sustainability

MDPI

Article

Toxicity-Based Evaluation of Material Recovery Potential in the Built Environment

Matan Mayer

IE School of Architecture and Design, IE University, 28046 Madrid, Spain; matan.mayer@ie.edu;
Tel.: +34-921-41-24-10

Abstract: Material recovery operations like recycling are now a common part of many product categories, and yet quantifying recycling potential is still a largely unresolved issue. Prior research into this matter focused on market value as an indicator of the readiness of recycling technologies. Although this is an effective measure, it fails to recognize the environmental, societal, and other impacts of recycling operations. Aiming to expand the evaluated factors of recycling potential, this article centers on assessing recyclability from a toxicity and human health perspective. The article describes the development of a toxicity index for recyclability, which is explained and demonstrated in a comparative study of four building material categories. Findings indicate that post-consumer content in synthetic products reduces toxicity and health-related impacts, while recycled content in extracted natural materials increases their toxicity and health impacts. The article concludes with a discussion about the implications of the findings, survey limitations, and future work.

Keywords: circular economy; material recovery; recycling; toxicity; built environment

check for updates

Academic Editors: Sheila Devasahayam and Sunil Kumar Tripathy

Received: 30 December 2024
Revised: 16 January 2025
Accepted: 21 January 2025
Published: 30 January 2025

Citation: Mayer, M. Toxicity-Based Evaluation of Material Recovery Potential in the Built Environment. *Sustainability* **2025**, *17*, 1139. https://doi.org/10.3390/su17031139

1. Introduction

Recovery and reutilization of materials are regarded as key strategies for reducing greenhouse gas emissions in the built environment [1–3]. Within those end-of-use scenarios, recycling is one of the widely used tactics, demonstrated by established infrastructure and developed supply chain networks in many geographic locations. While recycling is an increasingly common practice in the built environment, accurately defining recycling quality in order to compare technologies and material types remains challenging [4]. This is mainly due to the vast spectrum of scenarios that typically fall under the term ‘recycling’. Remanufacturing, downcycling, upcycling, and even reuse are all referred to as types of recycling, depending on the sector they occur in. The main challenge in assessing the material recovery quality of those solutions is that they exist on a continuum without clear boundaries [5]. Take, for example, end-of-use broken glazing being processed into translucent glass sheets. Would that process constitute an improvement in material quality (broken glass being turned back into a continuous sheet) and, therefore, be regarded as upcycling, or would it actually be considered a reduction in material quality (the glass loses some of its transparency in the process)? This ambiguity directly impacts the industry’s ability to determine the recycling potential of construction materials. In order to address this problem, the research community turned to an indicator that would allow simple and direct comparison between different material groups: market value [6,7]. The rationale behind the use of market value as an indicator is that fluctuations in value reflect the level of availability of technology and supply chains, as well as the industry’s demand for certain recycled materials over others. Even though the use of that indicator provides a clear measure of recycling feasibility, it fails to account for the wider environmental and societal implications of material recovery. Some recovered materials might have high market demand; however, their recycling process might be hazardous to human health or environmentally harmful to a degree that puts the justification of their recovery in question [8–11]. Similarly, some materials might have low market demand; however, due to their dwindling reserves in nature, it is critical to avoid using them in their primary ('virgin') form. To illustrate this point, Figures 1 and 2 show the gap between reserve abundance and actual recycling rates in the industry.

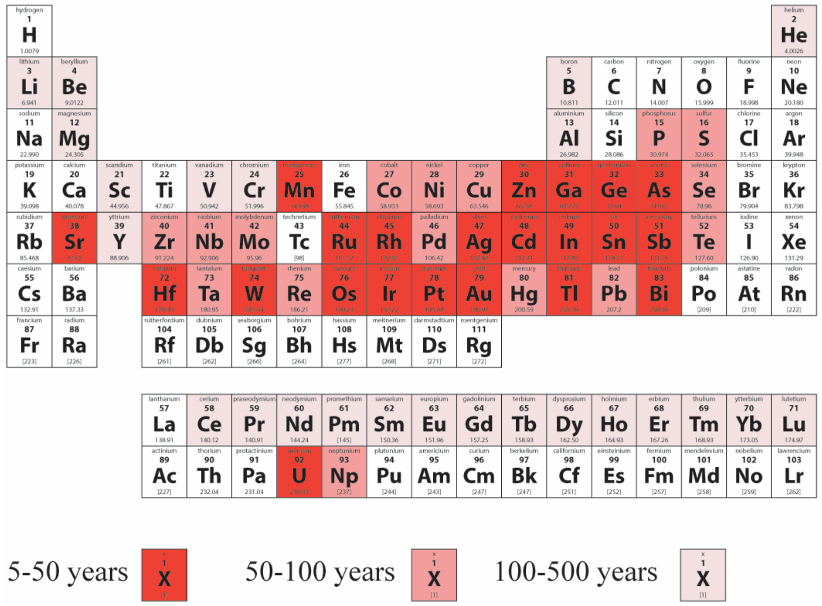

Figure 1. Remaining years until depletion of known material reserves. Data source: [12].

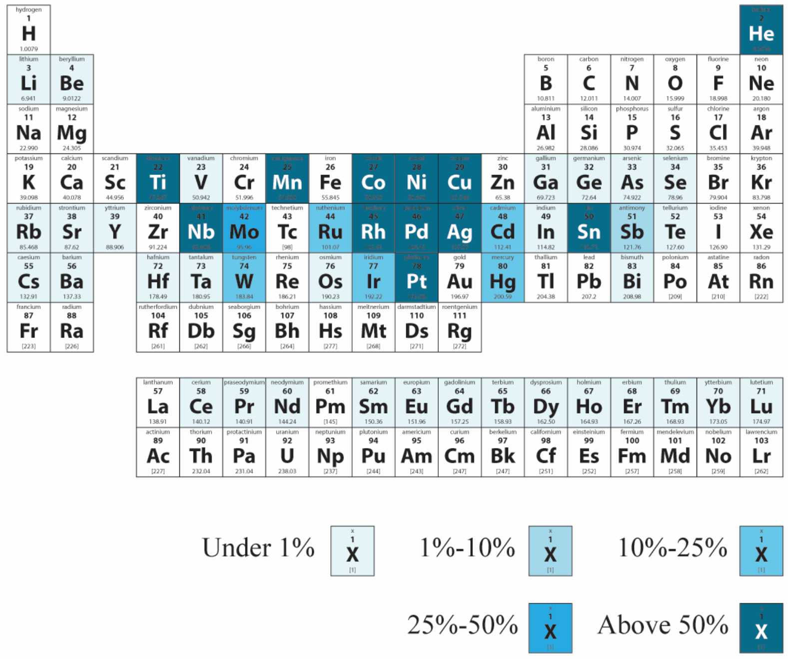

Figure 2. Current rate of recycling at scale. Data source: [12].

2. Literature Review

Toxicity above certain levels has been proven to have an adverse effect on human health. Studies found that prolonged exposure to rare earth elements causes DNA damage and cell death [13]; exposure to carbon nanoparticles leads to inflammation of the lungs [14];

and exposure to high doses of zinc can cause permanent brain damage [15]. An established evaluation method to quantify the release of toxins throughout the production process of materials and products is life cycle assessment (LCA) [16]. The results of an LCA study are expressed in a life cycle impact assessment (LCIA) output, where a series of indicators are displayed in order to express the impact on the environment and on human health [17]. In total, LCIA includes 12 impact categories: climate change, ozone depletion, eutrophication, acidification, human toxicity (cancer and non-cancer related), respiratory inorganics, ionizing radiation, ecotoxicity, photochemical ozone formation, land use, and resource depletion. Toxicity assessment in the construction industry has gained increased interest in sustainability research in recent years, in part due to its ability to directly reflect the cost in human health of material and design choices. Rey-Álvarez et al. [18] highlight the relative disregard for toxicity assessment in sustainability evaluation in relation to energy consumption and greenhouse gas emissions; Blumenthal et al. [19] propose expanding the notion of embodied carbon in sustainability research to account for toxicity as well, referring to it as embodied toxicity; and Pacheco-Torgal et al. [20] argue that a key gap exists in the limited understanding of the industry regarding the widespread existence of toxicity in common building types like housing. In the context of circular economy actions like recycling or reuse, the role of toxicity assessment is even more pronounced as it highlights the health risks that are associated with strategies that are otherwise considered environmentally conscious. To address this issue, the article focuses on the specific connection between recyclability and toxicity in the built environment. Although recycling processes often result in a significant release of toxic substances, there has been little research about characterizing recyclability through toxicity. Notable exceptions are Jun-Hui and Hang's [21] exploration of soil eco-toxicity resulting from e-waste recycling, and Awere et al.'s [22] investigation of exposure to toxic agents among e-waste workers in developing economies; however, the built environment remains largely understudied to date.

3. Materials and Methods

Considering the relative absence of prior research in this specific field, the main objective of the work presented here is to develop an indicator for assessing the benefits (or lack thereof) of using recycled building materials as opposed to primary-use materials from a toxicity point of view. Using this indicator, the project proposes a toxicity–recyclability evaluation index (TREI).

3.1. Data Collection

Given that such evaluation is heavily reliant on data, an emphasis was put on using only publicly accessible data sources. One of the major data transparency advocates in this space is the Health Product Declaration (HPD) Collaborative [23]. This not-for-profit organization hosts a fully accessible database of product declaration certificates on its website. Those certificates list the entire material composition of each product and the types of health and toxicity hazards associated with exposure to it. Two other notable toxicity standards with applications in the built environment are the Red List by the Living Building Challenge and GreenScreen for Safer Chemicals. The Red List, launched in 2006, is a joint initiative of the International Living Future Institute (ILFI), the Healthy Building Network, and the Pharos Project. It aims to target the building industry's most harmful substances to human health and the environment. The list, which is updated on an annual basis, currently identifies over 5800 prevalent substances in 19 chemical classes, based on function, application within the building products sector, and structural similarity [24].

GreenScreen is developed and managed by Clean Production Action, a nonprofit corporation based in the United States. Unlike the Red List, it does not identify a set of hazardous substances but rather offers a method to identify such substances and find non-hazardous alternatives. The assessment begins with a list of 18 hazard endpoints, which specify the type of health or environmental damage inflicted by the substance. For each endpoint, the level of hazard ranges from very high (vH) to very low (vL). Once this assessment has been established, the assessor assigns a level of confidence for each hazard endpoint category. In the next step of the assessment process, the substances are assigned a benchmark score based on a comparison with similar chemicals in GreenScreen's database. The score ranges from 1 to 4, where 4 indicates the safest chemicals [25]. Once the material has been assessed, the user is able to make informed decisions about material selection in the project. GreenScreen is advantageous in that it employs a peer-reviewed technical methodology, and is adopted across government, industry, research, and advocacy communities [26]. While the Red List and GreeScreen are widely used standards that provide a solid base for understanding and mitigating toxicity in building materials, both prove insufficient for the purpose of this specific study. Given that the focus of the study is recyclability, it requires substantial toxicity data regarding recycled substances. Out of the three examined standards, only Health Product Declarations (HPDs) included substances from recycled origins. Additionally, out of the three, HPD is the only standard that puts an emphasis on entire products rather than individual chemicals, including post-consumer content. Ideally, it would have been preferable to base the toxicity–recyclability evaluation index (TREI) on data regarding the recycling processes themselves; however, in the absence of such a database, the index is based on products that include post-consumer content resulting from those recycling processes. It is important to note that health product declarations list hazard types for each residual within the product; however, they do not list the exact quantity of each toxic substance causing the hazards. The index is, therefore, based on the number of hazard types associated with each product's components and residuals.

3.2. Index Calculation

Within this format, health product declarations list 18 key hazard types: Aquatic toxicity (AQU), cancer (CAN), developmental toxicity (DEV), endocrine activity (END), eye irritation/corrosivity (EYE), gene mutation (GEN), global warming (GLO), land toxicity (LAN), mammalian/systemic/organ toxicity (MAM), Multiple hazards (MUL), neurotoxicity (NEU), unknown or not found on Priority Hazard Lists (NF), ozone depletion (OZO), persistent, bioaccumulative, and toxic (PBT), physical hazard—flammable or reactive (PHY), reproductive (REP), respiratory sensitization (RES), and skin sensitization/irritation/corrosivity (SKI). The developed index considers the number of listed hazard types for each residual within the recycled product and compares it to the number of hazard types for each residual within the equivalent primary-use product. When the resulting number is smaller than 1.0, this indicates that the production and use of the recycled product is preferable from a toxicity and human health standpoint. A resulting number equal to 1.0 indicates an identical toxicity impact for the recycled and primary-use products, and a result greater than 1.0 points to a higher toxicity impact in the recycled product in comparison to the primary-use product. The index is, therefore, computed as follows:

$$R_T = \frac{HR}{HPU} \tag{1}$$

where R_T= recyclability toxicity index; HR = toxicity hazards in the recycled product (number of hazard types); and HPU = toxicity hazards in primary use product (number of hazard types).

3.3. Material Selection

In order to test and demonstrate the application of the index in practice, the article surveys four common product groups in the construction sector: concrete, resin-based composite, stone, and timber. The first two product groups are synthetic composites and the latter two are based on natural materials. Other common product groups like steel or aluminum were not included due to the high recycled content in all products on the market. In those product groups, it is challenging to find an entirely primary-use product. Other common product groups like brick and ceramic tiles were not included because due to their molecular makeup, they tend to be reused or downcycled rather than recycled into an identical product. Within each product group, two comparable and widely used products were selected as case studies—one of primary use and one recycled. The logic behind this selection is to attempt, as much as possible, to isolate the impacts of recycling processes. Due to data limitations, the compared products in each product group are not always entirely identical in their composition; however, in all cases, the application domain and the performance requirements are directly comparable. The results of the study are presented in the next section.

3.4. Weighting

A weighting scheme is typically applied in order to prioritize elements of an assessment index based on their importance toward achieving a stated goal [27]. In environmental assessment frameworks, weighting approaches usually rely on proxy, midpoint, or endpoint methods. Proxy approaches tend to cluster variables that represent similar aspects, like using carbon dioxide to represent a group of greenhouse gases in the Global Warming Potential category in LCIA [28]. Mid-point approaches focus on weighting based on a given problem, like for example, acidification in LCIA [29]. Endpoint approaches focus on a higher aggregation level for weighting, like for example, the effect on human health or biodiversity in LCIA [30]. Given that TREI aims to avoid setting any predetermined prioritization of any specific hazard at this early stage, it has been decided to apply uniform weighting in this study. A future publication of the index will feature a comparative study experimenting with a range of weighting options to determine a beneficial solution.

4. Results

This section features key findings from a demonstration of the proposed TREI framework on four material groups. It should be noted that TREI is implemented here rather than the more established Life Cycle Impact Assessment (LCIA) based on endpoint modeling (human health categories) for two main reasons. First, conducting an LCA study of the featured material groups requires the use of manufacturing and processing data that is not always publicly available. The findings of LCA studies for some products can be found in environmental product declarations (EPDs), but only those who opted to participate in the program. Second, in LCIA reporting, the results are essentially clustered into two categories: human toxicity (cancer) and human toxicity (non-cancer). TREI provides a much greater resolution of impact assessment with eighteen categories of health hazards.

4.1. Concrete

Two widely used products were compared in this material group: (1) HMX C1, which is a ready-mix concrete manufactured by Holcim Mexico. This product is mostly based on primary-use materials. (2) Eco Concrete, which is a ready-mix concrete manufactured by Holcim Mexico. This product has a far higher post-consumer material content than HMX C1. As Figures 3 and 4 show, concrete with the higher recycled content is found to have preferable performance in all hazard type categories, except for the cancer category (CAN), where its performance is equal to that of the primary use concrete. Accordingly, the highest recyclability–toxicity index numbers are recorded for the cancer hazard category and the endocrine activity (END) hazard category.

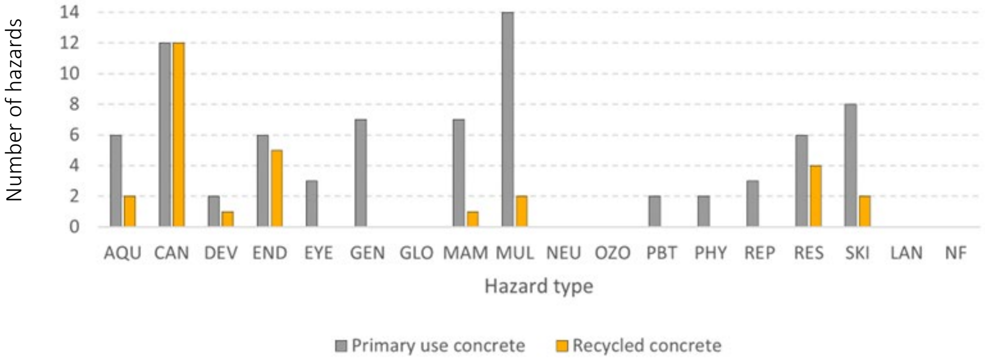

Figure 3. Number of hazards found for each hazard type for the concrete material group.

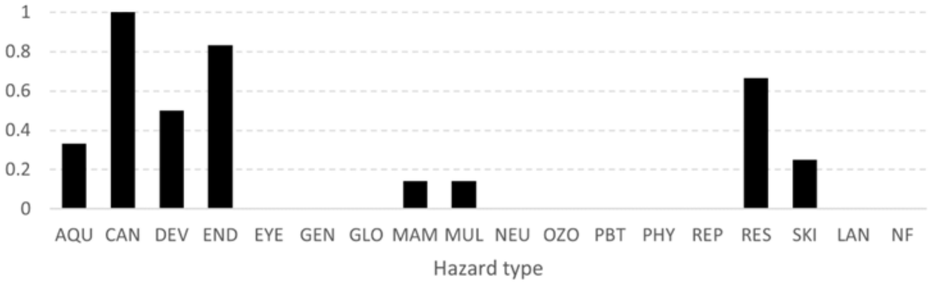

Figure 4. Index results for the concrete material group.

4.2. Resin-Based Composite

Two common products were compared in this material group: (1) STUDIO Collection, which is a resin-based surface product for interiors manufactured by Aristech Surfaces. This product is mostly based on primary-use materials. (2) Corian Solid Surface, which is a resin-based surface product using a mix of ground reclaimed minerals. The product is manufactured by DuPont Specialty Products USA and contains high post-consumer material content. As Figures 5 and 6 show, the resin-based composite with the high recycled content is found to have preferable performance in all hazard type categories without exception. The highest recyclability–toxicity index numbers are recorded for the respiratory sensitization hazard category (RES) and the eye irritation/corrosivity (EYE) hazard category.

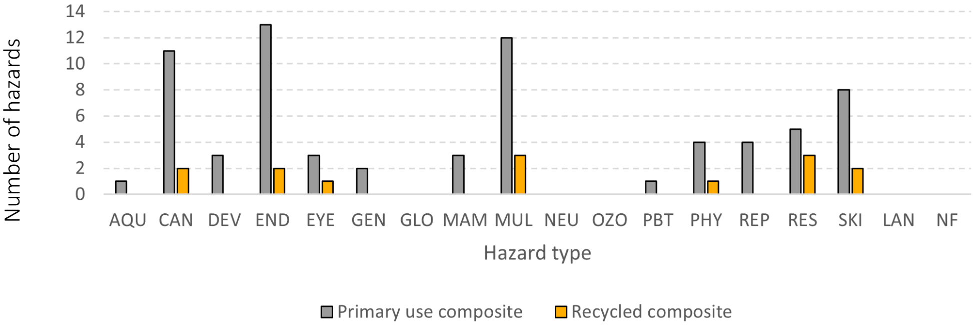

Figure 5. Number of hazards found for each hazard type for the resin-based composite material group.

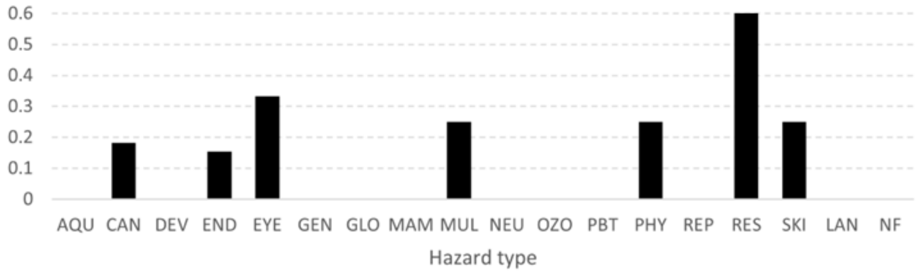

Figure 6. Index results for the resin-based composite material group.

4.3. Stone

Two leading products in the stone market were compared in this material group: (1) Cambria Natural Stone, which is a series of stone surface products manufactured by Cambria. This product is entirely based on the primary use of quarried stone. (2) a line of Limestone Composite Products, which is a fiber-backed surface product using reclaimed limestone. The product is manufactured by Polycor and contains high percentages of recycled material content. As Figures 7 and 8 show, the primary use stone product is found to be preferable from a toxicity performance standpoint in all hazard type categories except in the cancer (CAN) and the endocrine activity (END) categories. The two studied products perform equally in the developmental toxicity (DEV), eye irritation/corrosivity (EYE), reproductive toxicity (REP), and respiratory sensitization categories. The highest recyclability–toxicity index numbers are recorded for the Skin sensitization/irritation/corrosivity category (SKI) and the multiple hazards (MUL) category.

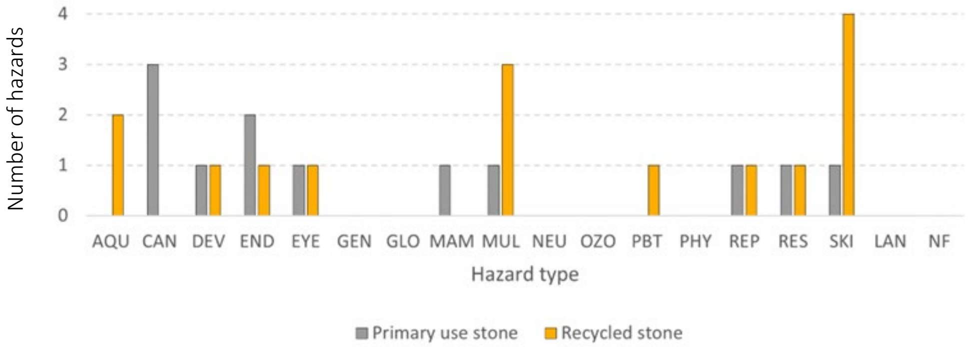

Figure 7. Number of hazards found for each hazard type for the stone material group.

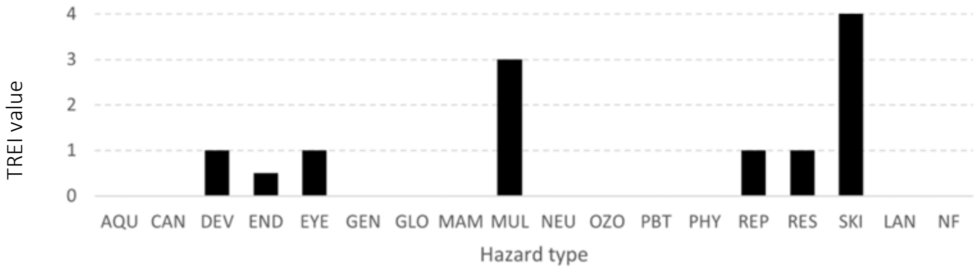

Figure 8. Index results for the stone material group.

4.4. Timber

Two popular products were compared in this material group: (1) Nordic X-Lam, which is a cross-laminated timber (CLT) slab or panel product made of spruce-pine-fir or black spruce and manufactured by Nordic Structures. This product is entirely based on the primary use of timber. (2) Encore FR Particle Board, which is a particleboard panel for interior and exterior applications made entirely from recycled timber, manufactured by Ampine. As Figures 9 and 10 show, the primary use cross-laminated timber product is found to have preferable performance over the recycled particleboard product in all hazard type categories without exception. The highest recyclability–toxicity index numbers are recorded for the eye irritation/corrosivity (EYE) hazard category, the skin sensitization/irritation/corrosivity category, and the multiple hazards (MUL) category.

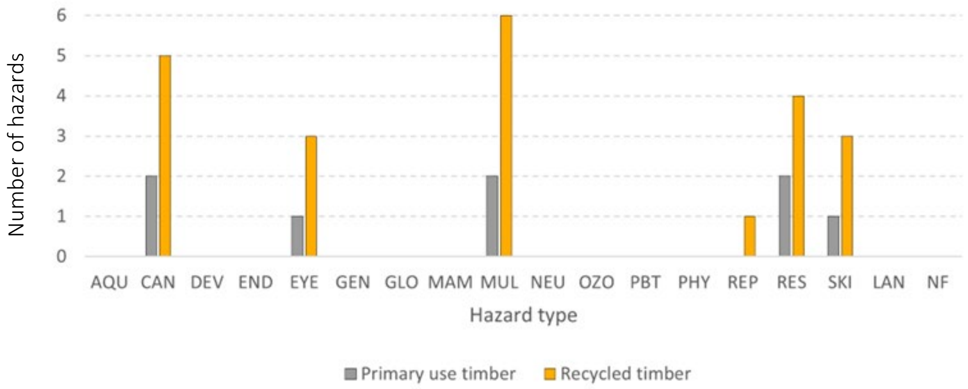

Figure 9. Number of hazards found for each hazard type for the timber material group.

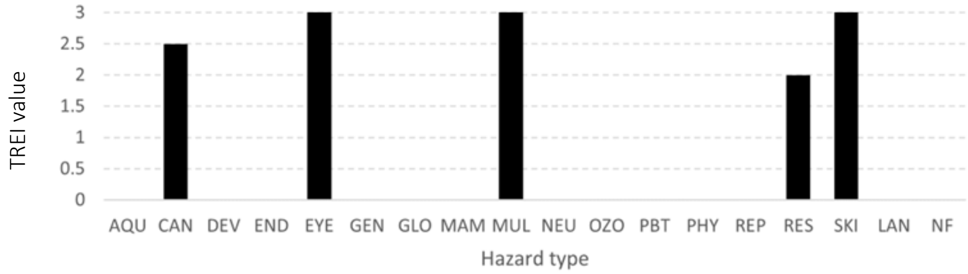

Figure 10. Index results for the timber material group.

5. Discussion

5.1. Findings

The presented index and its demonstration on a comparative assessment of product pairs in four common construction material groups aim to provide a recyclability measure that is focused on toxicity and human health impacts rather than only on market demand. Although the study is relatively limited in scale and scope, a number of significant issues emerge. Most notably, there seems to be a clear distinction in toxicity performance between natural and synthetic materials. In the studied synthetic material groups (concrete and resin-based composite), the products with higher recycled content have been found to outperform the primary-use products in almost every hazard type, with the only exception being the cancer hazard in the concrete group, which was identical for the primary use and the recycled products. These findings support the notion that using post-consumer content is not only environmentally beneficial but could also be less harmful to human health. In the natural material groups in the study (timber and stone) on the other hand, the trend seems to be the opposite. The primary use products in both the timber and stone categories are found to be superior to the recycled options in almost all hazard-type groups except for endocrine activity in the stone material group. In this context, it should be noted that both stone and timber are ground or shredded in their recycled form, requiring the introduction of a bonding matrix in order to resist functional loads, thereby potentially rendering them synthetic materials by some definitions.

The contrast between the performance of recycled materials in the synthetic and natural material groups suggests that although material recovery is almost always desirable from an environmental standpoint, it has toxicity and human health disadvantages in some materials. Synthetic materials inherently consist of a mixture of various substances; therefore; replacing some of those ingredients with post-consumer content has a positive effect from a toxicity standpoint. Natural materials, in contrast, typically include only one key component and require relatively less processing between extraction and use. When recycled content is introduced into those products, it is typically in-ground or shredded format, essentially transforming what was a single-material product into a composite. That transformation has negative toxicity and human health implications.

Figure 11 shows an overall view of the average index results in this comparative study for all four material groups side by side. Resin-based composite is found to gain the most from a transition to recycled content from a toxicity standpoint, while timber stands to lose the most from such a transition. The differences in intensity between the different material groups are substantial, with an 85% increase between resin-based composite and concrete, and a 120% increase between stone and timber. The index result for timber is over 13 times larger than the index result for resin-based composite. This gap suggests that a transition into recycled content in a timber product is far more harmful from a toxicity standpoint than a transition from recycled resin-based composite to a primary-use product within that material group.

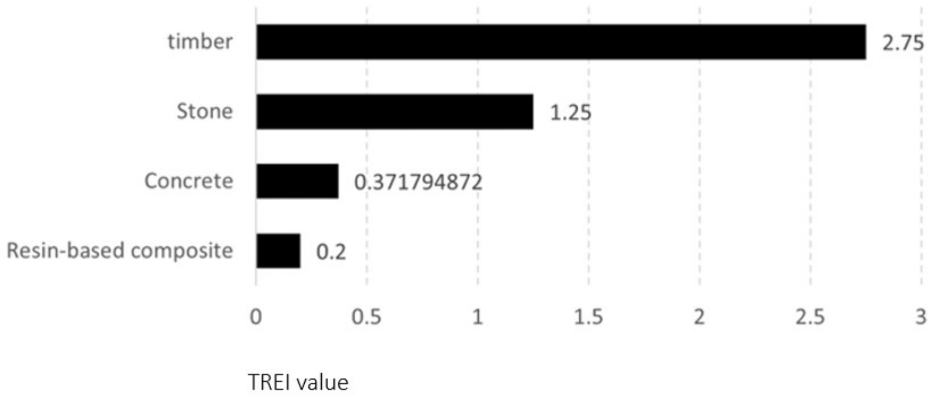

Figure 11. General index results for the studied material groups.

5.2. Applications in Industry and Policymaking

As a tool for measuring the health cost of circular economy operations, TREI could be used for decision-making in both industry and government. In the industry, TREI is able to assist stakeholders in identifying recycling processes that pose less risk to human health and prioritize them over riskier manufacturing. In government and non-governmental organizations (NGOs), TREI can be employed toward two ends. First, provide a performance verification platform for compliance with regulations limiting toxic recycling processes in the building sector. Second, the index can be utilized to inform new policy at the municipal, regional, or national level to reduce toxicity in both recycling processes and recycled products.

5.3. Limitations and Future Work

While the developed index provides a view of the nexus between recyclability and toxicity, some limitations, which warrant future research on this topic, can be observed. Primarily, the quality of the index's output depends on the availability and quality of obtained data. The current index is based on a data set that, while publicly available, focuses on the impact of products rather than on manufacturing processes and lists hazard types but does not quantify the levels of each hazardous substance in the studied product. Ideally, this index should be based on data regarding the exact amounts of toxins emitted in each step of the manufacturing and recycling processes of construction materials. Additionally, the data used focuses on toxicity hazards only to users, disregarding health impacts to workers along the extraction, manufacturing, and installation chains. Future work in this domain should, therefore, put an emphasis on setting up a publicly available database of toxicity-related impacts of extraction, processing, manufacturing, and recycling processes of building materials. An additional limitation of the index is the inherently exclusive nature of looking at only one aspect (toxicity) when assessing recycling potential. In order to obtain a full picture of recyclability, one would need to use the developed index in concert with other indexes that focus on other environmental, societal, and financial implications of recycling versus employing primary-use materials. When other aspects are considered alongside toxicity, weighing becomes a key consideration that should be investigated in depth.

6. Conclusions

Given the positive image of environmental impact reduction strategies like recycling, their adverse effects tend to be overlooked. To address this issue, the toxicity–recyclability evaluation index (TREI), which is presented and demonstrated in this paper, aims to quantify and express the human health cost of recycling operations. The index compares the toxicity performance of primary use and recovered building products across 18 impact categories to assess which materials maintain or decrease their toxicity throughout their life cycle and recovery process. Of the four material groups that were tested, resin-based composite and concrete were found to outperform the natural material groups of stone and timber. Broader implications for sustainability practices in the built environment of the index relate to the notion that manufacturers and consumers alike should be aware that all industrial operations bear an environmental and human health cost that needs to be taken into consideration in the decision-making processes. A key actionable recommendation for researchers, practitioners, and policymakers is that while the use of natural, low-carbon materials like timber or stone is beneficial in primary use, those materials tend to lead to downcycling in their second and third lives as recycling cannot bring them back to their original chemical state.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data used in this study are available from the author upon request.

Conflicts of Interest: The author declares no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

TREI	Toxicity–Recyclability Evaluation Index
HPD	Health Product Declaration
ILFI	International Living Future Institute
AQU	Aquatic Toxicity
DEV	Developmental Toxicity
END	Endocrine Activity
EYE	Eye Irritation/Corrosivity
GEN	Gene Mutation
GLO	Global Warming
LAN	Land Toxicity
MAM	Mammalian/Systemic/Organ Toxicity
MUL	Multiple Hazards

NEU	Neurotoxicity
NF	Unknown or Not Found on Priority Hazard Lists
OZO	Ozone Depletion
PBT	Persistent, Bioaccumulative, And Toxic
PHY	Physical Hazard—Flammable Or Reactive
RES	Respiratory Sensitization
SKI	Skin Sensitization/Irritation/Corrosivity

References

1. Awere, E.; Obeng, P.A.; Bonoli, A.; Obeng, P.A. E-waste recycling and public exposure to organic compounds in developing countries: A review of recycling practices and toxicity levels in Ghana. *Environ. Technol. Rev.* **2020**, *9*, 1–19. [CrossRef]
2. Blumenthal, J.; Diamond, M.L.; Liu, G.; Wang, Z. Introducing "Embedded Toxicity": A Necessary Metric for the Sound Management of Building Materials. *Environ. Sci. Technol.* **2022**, *56*, 9838–9841. [CrossRef] [PubMed]
3. Brouziotis, A.A.; Giarra, A.; Libralato, G.; Pagano, G.; Guida, M.; Trifuoggi, M. Toxicity of rare earth elements: An overview on human health impact. *Front. Environ. Sci.* **2022**, *10*, 948041. [CrossRef]
4. Clean Production Action. The GreenScreen Method. 2024. Available online: https://www.greenscreenchemicals.org/learn/full-greenscreen-method (accessed on 2 November 2024).
5. Eldh, P.; Johansson, J. Weighting in LCA based on ecotaxes-development of a mid-point method and experiences from case studies. *Int. J. Life Cycle Assess.* **2006**, *11*, 81–88. [CrossRef]
6. Finnveden, G. *A Critical Review of Operational Valuation/Weighting Methods for Life Cycle Assessment*; AFR-REPORT 253; Swedish Environmental Protection Agency: Stockholm, Sweden, 1999.
7. Foster, G. Circular economy strategies for adaptive reuse of cultural heritage buildings to reduce environmental impacts. *Resour. Conserv. Recycl.* **2020**, *152*, 104507. [CrossRef]
8. Hoy, M.; Horpibulsuk, S.; Rachan, R.; Chinkulkijniwat, A.; Arulrajah, A. Recycled asphalt pavement–fly ash geopolymers as a sustainable pavement base material: Strength and toxic leaching investigations. *Sci. Total Environ.* **2016**, *573*, 19–26. [CrossRef]
9. International Living Future Institute. The Living Building Challenge Red List. 2024. Available online: https://living-future.org/lbc/red-list/#red-list-and-watch-list-casrn-guide (accessed on 2 November 2024).
10. *ISO 14040:2006(en)*; Environmental Management—Life Cycle Assessment—Principles and Framework. International Organization for Standardization: Geneva, Switzerland, 2006.
11. Itsubo, N. Weighting. In *Life Cycle Impact Assessment*; Springer: Berlin/Heidelberg, Germany, 2015; pp. 301–330.
12. Zhang, J.-H.; Min, H. Eco-toxicity and metal contamination of paddy soil in an e-wastes recycling area. *J. Hazard. Mater.* **2009**, *165*, 744–750.
13. Kokai, A.; Blake, A.; Dedeo, M.; Lent, T. Building shared information infrastructure for chemical alternatives assessment. *Elem. Sci. Anthr.* **2020**, *8*, 26. [CrossRef]
14. Kokai, A.; Iles, A.; Rosen, C.M. Green Design Tools: Building Values and Politics into Material Choices. *Sci. Technol. Hum. Values* **2021**, *46*, 1139–1171. [CrossRef]
15. Krewitt, W.; Pennington, D.W.; Olsen, S.I.; Crettaz, P.; Jolliet, O. Indicators for human toxicity in life cycle impact assessment. In *Toward Best Available Practice for Life Cycle Impact Assessment*; SETAC Press: Pensacola, FL, USA, 2002; pp. 123–148.
16. Kurda, R.; Silvestre, J.D.; de Brito, J. Toxicity and environmental and economic performance of fly ash and recycled concrete aggregates use in concrete: A review. *Heliyon* **2018**, *4*, e00611. [CrossRef]
17. MacArthur, E. Towards the circular economy. *J. Ind. Ecol.* **2013**, *2*, 23–44.
18. Mayer, M. Economic indicators for material recovery estimation. In *Environmental Sustainability and Economy*; Elsevier: Amsterdam, The Netherlands, 2021; pp. 139–150.
19. Mayer, M. Recycling Potential of Construction Materials: A Comparative Approach. *Constr. Mater.* **2024**, *4*, 238–250. [CrossRef]
20. Muthu, S.S.; Li, Y.; Hu, J.Y.; Mok, P.Y. Recyclability Potential Index (RPI): The concept and quantification of RPI for textile fibres. *Ecol. Indic.* **2012**, *18*, 58–62. [CrossRef]
21. Omer, M.M.; Rahman, R.A.; Fauzi, M.A.; Almutairi, S. Key competencies for identifying construction activities that produce recyclable materials: An exploratory study. *Int. J. Build. Pathol. Adapt.* 2024. [CrossRef]
22. Pacheco-Torgal, F.; Jalali, S. Toxicity of building materials: A key issue in sustainable construction. *Int. J. Sustain. Eng.* **2011**, *4*, 281–287. [CrossRef]
23. Pietroiusti, A.; Stockmann-Juvala, H.; Lucaroni, F.; Savolainen, K. Nanomaterial exposure, toxicity, and impact on human health. *Wiley Interdiscip. Rev. Nanomed. Nanobiotechnol.* **2018**, *10*, e1513. [CrossRef]
24. Plum, L.M.; Rink, L.; Haase, H. The essential toxin: Impact of zinc on human health. *Int. J. Environ. Res. Public Health* **2010**, *7*, 1342–1365. [CrossRef]

25. Rey-Álvarez, B.; Silvestre, J.; García-Martínez, A.; Sánchez-Montañés, B. A comparative approach to evaluate the toxicity of building materials through life cycle assessment. *Sci. Total Environ.* **2024**, *912*, 168897. [CrossRef]
26. Sáez, P.V.; Osmani, M. A diagnosis of construction and demolition waste generation and recovery practice in the European Union. *J. Clean. Prod.* **2019**, *241*, 118400. [CrossRef]
27. Silvestre, J.D.; De Brito, J.; Pinheiro, M.D. Environmental impacts and benefits of the end-of-life of building materials–calculation rules, results and contribution to a “cradle to cradle” life cycle. *J. Clean. Prod.* **2014**, *66*, 37–45. [CrossRef]
28. Smurthwaite, M.; Jiang, L.; Williams, K.S. A review of the LCA literature investigating the methods by which distinct impact categories are compared. *Environ. Dev. Sustain.* **2024**, *26*, 19113–19129. [CrossRef]
29. Vefago, L.H.M.; Avellaneda, J. Recycling concepts and the index of recyclability for building materials. *Resour. Conserv. Recycl.* **2013**, *72*, 127–135. [CrossRef]
30. Yang, H.; Ma, M.; Thompson, J.R.; Flower, R.J. Waste management, informal recycling, environmental pollution and public health. *J. Epidemiol. Community Health* **2018**, *72*, 237–243. [CrossRef] [PubMed]