The Cradle to Cradle Certified® Product Standard (C2C) offers an alternative to measuring progress toward the Sustainable Development Goals in product design and manufacturing in relation to natural resource stewardship, social equity, and sustainable production and consumption (Cradle to Cradle Products Innovation Institute, n.d.). Futas et al. (2019) conclude that C2C certification leads the construction industry toward a circular economy by comprehensively evaluating materials and implementing a design for reversible construction in the interest of decreasing greenhouse gas emissions and transforming environmental impacts into a low carbon footprint (Torcátoru et al., 2022; Hartley and Kirchherr, 2023; Yin et al., 2023).

The reason for this research is to propose an eco-effective risk assessment model for mortars with HSW (hereinafter called "eco-effective model") based on the C2C paradigm and in accordance with the guidelines of sustainable development, which generates a change of perspective, whose priority is to offer products with the same benefits, without harming the health of living beings and nature.

TABLE 2 Potential hazards from solid waste chemicals.

Incorporation	Expert authors	Source
Cu Metallic fibers (Cu and Zn)	❖ Highly toxic ❖ Teratogenic effects ❖ Cancer ❖ Cellular aging ❖ Death ❖ Persistent ❖ Bioaccumulative	Londoño et al., 2016; Feoktistova and Clark, 2018; Santana et al., 2018; Kherbache et al., 2019; Rosales et al., 2019
Titanium dioxide	❖ Produces respiratory inflammation ❖ Possible carcinogen ❖ Persistent	Huerta, 2018; IARC, 2021
Sulfur	❖ Neurological effects ❖ Affects the immune, cardiac, digestive, reproductive, and respiratory systems. ❖ Alters hormone metabolism ❖ Dermatological effects ❖ Chronic acute irritation and inflammation ❖ Responsible for mortality in older adults ❖ Responsible for acid rain and air pollution ❖ Contributes to the formation of inorganic aerosols	Mexican Official Standards, 2009; Palacios, 2013; Alvarez, 2018
PET	The scale of health impacts that it generates throughout its life cycle is overwhelming; recommending its use requires a model based on the precautionary principle.	Rosales et al., 2019
Recycled rubber	Recycled rubber releases a wide variety of toxic substances; caution argues against its use where human exposure is likely.	Benoit and Demmars, 2018
Ground glass	❖ Environmentally friendly ❖ 100% recyclable ❖ It is stable ❖ Does not decompose ❖ Recycling reduces the consumption of silica and calcium carbonate ❖ Allows for energy savings and emission reductions	Pérez et al., 2019
Cassava shell	❖ Safe use in foodstuffs for both human and animal consumption is feasible	Gómez et al., 2020; Román et al., 2015

TABLE 3 Human health, environmental, and chemical exposure risk profiles.

C2C materials health certification evaluation criteria		
Risk to human health	**Risk to the environment**	**Risk of chemical exposure**
Carcinogenicity	Toxicity to fish	Organohalogen compounds
Endocrine disorder	Toxicity in aquatic invertebrates	Toxic metals
Mutagenicity	Toxicity in algae	
Reproductive and developmental toxicity	Terrestrial toxicity	
Oral toxicity	Persistence	
Dermal toxicity	Bioaccumulation	
Inhalation toxicity	Climate relevance	
Neurotoxicity	Another	
Corrosion and irritation to the skin, eyes, and respiratory tract		
Sensitization of skin and respiratory tract.		
Others		

TABLE 4 Risk flags for human health.

BRQ	Conditions
Carcinogens	
Green	Not classified as GHS 1A, 1B, or 2. Not a known or suspected carcinogen. Negative long-term cancer studies. Classified as: TLV A5, IARC 3.
Yellow	Not classified as GHS 1A, 1B, or 2. Limited, marginal, equivocal, or conflicting evidence of carcinogenicity. Classified as: MAK III 3A, 4, 5.
Red	Classified as GHS 1A, 1B, or 2. Known or suspected carcinogen. Classified as: MAK III 1, 2, 3B or IARC Group 1, 2A, 2B or IARC Group 2A, 2B. TLV A1, A2, A3 or H350; H351.
Gray	No data available for classification. Classified as: IARC group 3 or TLV A4.

Source: Own elaboration.

According to the degree of depth and type of result, the eco-effective model is the product of projective research since its application dissipates the uncertainty surrounding the effect on the health of living beings and the planet generated by the incorporation of HSW in the mixture by identifying the potential risks of the substances that compose it.

Therefore, a documentary review is carried out on the chemical substances present in the solid wastes in Table 1, referring to the potential risks that they can cause, showing worrying characterizations in some of them (Table 2).

Eco-effective model for homogeneous solid waste evaluation

The model is based on the Material Health Assessment Methodology, version 3.1 of the Cradle to Cradle Products Innovation Institute (2019), which regulates the use of chemicals and seeks to raise awareness of their implications for the ecosystem. It is based on the Globally Harmonized System (GHS) of Classification and Labeling of Chemicals (Globally Harmonized System (GHS), 2019), the International Agency for Research on Cancer (IARC, 2021), and the European Union EU (n.d.) classification system and toxicity tests of the Organization for Economic Cooperation and Development (OECD) and uses 21 specific study criteria (Table 3) to assign a classification for human health (11), environmental health (8), and chemical class (2) (Organization for Economic Cooperation and Development (OCDE), 2020). The methodology is supported using the Chemical Risk Flags (BRQ). As an example, the BRQs related to carcinogens are shown in Table 4; the rest of the evaluation criteria are found in Cradle to Cradle Products Innovation Institute (2019).

Eco-effective chemical risk assessment model procedure

The model assigns an A, B, C, X, or Gray rating to an HSW subject for review through the following six (6) steps.

Stage 1. Identification of the chemical substances in the HSW.

The European Agency for Safety and Health at Work (EU-OSHA, n.d.) defines the minimum information on physicochemical properties of mandatory knowledge and recommends: EC No., CAS No., molecular formula, and available physicochemical properties.

Stage 2. Assignment of BRQs across the 21 chemical evaluation criteria subject to review (Figure 1).

The rating scheme follows a "traffic light" hierarchy, where the risk of the chemical is communicated by a red, gray, yellow, or green BRQ withdraw to the 21 study criteria, with red being the most dangerous and green being the least toxic.

Stage 3. Assignment of BRQ for combined aquatic toxicity.

The procedure is based on the worst of its three BRQs of fish, daphnia, and algal toxicity, as well as its persistence and bioaccumulation rating (Figure 1), which generates one BRQ; for better understanding, it is applied for Cu (Figure 2):

1. The BRQ for aquatic toxicity is defined based on the worst of its three risk indicators for fish, daphnia, and algae toxicity.
2. The combined aquatic toxicity BRQ is defined.
3. The *Cradle to Cradle Products Innovation Institute* (p. 69, 2019) is consulted for the combined aquatic toxicity BRQ, which compiles all possible combinations of aquatic toxicity, persistence, and bioaccumulation BRQs.
4. Finally, one BRQ of the chemical under review is obtained for the 17 resulting criteria.

Step 4. Exposure assessment of the chemical under review.

For each evaluated criterion marked with a red or gray BRQ, the assessor must apply professional judgment based on the product scenarios and material context to establish whether exposure is plausible to humans or the environment *via* oral, dermal, or inhalation routes through volatile emissions, water, or other routes, including all aspects of reasonably foreseeable use and maintenance of the product (Figure 1). The steps to complete an exposure assessment are:

(a) Define manufacturing, intended and likely unintended product use, and end-of-use scenarios (such as recycling, composting, landfilling, incineration, and uncontrolled burning, among others).
(b) If exposure is not plausible at any level, in any of the defined scenarios, through any exposure pathway relevant to a specific criterion with a red or gray risk rating, the final BRQ is yellow.
(c) If the chemical is of regulatory concern, it remains red or gray.

Step 1. Identification of the Chemical Substance	
Step 2. Assignment of BRQs in the 21 endpoints of the chemical under review	
Green	No hazard identified for the criterion analysed
Yellow	Limit hazard identified for the analysed criterion
Grey	There is insufficient data available to determine the hazard level for the criterion under consideration.
Red	Considered dangerous for the criterion analysed

Step 3. Assignment of the BRQ for Combined Aquatic Toxicity

Fish toxicity	→	**Aquatic Toxicity**
Toxicity of daphnia		
Toxicity of algae		
Aquatic toxicity	→	**Combined Aquatic Toxicity**
Persistence		
Bioaccumulation		

Step 4. Exposure assessment for the chemical under review

If exposure is NOT plausible to humans or to AM via oral, dermal, or inhalation routes through volatile emissions, water, or other routes

Red	→	**Yellow**
Grey		

If exposure is plausible to humans or to AM via oral, dermal, or inhalation routes through volatile emissions, water, or other routes

Red	→	**Red**
Grey	→	**Grey**

Step 5. Chemical hazard qualification of the chemical under review.

a	Ideal safe chemical
b	Chemical substance without moderate or significant risk
c	Chemical with one (1) or more moderate hazards
grey	Insufficient data to assess the chemical
x	Chemical with one (1) or more significant hazards

Stage 6. RSH chemical risk rating

A	Healthy material
B	Material that largely supports the C2C paradigm
C	Material with some concerns
GREY	Material cannot be fully assessed due to lack of data.
X	Material with highly problematic properties, should be phased out
FLAG	Material containing one or more chemicals as intentional inputs above 1000 ppm.

FIGURE 1
Stages of the eco-effective chemical risk assessment model at RSH.

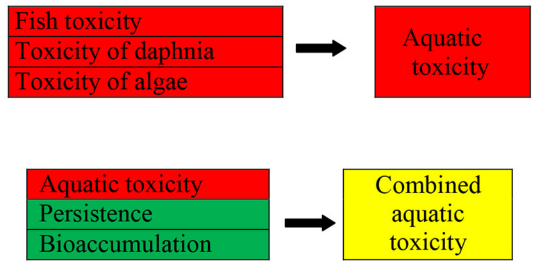

FIGURE 2
Risk indicator for the combined aquatic toxicity for Cu.

(d) This step, in the selected cases, is not applied in accordance with the selected investigations whose authors do not study the consequences of mixing with HSW in these scenarios.

Step 5. Chemical hazard qualification of the chemical under review.

This is achieved by assigning a chemical hazard classification of a, b, c, x, or gray to each chemical based on the BRQs obtained (Figure 1), using the following hierarchy of rules:

1. If the chemical has received one red BRQ on some of the 17 risk criteria evaluated, the chemical risk rating is "*x*" and rules 2–5 do not apply.
2. If the chemical has received one gray BRQ for any endpoint other than carcinogenicity, endocrine disruption, neurotoxicity, or terrestrial toxicity, the chemical hazard rating is "gray" and rules 3–5 below do not apply.
3. If the chemical has received one yellow or gray BRQ for carcinogenicity, endocrine disruption, neurotoxicity, or terrestrial toxicity, the chemical hazard rating is "c" and rules 4–5 do not apply.
4. If the chemical has received one yellow BRQ, the chemical hazard rating is "b" and Rule 5 does not apply.
5. Finally, when the chemical has received all green BRQs, the chemical hazard rating is "a".

Step 6. HSW risk rating.

Once the risk rating for each chemical present in the HSW has been obtained, the HSW is finally assigned an evaluation rating of A, B, C, X, or Gray based on the worst chemical risk rating among all the substances subject to review (Figure 1).

To establish the rating for the HSW, the following rules must be followed:

1. If the HSW contains one or more chemicals banned as intentional entries above 1,000 ppm, the evaluation rating for the material is Flag and rules 2–6 do not apply.
2. If any HSW chemical has received a chemical hazard rating of "x", the evaluation rating for the material is X and rules 2–6 do not apply.
3. If any chemical in the HSW has received a chemical hazard rating of "gray", the evaluation rating for the material is Gray and rules 4–6 do not apply.
4. If any chemical in the HSW has received a chemical hazard rating of "c", the evaluation rating for the material is C and rules 5 and 6 do not apply.
5. If any chemical in the HSW has received a chemical hazard rating of "b", the evaluation rating for the material is B and Rule 6 does not apply.
6. The HSW evaluation grade is A, which confirms that the material contains only substances with no known, suspected, or undefined hazards in any of the final criteria evaluated.

If any substance present in the HSW is qualified as Flag or X, the HSW can be stated as Flag or X, respectively, for its presence in the HSW.

Results

The eco-effective model is then applied to the HSWs in Table 1, whose BRQs of the chemicals present are (Table 4):

The proposed eco-effective method yields the following results:

1. The use of Cu slag is considered to have high-risk properties because it produces inhalation toxicity and can generate neurotoxic problems.
2. The use of metallic fibers composed mainly of Zn and Cu is not recommended due to the presence of copper. However, Zn presents moderate or significant risks that largely support the C2C paradigm.
3. TiO_2 is highly harmful to aquatic organisms. Additionally, it is suspected to cause cancer, genetic defects, and organ damage after prolonged or repeated oral exposure.
4. S causes skin and respiratory sensitization and adversely affects aquatic organisms.
5. PET contains C_2 H_6 O_2, which is orally toxic to terrestrial life; it produces reproductive and growth problems and causes mutagenicity and neurotoxic problems. Upon demonstrating the presence of at least one harmful chemical, the recommendation for use of the HSW with that chemical is discarded.

Table 5 summarizes the conclusions reached by the authors of the selected scientific articles (expert authors) and the results obtained by applying the eco-effective model.

Discussion

It should be noted that this research does not intend to limit the testing of non-traditional materials or materials considered waste or residues in their primary processes to include them in mortars. However, these proposals must be accompanied by scientific support that certifies their harmlessness to living beings and the environment and limits their use until their effects have been proven from the beginning.

Mortars with HSW must demonstrate that in addition to contributing to the effective use of NR in

TABLE 5 Comparison of chemical evaluations.

Evaluation	Chemical substance	Expert authors	Ecoeffective model
Copper slags	Cu	Highly toxic, carcinogenic, reproductive and developmental toxicity, neurotoxicity	With significant risks, with highly problematic properties (inhalation toxicity, neurotoxicity)
Metallic fibers	Cu		
	Zn	Respiratory toxicity	No moderate or significant risks
Titanium dioxide	TiO_2	Respiratory toxicity, neurotoxic, possibly carcinogenic.	Significant hazards, with highly problematic properties: Carcinogenic, mutagenic, oral, and aquatic toxicity, neurotoxic.
Sulfur	S	Neurotoxic, mutagenic, oral, terrestrial, reproductive, and developmental toxicity, dermal and respiratory tract irritation.	With significant risks, with highly problematic properties: Respiratory sensitization, aquatic toxicity.
Ethylene glycol	$C_2 H_6 O_2$	Not suitable for recycling	With significant risks, with highly problematic properties: Mutagenic, reproductive, and growth toxicity, oral and terrestrial, neurotoxic.

the construction of civil works, they contribute to the preservation of all living beings and the planet, do not harm the environment, contribute to the quality of life of people of this generation, and preserve the planet for future generations.

The eco-effective method contributes to providing information on:

1. HSW that meets world-class requirements for safe chemicals and healthy materials, designed to be returned to nature or industry after use (e.g., Zn).
2. HSW with chemicals of concern, and it is recommended to expand studies on exposure potential as well as prevention of use.
3. HSW not recommended due to its potentially harmful effects, such as Cu, TiO_2, and S, among others.

The application of the eco-effective model provides researchers with a tool to evaluate and profile the hazards associated with chemical substances and to be able to make pertinent decisions on the incorporation of an HSW in masonry mortars in their design phase, determining their degree of affectation according to the agreed criteria in order to carry out their tests, culminating in conclusions and recommendations that take into account the health of everyone on the planet; this procedure recognizes the needs of the industry and continuously increases sustainable productivity.

Making HSW mortars with the highest capacity for biological and technological cycles selected in line with the C2C paradigm available to the public increases the likelihood that these materials will retain their value and move through subsequent cycles of use. It is also important to make the limitations that prevent the use of a specific material known within the scientific community.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

CB has revised the English version of the document and participated in the conclusion. All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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