Sustainable
Manufacturing and
Environmental
Pollution
Programme

IMPACTS OF PLASTIC POLLUTION ON HUMAN HEALTH

Insights from the SMEP Programme

April **2024**

UK International Development
Partnership | Progress | Prosperity

This study is part of the Sustainable Manufacturing and Environmental Pollution (SMEP) programme, funded by the Foreign, Commonwealth and Development Office (UK-FCDO) and implemented in partnership with the UN Trade an Development (UNCTAD). The Instituto 17 (i17) prepared the study under the guidance of Henrique Pacini and Glen Wilson from UNCTAD, under the overall coordination of Chantal Line Carpentier, head of UNCTAD's Trade, Environment, Climate Change and Sustainable Development Branch.

Alessandro Sanches Pereira coordinated the team of experts, which included Camila Ester Hollas, Karina C G do Amaral, Lilian B E Veiga, and Marcela V L Ferron as lead authors; and Dipesh Pabari, Gadzikano Munyuki, Leonard Schurg, Soroush Abolfathi, and Vy Dinh as project contacts and data providers.

The authors thank the inputs and suggestions by Sinaia Netanyahu (WHO One Health), Halshka Graczyk, Yasuhiko Kamakura, Mustapha Kamal Gueye and Casper Edmonds (ILO) as well as numerous anonymous reviewers for valuable suggestions provided.

Renata Dahmer from i17 provided project support, and Lia Tostes worked on graphic design and Lana Barcellos illustrated the cover art.

Contents

Abbreviations

BPA	Bisphenol A
CBOs	Community-Based Organisations
cm	Centimeter
DALYs	Disability Adjusted Life Years
FAO	Food and Agriculture Organization of the United Nations
Gt CO2eq	Gigatonnes of carbon dioxide equivalent
HDPE	High-density polyethylene
InfCollR	Informal Collection Rate
ISO	International Organization for Standardization
kg	Kilograms
kt	Kilotonnes
LCA	Life Cycle Assessment
LRV	Low Residual Value
LR	Loss Rate
m^2	Square meter
m^3	Cubic meter
MPW	Mass of Plastic Waste
OIE	World Organisation for Animal Health
PET	Polyethylene terephthalate
PPE	Personal protective equipment
RelR	Release Rate
RedR	Redistribution Rate
SDGs	Sustainable Development Goals
SMEP	Sustainable Manufacturing and Environmental Pollution
t	Metric ton or tonne
UNEA-5	5th United Nations Environment Assembly
UNCTAD	United Nations Conference on Trade and Development
UNEP	UN Environment Programme
WHO	World Health Organisation

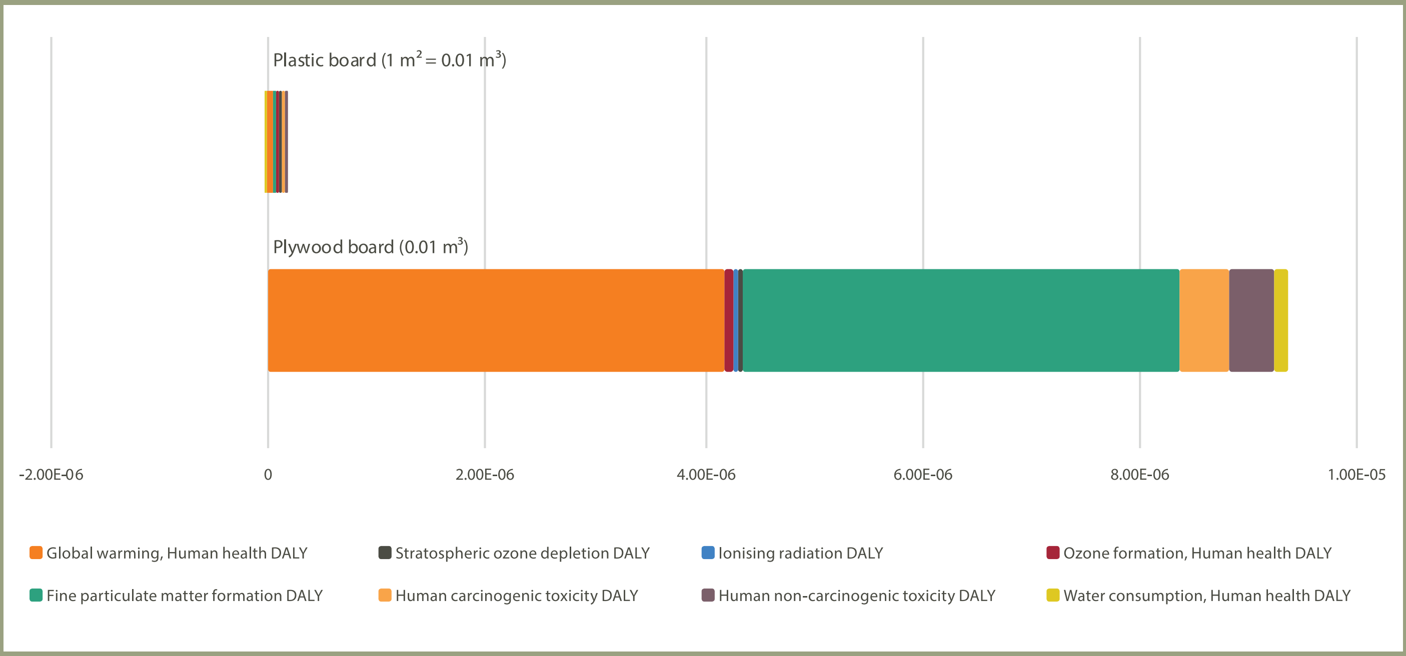
Executive Summary

The Sustainable Manufacturing and Environmental Pollution (SMEP) programme was established by the United Kingdom's Foreign, Commonwealth, and Development Office (FCDO) and implemented in partnership with the UN Trade and Development (UNCTAD). This study used empirical evidence from projects in Ghana, Zimbabwe, Nigeria, and Kenya which are part of the SMEP programme plastic portfolio, to analyze the role of their plastic recycling and upcycling systems and estimate reductions in human health impacts. A Life Cycle Assessment (LCA) modeling was used to estimate health impacts from avoided plastic material leakage into the environment, a causal factor of environmental pollution with direct and indirect detrimental effects on human health. This was done by combining the LCA analysis with the Disability-Adjusted Life Year (DALY) metric based on the ReCiPe methodology using regional and demographic factors where the projects are deployed. While results are context-dependent, the analysis provides a concrete way to estimate the effects of recycling initiatives on human health. This provides a novel way to understand the linkages between plastic recycling and human health measured as DALYs. A DALY is one lost year of a "healthy" life. The sum of these DALYs across the population, or the burden of disease, measures the gap between current health status compared to a baseline where normal life expectancy would be achieved, free of disease and disability. DALYs are calculated as the sum of the Years of Life Lost (YLL) due to premature mortality in the population and the Years Lived with Disability (YLD) for people living with the worsen health condition or its consequences.

HEALTH IMPLICATIONS OF SAMPLED RECYCLING INITIATIVES

Using selected plastics recycling and upcycling projects from the SMEP Programme, this study evaluate health impacts attributable to environmental emissions of plastic waste recycling and estimates emissions from reference materials that the recycled plastic replaces in each project. Key health-damaging categories have been identified upon project analysis based on LCA parameters. Despite variations across systems and contexts, as expected particulate matter formation was consistently recognized as the main impact categories on human health. Less expected, global warming potential was also identified as a major impact category on human health. In part because mechanical recycling processes, known for their high energy demand and particulate emissions, significantly contribute to environmental pollution and detrimental impacts on human health across all projects. Other impact categories such as water consumption, ozone formation, or non-carcinogenic toxicities were estimated to have lower impacts on human health

In the Ghana Beach Clean-up Project, which recovers plastic litter from Accra beaches and rivers, waste transportation and washing stages significantly contributed to fine particulate matter formation, impacting the overall DALYs. Conversely, the project demonstrated a positive impact on DALYs through efficient wastewater management, particularly in the washing stage, which is crucial in regions like sub-Saharan Africa, where wastewater management is challenging (see Figure 1).

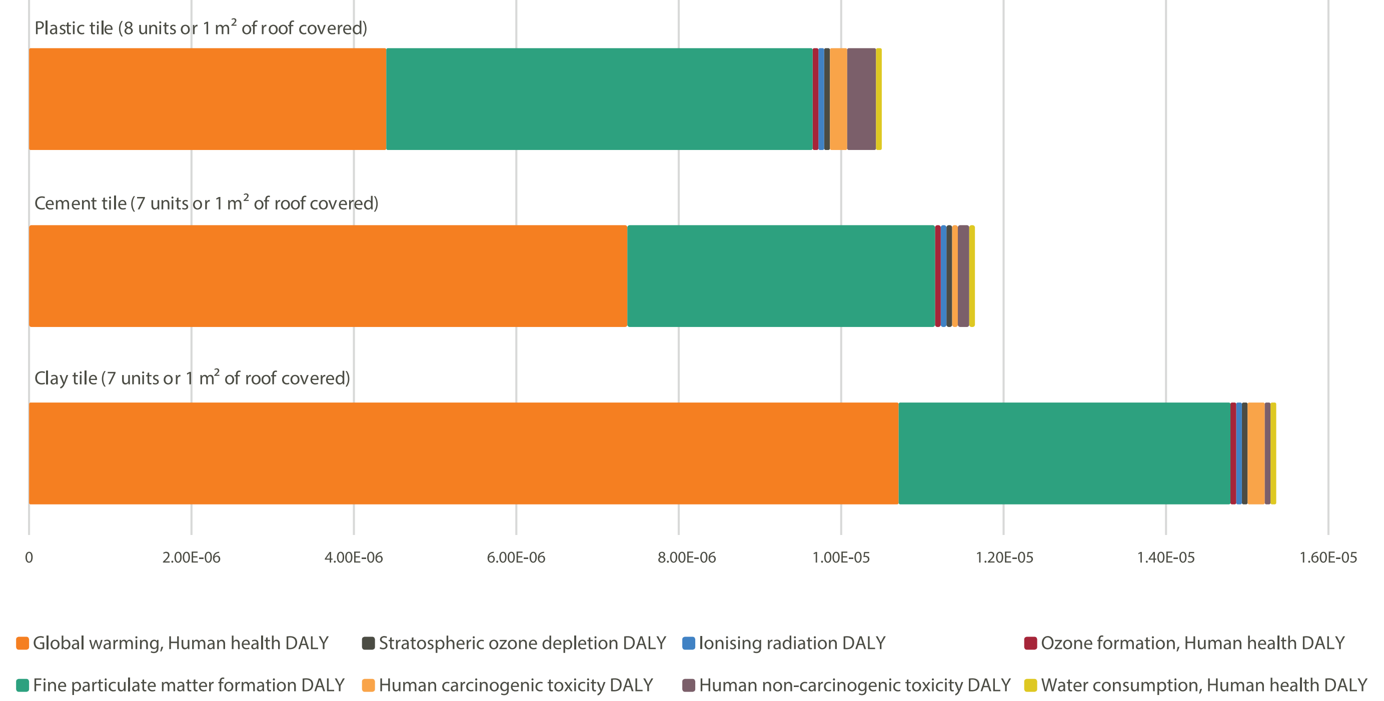

↓ **Figure 1.** Health Impact Distribution from Ghana Clean-up activities / Ghana Clean-up Project - Plastic board

Source: Prepared by i17

The initiative in Ghana focuses on transforming waste plastic into plastic boards. For every 1 thousand tonnes of waste plastic recycled, an estimated 1 year of life is gained, reducing the overall disease burden and enhancing public health. This demonstrates the significant health benefits of recycling activities considering materials replaced, particularly in reducing the impacts of global warming and particulate matter.

The Chinhoyi University Project in Zimbabwe, which transforms recovered plastics into roof tiles, highlighted energy-intensive processes such as mixing and extrusion as significant contributors to health impacts, exacerbated by the country's reliance on coal power due to insufficient hydropower and other renewables (see Figure 2). This scenario shows the need for recycling facilities to improve energy efficiency and reduce power consumption to indirectly mitigate health risks.

The production of plastic tiles in Zimbabwe as alternatives to cement and clay tiles shows varied health benefits. Replacing cement tiles results in a life gain of 50 days per 1 thousand tonnes of recycled plastic, reflecting a significant reduction in the total DALY. When replacing clay tiles, the life gain increases to 189 days per 1 thousand tonnes. These results highlight the environmental and health advantages of substituting traditional building materials with recycled plastic



↑ **Figure 2.** Health Impact Distribution from Chinhoyi University activities

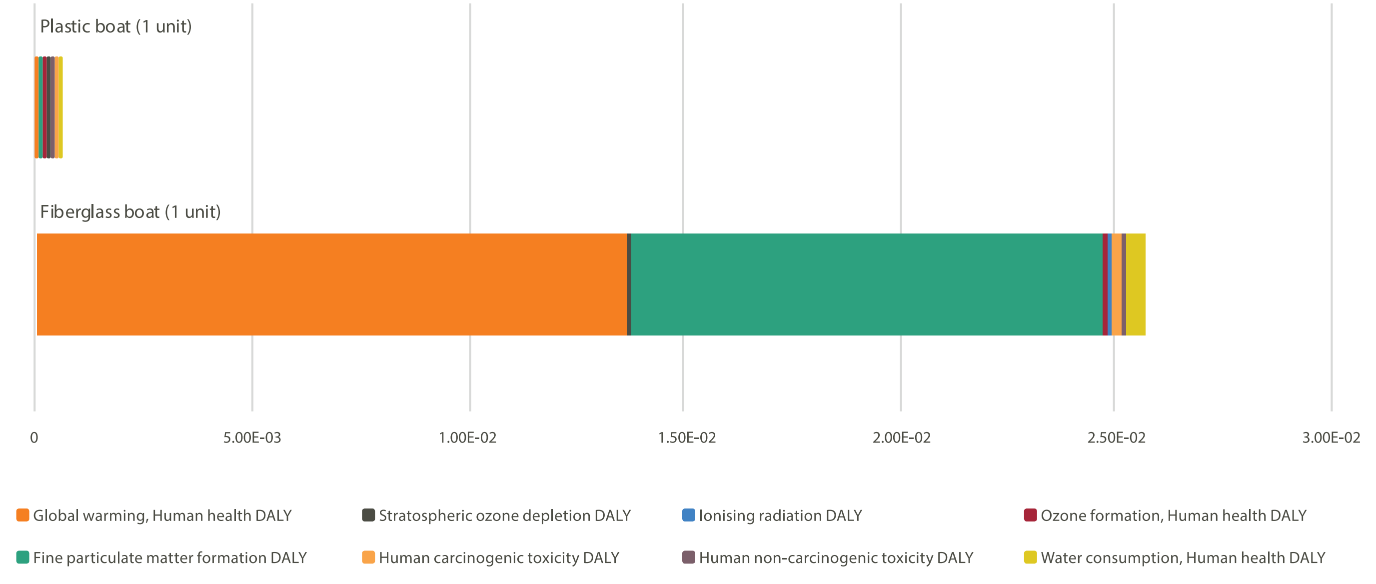
Source: Prepared by i17

alternatives. This finding is compatible with Souza et al. (2015) comparative LCA of ceramic versus concrete roof tiles within the Brazilian context- cement used in concrete tiles has a greater environmental impact. However, when the analysis focused specifically on human health, the results were reversed, suggesting that ceramic tiles might pose more of a health risk than concrete ones. It is therefore important to consider overall environmental impacts in combination with human health, in selecting superior products.

In the Kenya-based Flipflopi Project, transforming recovered plastic litter into heritage boats in Kenya's Lamu archipelago, the main health impact categories identified were global warming, fine particulate matter formation, and carcinogenic toxicity (see Figure 3). The boat-building phase, requiring extensive electricity and involving materials like metal screws and nails, was the primary source of health impacts.

↓ **Figure 3.** Health Impact Distribution from Flipflop project activities

Source: Prepared by i17



This initiative in Kenya stands out for its remarkable health impact. Building boats from recycled plastic waste results in an impressive life gain of 24 years per 1 thousand tonnes of recycled plastic. This emphasizes the substantial health and environmental benefits of repurposing plastic waste into valuable products, especially in regions with limited alternative waste management options, such as islands and archipelagos. The notable health gains associated with the Flipflopi project, particularly the favorable tonnage-to-DALYs relationship, are influenced by multiple factors. These benefits primarily arise from the efficiency of the recycling processes, including considerations for electricity and water consumption. Additionally, the gains are significantly impacted by the energy and resource intensity of the products that the recycled materials replace and the emissions profiles of these substituted products. Thus, the overall health benefits are a function of both the effectiveness of the recycling process and the environmental footprint of the alternative product systems.

In the GIVO Project, a Nigeria-based initiative collecting and flaking plastics in neighborhoods of Lagos and Abuja using modular, data-enabled, solar-powered container units, our analysis indicated that global warming and fine particulate matter formation were the main contributors to health impacts. The material sorting phase stands out as a significant contributor (see Figure 4). The project's reliance on sustainable practices like photovoltaic electricity and electric bicycles for waste collection and transportation contributed to lower impacts on health.

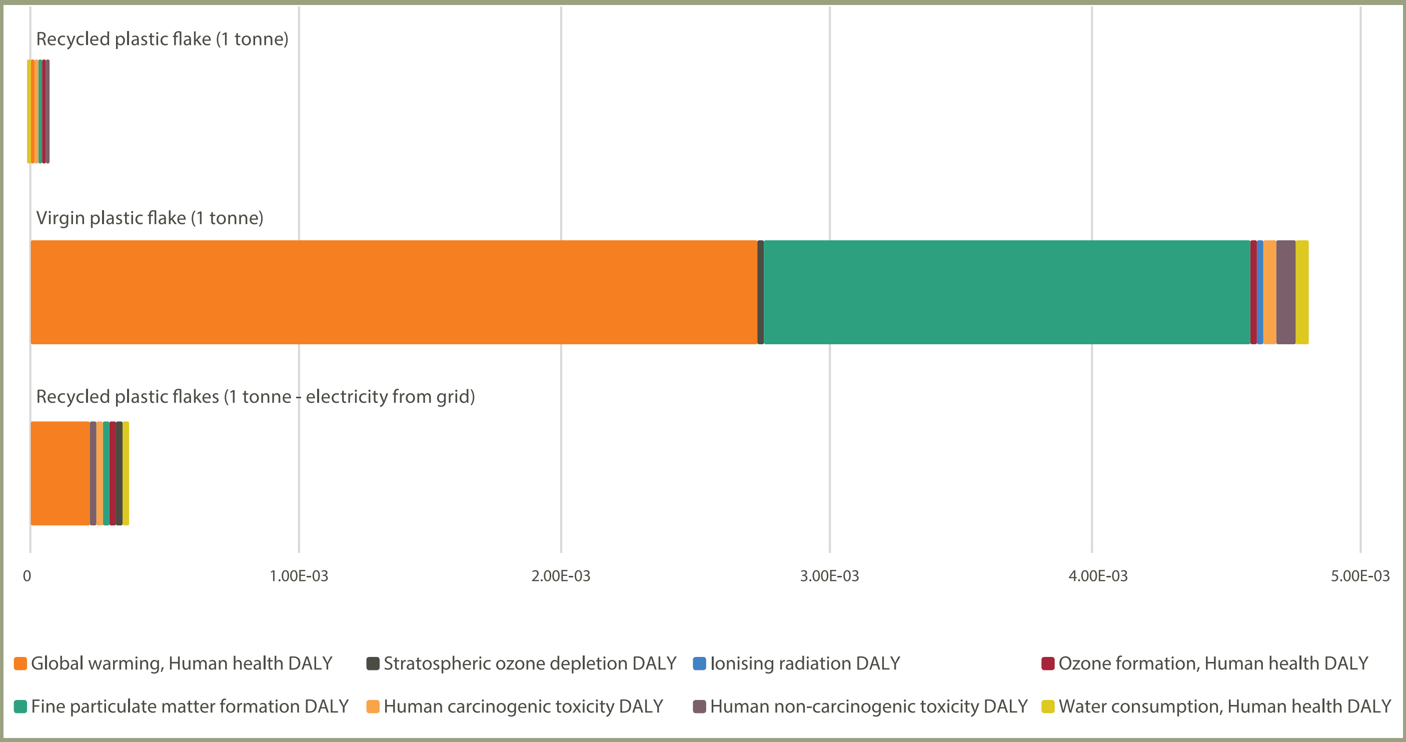


Figure 4. Health Impact Distribution from the GIVO project

↓ Source: Prepared by i17

In the Nigerian recycling initiative, replacing virgin plastic flakes with recycled materials has a notable health benefit, equating to an additional four years of life per 1 thousand tonnes of recycled plastic waste. While this increase is less pronounced than the remarkable 24-year gain per 1 thousand tonnes observed in the Kenyan project, it substantially reduces health risks linked to environmental contaminants. The health advantages of recycling extend beyond merely enhancing recycling rates. The type of product that recycled products replace plays a pivotal role in determining the overall health benefits. Thus, the focus should be on increasing the recycling volume and considering the specific environmental and health impacts of the substituted materials.

IMPACT ON THE PRODUCT RECYCLING SYSTEM

Evaluating the recycled products system shows the importance of recycling services in reducing environmental and health impacts. This is achieved by diminishing the need for new product manufacturing and lessening reliance on virgin raw materials. The avoided health impact observed in all scenarios emphasizes the importance of recycling in mitigating both environmental and health impacts. The study shows that recycling activities contribute positively to human health by decreasing the number of DALYs, which indicates a reduction in overall health burdens associated with environmental factors. Table 1 provides an overview of the health benefits of increased recycling efforts per recycling project.

Table 1. Projected life years gained from recycling 1 thousand tonnes of plastic waste

Country	Project	Final Product	Life gained per 1 thousand tonnes of waste plastic recycled	
			Total (days)	Total (DALY)
Ghana	Ghana Clean-up Project	Plastic board	1 year	1.076E+00
Kenya	Ghana Clean-up Project	Plastic boat	24 years	2.45E+01
Nigeria	GIVO Project	Recycled plastic flakes	4 years	3.98E+00
Zimbabwe	Chinhonyi University Project	Plastic tiles replacing cement titles	50 days	1.36E-01
		Plastic tiles replacing clay titles	189 days	5.19E-01

This also shows the necessity of enhancing plastic recycling and collection services to address the significant environmental challenges caused by plastic leakage into the environment. The high waste generation and low recycling rates in countries where the SMEP project cases are located, stress the need for improved recycling infrastructures and services to protect public health and the environment.

KEY CONSIDERATIONS AND RECOMMENDATIONS

This analysis mostly focused on the midstream of plastics recycling chain. Future research should focus on the collection stages of recycling processes, the health risks faced by waste pickers, and the use and disposal stages of recycled products. Analyzing those additional up- and downstream stages could produce a significantly more accurate picture of how plastics recycling systems impact human health, both domestically and across borders via the trade in secondary plastics. A combination of life cycle assessments and human health impact categories is essential for evaluating recycling practices' environmental, health, and social implications as illustrated in the cases of this study

The findings support calls for global efforts to improve recycling practices, aligning them with the health dimension of the sustainable development goals. By increasing recycling rates and integrating sustainable practices, such as energy efficiency, sound wastewater management, and emissions and particulate controls, countries can contribute significantly to global efforts to combat the triple planetary crisis of climate change, pollution, and biodiversity loss and reduce pollution-related diseases.

1.

Introduction

Plastics have emerged as a pivotal component across diverse sectors such as packaging, construction, industry, transportation, and agriculture, significantly contributing to the advancement of modern society (Vlasopoulos et al., 2023). Their unique attributes, including durability, resistance, lightweight nature, cost-effectiveness, and transparency, have led to large growth in global plastic consumption since their market inception (Ali et al., 2023). Nonetheless, the prevailing linear approach to materials management, characterized by intensive resource utilization and substantial waste generation, coupled with plastics' long degradation periods, leads to considerable environmental degradation and increased risks to human health (Deeney et al., 2023; Tiwari et al., 2023).

Plastic pollution has become one of the most pressing environmental issues, as the rapidly increasing production of disposable plastic products overwhelms the world's ability to deal with them. This pollution is most visible in developing Asian and African nations, where municipal waste collection systems are often inefficient or non-existent. However, even developed countries struggle to properly collect discarded plastics, especially those with low recycling value. The One Health approach, a quadripartite collaboration signed by the Food and Agriculture Organization of the United Nations (FAO), the World Organisation for Animal Health (OIE), the UN Environment Programme (UNEP), and the World Health Organisation (WHO) recommends addressing the full spectrum of good health control – from prevention to detection, preparedness, response, and management – and contributing to global health security (WHO, 2024). The One Health approach can be applied to understand and address the impacts of plastics and chemical additives on human and environmental health. The state of the science on plastic chemicals reveals that over 16,000 chemicals are detected in plastics, from which 1,300 are of concern and over 10,000 have no hazard information available, meaning that chemicals of concern can be present in all plastic types (Wagner et al., 2024).

By the year 2024, it is projected that the global production of plastic waste will reach approximately 399 million metric tons (OECD, 2022), with a significant fraction destined for landfills, unregulated dumping sites, open burning, or uncontrolled release into natural environments, including marine ecosystems (Kibria et al., 2023). Research conducted by Smith et al. (2023) indicated that approximately 40% of current plastic production needs to be more adequately managed, with a mere 9% subjected to recycling processes (Maria Tsakona et al., 2021). Should the existing production, consumption, and waste management paradigms persist, the plastic industry is poised to account for 20% of total global oil consumption by the year 2050, effectively extending the market life of fossil fuels even as combustion technology is gradually phased out (Ellen MacArthur Foundation et al., 2016). Furthermore, Smith et al. (2023) propose that, even under optimistic recycling scenarios, the generation of virgin plastic waste could be curtailed by only 34% by the mid-21st century.

The current ineffective plastic waste management crisis has garnered widespread attention within scientific, legislative, and civil society fora (Tenhunen-Lunkka et al., 2023). A landmark development was the endorsement of a resolution for a Global Treaty on Plastics during the fifth United Nations Environment Assembly (UNEA-5) in Nairobi, Kenya, in 2022. The resolution specifically targeted curtailing plastic pollution across marine and terrestrial environments (UNEP, 2022). This development produced a pathway for a global treaty framework that addresses plastics' life cycle from production to disposal, including material substitution and plastic waste prevention and mitigation through end-of-life management services. This resonates with the

Sustainable Development Goals (SDGs) by promoting responsible resource utilization and waste minimization while advocating for circular economy practices such as recycling and reuse (Deeney et al., 2023; United Nations, 2015).

Reflecting global concerns, the African continent is witnessing a rapid escalation in plastic consumption and waste generation, often outpacing the development of adequate management infrastructure (Rossouw et al., 2023). In numerous African nations, approximately 80% of plastic waste is relegated to poorly managed landfills or dispersed across natural settings, exacerbating pollution in oceans, rivers, and terrestrial systems (Akan et al., 2021; Angnunavuri et al., 2023). Challenges within the African recycling sector, such as elevated operational costs and the absence of stable secondary markets for recycled materials locally, significantly hinder effective waste treatment and management strategies (Shomuyiwa et al., 2023). The plastic recycling industry in Africa is characterized by its volatility and fragmentation. Market participants often need help with an underdeveloped market for various grades of recycled plastic. This instability can hamper growth within the region. Due to the lack of end markets for recycled material, most recyclers are in Northern Africa (e.g., Marrocco and Egypt) and export their output to Europe, where demand for them is much higher than in local African markets (Holland, 2021). While recycling is promoted as a viable strategy to alleviate environmental and public health dilemmas, the comprehensive impacts of plastic waste management, particularly concerning human health, still need to be explored and better understood (Cook et al., 2023; Smith et al., 2023; Landrigan et al., 2023). Circular waste management models, while beneficial, are not devoid of health hazards, including occupational exposure to harmful substances during collection and recycling processes, as well as potential consumer exposure to chemicals of concern, which eventually make their way into recycled goods (Dada et al., 2023; Rodrigues Gonçalves et al., 2024; Undas et al., 2023; UNEP, 2023).

The Life Cycle Assessment (LCA) methodology is increasingly recognized as crucial for evaluating plastic-related initiatives' environmental and health ramifications (Ali et al., 2023). Serving as an effective tool within the circular economy framework, LCA enables the estimation of health impacts in terms of Disability Adjusted Life Years (DALYs), a metric that links morbidity and mortality to quantify health loss due to disease and premature death (Duane et al., 2020). For instance, research by Mazhandu et al. (2023) on South African plastic waste management scenarios revealed that recycling could reduce the health impacts measured in DALYs by approximately seventeenfold compared to landfill disposal. Similarly, Di Maria et al. (2020) demonstrated the positive health outcomes of plastic waste recycling within Italy's waste management system, attributing significant health benefits to increased recycling efforts. In their meta-analysis, Deeney et al. (2023) examined the relationship between the use of recycled plastics and public health. Their research confirms that using recycled plastics instead of virgin plastics can lead to tangible health improvements. Specifically, their findings suggest that for every tonne of plastic recycled and reused in the food sector, there is an estimated increase of one day in healthy life expectancy. This indicates that higher utilization of recycled plastics can reduce the health risks traditionally associated with producing and using new plastics.

As the global community intensifies its focus on the health implications of plastic pollution, comprehensive research, and diverse data are becoming increasingly imperative (Kibria et al., 2023). This study delves into the environmental and health benefits, the advantages of supplanting non-recycled products, and the critical role of robust plastic waste management strategies in averting environmental contamination and protecting human health. Employing a methodological framework based on case studies, life cycle inventory analysis, and impact assessment techniques, this analysis offers a sample view of the prevailing challenges in developing regions, with a particular emphasis on empirical cases from Sub-Saharan African countries such as Ghana, Kenya, Nigeria, and Zimbabwe.

This report evaluates the health impacts attributable to environmental emissions from plastic waste recycling and is divided into four sections. Section 1 presents an overview of the four targeted Sub-Saharan African countries where empirical project evidence was sourced: Ghana, Kenya, Nigeria, and Zimbabwe. Section 2 describes the methodologies employed in our investigation, including an overview of case studies, life cycle inventory analysis, and impact assessment methodologies. It further explores the phenomena of plastic leakage into the environment and conducts a sensitivity analysis to test the robustness of the findings. It then sets the stage for a nuanced understanding of plastic use and disposal on environmental and health impacts. It serves as a basis for the subsequent analyses with a solid methodological framework. Section 3 presents the core findings. It examines the health implications of recycling initiatives, evaluates the product recycling system's efficacy, and assesses waste management practices' performance in mitigating plastic leakage. Section 4 synthesizes the insights from the analysis, highlighting the main limitations encountered during the study and proposing future recommendations. By reflecting on the challenges and gaps identified, this study offers a forward-looking perspective, calling for enhanced strategies and practices that could pave the way for more sustainable, health-conscious, and effective waste management solutions.

2.

Environmental and Health Impacts of Plastic Waste Management in Targeted Developing Regions

In the complex lifecycle of plastics, a significant role is attributed to the workforce, notably the informal sectors such as waste pickers. These individuals play a crucial role in mitigating the environmental impact by reducing the volume of plastic waste destined for landfills and open dumpsites. In many regions of the developing world, waste-picking is a critical waste management service and provides a livelihood for individuals lacking more formal education and marketable skills. However, this activity exposes them to various health and safety risks due to waste materials' hazardous and unpredictable nature and often inadequate working conditions.

During consumption and disposal, plastics can become contaminated with various hazardous substances, such as household bleach, insecticides, and discarded medication. These contaminants, not inherent to the plastics but acquired from environmental exposure, can pose risks to human health and the environment. According to the UNEP Technical Report on Chemicals in Plastics, while some plastics may contain hazardous chemicals (whether added intentionally or unintentionally) that can potentially leach out, it is also common for plastics to absorb harmful chemicals from their surroundings during their lifecycle (UNEP, 2023). Other substances like additives and residual monomers are known to disrupt endocrine functions and contribute to a host of health issues, including but not limited to premature births, neurodevelopmental disorders, and an increased risk of cancer (UNEP, 2023; Landrigan et al., 2023). Workers engaged in plastic recycling, encompassing both mechanical and chemical processes, face heightened risks of cardiovascular diseases, toxic metal exposure, and cancer, compounded by poor working conditions and a lack of appropriate safety measures (Soares et al., 2021).

Particularly vulnerable within this workforce are women, who, in addition to facing the general hazards associated with waste picking and recycling, encounter gender-specific health risks and societal marginalization. Exposed to harmful chemicals, they are at increased risk of urinary infections, reproductive health issues, and altered hormone levels, which can adversely affect pregnancy and child development (Landrigan et al., 2023). The occupational hazards extend to children, who, even from gestation, face risks from plastic-related contaminants, leading to a spectrum of developmental and health issues with lifelong consequences.

The challenges extend beyond immediate health risks to include long-term occupational disorders such as respiratory and gastrointestinal problems, musculoskeletal damage, and mental health issues among waste workers. These are often exacerbated by the absence of personal protective equipment and safety training (Gutberlet et al., 2017). Furthermore, plastic recycling introduces additional hazards, particularly when inadequate safety measures allow the release of hazardous compounds during the heating and extrusion of recycled plastics (Cook et al., 2023).

Emerging research highlights the role of climate change on plastics' environmental and health impacts. The interaction between climate phenomena and the life cycle of plastics has been shown to intensify the release of plastics and associated chemicals into the environment, presenting a growing threat to human and ecological health (Landrigan et al., 2023).

The plastic trade relations between Africa and the rest of the world reveal a complex interplay of economic, environmental, and social dynamics. In 2021, the continent imported 14,251 kilotonnes (kt) of plastics, indicating Africa's substantial demand for plastic materials, whether for consumption, as raw material for manufacturing, or for other uses within various sectors. On the other hand, the exports, totaling 3,597 kt, are less than the imports, confirming that Africa is a net importer of plastics (UNCTAD, 2024).

Africa's share of global plastic imports peaked at 4.80% in 2020 before slightly declining to 4.26% in 2021 (UNCTAD, 2024). This reflects the continent's growing demand for plastic materials, likely driven by rapid urbanization and the growing middle class creating new consumer markets (Jambeck et al., 2018). These figures point to an influx of plastics into the continent, further complicating the waste management challenge and exacerbating health risks for those in the informal recycling sector. Some countries, like Kenya, have taken steps to reduce plastic waste by banning single-use plastic bags. Despite these efforts, the region still needs more formal waste management systems, leaving a significant burden on the informal sector. These informal workers, including many women and children, are exposed to various health risks due to the hazardous nature of waste materials, including plastic contaminated by household bleach, insecticides, and discarded medication.

This section presents an overview of the targeted Sub-Saharan African nations: Ghana, Kenya, Nigeria, and Zimbabwe. This comparative analysis aims to uncover unique characteristics and usual challenges that recycling and upcycling initiatives in these countries face, thereby facilitating an understanding of their individual and collective needs.

2.1. Ghana

Ghana's plastic production reached 205 kt in 2019 (Massa et al., 2024). During the same period, the country experienced a notable rise in plastic imports, increasing from 150 kt in 2005 to a peak of 598 kt in 2019 (UNCTAD, 2024). Ghana faces significant environmental, public health, and occupational challenges from extensive plastic waste generation, collection, recovery, recycling, and disposal. The country produces approximately 13 kt of solid waste daily, about 0.47 kilograms (kg) per person (Kwarteng et al., 2020). Alarmingly, an estimated 22% of this waste remains uncollected and untreated within communities. At the same time, the remainder is sent to landfills and dumpsites that need more essential controls, such as leachate management and secure covering. This situation renders these sites accessible to waste pickers, animals, and various disease vectors, escalating the environmental crisis and health risks (Kwarteng et al., 2020). Mismanagement in waste disposal notably heightens the health and occupational hazards for individuals residing near disposal sites and for those involved in waste management, correlating directly with increased occurrences of congenital disabilities, reproductive disorders, elevated cancer risks, and respiratory diseases (Mudu et al., 2021).

Regarding plastic waste, the World Economic Forum (2023) reports that Ghana generates approximately 840 kt of plastic waste each year, with around 9.5% being collected for recycling initiatives. However, according to Daraskevich et al. (2023), Ghana annually produces an estimated one million tonnes of plastic waste, a significant portion of which consists of polyethylene terephthalate (PET) bottles. The discrepancy between these figures highlights different aspects or scopes of waste management studies.

Investigations into waste composition at key dumpsites within Accra reveal that PET bottles dominate the recovered waste materials. Still, less than 10% is recycled stressing the need for enhanced recycling initiatives covering a broader spectrum of polymers (Kwarteng et al., 2020).

Ghana's plastic waste value chain involves diverse stakeholders, including the informal sector, which plays a pivotal role in collecting and aggregating plastic waste, contributing to the country's recycling efforts, albeit under challenging conditions.

While plastic waste collection, transport, sorting, recovery, and recycling provide essential income and employment for many Ghanaians, these activities predominantly occur within an informal framework marked by labor-intensive, low-tech, and low-paid conditions. This sustains a livelihood for the poor and vulnerable and exposes them to severe physical, mental, and occupational hazards (Kwarteng et al., 2020). The informal nature of waste picking, compounded by a lack of formal recognition and inadequate occupational health and safety measures, significantly heightens the risks associated with this sector (Mensah et al., 2024).

Recent studies and reports have begun to shed light on the intricate relationship between human health, occupational hazards, and inefficiencies in plastic waste collection and recycling. This growing body of evidence highlights the adverse impacts on informal waste collectors, underlining the need for systemic interventions to mitigate these risks (Owusu-Sekyere, 2014; GAIA, 2021).

Notably, the lack of access to personal protective equipment (PPE), safe waste sorting and storage facilities, and healthcare services exacerbate the vulnerability of waste pickers and processing workers to a spectrum of health and occupational hazards. The prevailing conditions at dumpsites, characterized by inadequate protection and hygiene, further aggravate these risks, disproportionately affecting women and leading to significant disparities in access to resources and support within the sector (Nuripuoh et al., 2022).

2.2. Kenya

Economic growth and an increasing population in Kenya have led to increased consumption of products and services, notably plastics. The country's annual plastic consumption ranges between 500 and 800 kt, a significant portion of which is imported. Despite this high consumption rate, plastic waste management and recycling efforts still need to be improved. Specifically, only 15% of the generated urban waste is recycled or properly disposed of in landfills. In contrast, approximately 70% of this waste is discarded in the environment or illegal dumpsites, with plastic packaging materials constituting 9 to 15% (Kimani, 2021).

The lack of structured waste management strategies has led to the rise of an unregulated informal sector. Despite introducing the Sustainable Waste Management Act of 2021, which aimed to address these issues through measures like the establishment of the Waste Management Board, mandatory producer responsibility programs, and the shutdown of illegal landfills, its implementation has yet to be effective. The inefficiency of governmental waste collection and separation exacerbates this issue, pushing informal waste pickers to the forefront of plastic recovery. However, this approach needs more efficiency due to the absence of waste separation practices at the household level, complicating the retrieval of recyclable plastics and making the process labor-intensive and inefficient.

Informal waste pickers in Kenya face hazardous working conditions without adequate protection, leading to significant health risks due to exposure to pollutants at dumpsites. Proper PPE is needed to make plastic collection safer and reduce exposure to serious health risks. Work conditions are also marked by harassment, discrimination, respiratory diseases from continuous smoke exposure, injuries from handling hazardous materials, and a glaring absence of sanitation facilities (GAIA, 2021).

Recent studies highlight the low level of hazard awareness among waste pickers, raising the importance of protective measures. The usage of PPE is rare and, when available, is often ignored due to a lack of understanding of its importance. This ignorance extends to personal hygiene, with some workers wearing the same clothes for extended periods without washing, increasing susceptibility to infections and other indirect health problems (Hashim et al., 2020).

Local initiatives attempt to bridge the gap between the formal and informal sectors by sourcing post-consumer plastics from waste pickers and offering incentives for regular supplies. However, challenges persist as waste pickers, driven by immediate financial needs, often sell the provided PPE rather than utilize it for their own safety (Gall et al., 2020).

Further research in various Kenyan dumpsites has consistently revealed the dire conditions under which waste pickers operate, including the absence of PPE, inadequate knowledge of sanitation, and exposure to multiple health hazards. Women, in particular, face additional challenges related to reproductive and urinary health due to the lack of clean facilities and safe working conditions (Peninah et al., 2022; Kimani, 2021). These conditions underscore the urgent need for comprehensive waste management reforms in Kenya, emphasizing the protection and education of waste pickers, especially women, to mitigate the severe health and environmental impacts of improper plastic waste handling and processing.

2.3. Nigeria

With its growing population and rich natural resources, Nigeria stands on the cusp of becoming a significant player in the global economy. However, it needs to help sustainably leverage its growth potential, notably in managing plastic waste. Nigeria alone represents 17% of Africa's total plastic consumption.

Nigeria produced 513 kt of plastics in 2020 and was among the biggest African plastic producers. The country is a major plastic importer, contributing up to 5.85% of Africa's total imports, increasing from 1,498 kt to 1,962 kt between 2005 and 2020. The country generates an estimated 3,200 kt of solid waste per year, one of the highest amounts in Africa (Yalwaji et al., 2022). The current mismanagement of plastic materials significantly endangers public health and the environment, as the country generates approximately 2.5 kt of plastic waste annually, mostly from packaging (Yalwaji et al., 2022). Despite these staggering figures, only a minor fraction of this waste undergoes recycling or proper disposal (Heinrich Böll Foundation, 2019).

Informal waste pickers remain at the core of the nation's plastic waste collection and recycling efforts, often operating under hazardous conditions in open dumpsites. These settings pose significant risks, including exposure to toxic emissions from plastic burning, leading to severe health implications. Studies highlight a prevalent lack of PPE and low awareness of health risks among these workers, exacerbating their exposure to respiratory and other severe health risks (Kehinde et al., 2020; Ogunkoya et al., 2022).

In Lagos, the Olusosun dumpsite, one of Nigeria's largest, exemplifies the challenges of waste pickers who need access to regulated working environments and health and safety training. Both adults and children, many of whom are out of school, navigate daily hazards such as insect stings, injuries from sharp objects, and exposure to harmful waste, often without any protective gear (Taiwo, 2022; Afon, 2012).

Similar conditions prevail across various regions, from the Awotan site in Southwest Nigeria to the capital city of Abuja. Workers face social marginalization and operate without basic security, exposed to numerous health hazards. Despite their essential role, waste pickers lack social recognition, proper sanitation, and limited access to healthcare. They are often stigmatized (Ogwueleka, 2021; Dada, 2022).

Recent studies in Lagos have further documented the occupational risks and adverse health outcomes waste pickers face, underlining the urgent need for systemic change. The extreme poverty, unsanitary working conditions, and lack of education on safety measures contribute significantly to their vulnerability to diseases and injuries (Dada et al., 2023; Taiwo et al., 2022).

The repercussions of plastic pollution extend beyond the immediate environment to public health, with chemical components like bisphenol A (BPA) posing long-term risks such as heart and reproductive system damage and potential cancers (Ma et al., 2019). The situation is compounded by the inadequate use of PPE, lack of safety training, and general unawareness of the risks associated with waste management among workers (Dibia et al., 2023; Raufu et al., 2023). In short, Nigeria's plastic waste crisis requires concerted efforts to improve waste management infrastructure, enhance worker safety, and promote public health through comprehensive environmental policies and education initiatives.

2.4. Zimbabwe

Zimbabwe has the smallest figures among the highlighted countries, with imports relatively stable and slightly increasing from 86 kt in 2005 to 213 kt in 2021. The exports show incremental growth, suggesting a gradually expanding trade from 4 kt in 2005 to 11 kt in 2021, maintaining a relatively minor position in the plastics trade compared to its counterparts (UNCTAD, 2024). Zimbabwe's rising population and improved living standards have led to increased waste generation, exacerbating challenges in waste management similar to those faced by many developing countries. The country faces significant environmental and public health challenges due to indiscriminate and illegal dumping of solid waste. Financial constraints have led local governments to adopt low-cost yet inefficient waste management solutions, placing waste workers in perilous conditions and exposing them to various occupational hazards (Makwara et al., 2013; Intauno et al., 2023).

Research in Gweru, a city in central Zimbabwe, highlighted the risks faced by informal waste management sectors, noting issues like odors from decaying waste, smoke from burning trash in the open, and rodent infestations as common hazards. Workers, primarily involved in manual tasks, encounter risks at every stage of waste management, from collection to processing and disposal. They face risks of mechanical injuries from sharp objects, ergonomic strains from handling heavy materials, and chemical exposures that lead to various health issues (Jerie, 2016; Jerie et al., 2014).

A study at the Pomona dumpsite in the capital city of Harare revealed the living conditions of waste pickers, many of whom reside in makeshift shelters on-site, highlighting a lack of basic sanitation facilities. The informal sector's crucial role in waste recycling contrasts starkly with their working conditions, marked by exposure to biological, chemical, and physical hazards without adequate PPE (Nemadire et al., 2017).

Further studies in rural areas like Murewa reveal the pervasive issues of irregular garbage collection and the associated risks to waste pickers from uncollected refuse. These workers face ergonomic and biological dangers, lack proper sanitation, and work without suitable protective gear, highlighting a systemic disregard for their safety and health (Intauno et al., 2023).

Investigations in Hopley and Masvingo examined the impact of environmental and occupational hazards on informal waste workers and residents. The studies also highlighted risks posed by climatic factors such as heat, drought, and storms, which exacerbate the health hazards from poor air quality, leading to increased respiratory and cardiovascular conditions among waste workers. The lack of facilities, sanitation services, and protective clothing exacerbates these challenges, significantly impacting workers' health and well-being (Machemedze et al., 2021).

Kadungure et al. (2023) assessed climate-related risks, finding that extreme weather conditions, such as heatwaves, reduce working hours and income for waste pickers and urban agriculture workers. The lack of access to adequate housing, healthcare, and clean water intensifies their vulnerability to occupational injuries and illnesses, compounded by their marginalized social and legal status. In short, Zimbabwe's solid waste management crisis poses severe environmental, health, and occupational risks, particularly for informal sector workers. Comprehensive waste management strategies, improved working conditions, and access to enhanced health and safety resources are critical to addressing these challenges.

3.

Methodological Framework and Preliminary Analysis

This section describes the methodologies applied in the report, including an overview of case studies, life cycle inventory analysis, and impact assessment techniques. Additionally, it addresses the issue of plastic leakage and undertakes a sensitivity analysis to validate the reliability of the results. This foundational part establishes a thorough understanding of plastic utilization and disposal's environmental and health ramifications, laying the groundwork for the following in-depth analyses.

The environmental evaluation of four plastic recycling initiatives in Sub-Saharan Africa was conducted using the LCA methodology outlined in ISO 14040/2006 standards and ISO 14044/2006. For this LCA analysis, the SimaPro 9.5 software was used to simulate the life cycles of the empirical project studies. This simulation facilitated the estimation of environmental burdens and health-related damages associated with each project. Specifically, the assessment focused on quantifying health impacts resulting from industrial pollution and the leakage of plastics into the environment.

3.1. Overview of the SMEP project cases

This section evaluates the environmental and health-related impacts, both beneficial and detrimental, of four case studies related to plastic recycling initiatives in Ghana, Zimbabwe, Kenya, and Nigeria, as detailed in Table 2. These initiatives are part of the Sustainable Manufacturing and Environmental Pollution (SMEP) programme, which funds research and related interventions aimed at reducing the environmental and socio-economic impacts of the manufacturing sector in Sub-Saharan Africa and South Asia, as well as addressing some of the most pressing challenges associated with plastic pollution in these regions.

↓ Source: Prepared by i17 based on information from the SMEP programme.

Table 2. Overview of SMEP target projects (case studies)

Project	Recycling process description	Facilitation Consortium	Location
The Ghana Clean-up Project	Mechanical recycling of lower-value plastic waste (LVP) collected from the environment to produce plastic boards	Riverrecycle Oy, Beach Cleanup Ghana, and AmbitiousAfrica.	Ghana
The Chinhoyi University Project	Mechanical recycling of plastic waste collected from the dumpsites, producers, and community-based organisations (CBOs) to produce plastic roof tiles	Chinhoyi University of Technology, Zimbabwe, and Kudiwa Waste and Energy Solutions.	Zimbabwe
The Flipflopi Project	Mechanical recycling of plastic waste collected from households, local businesses, and peri-urban areas in Lamu, upcycled into plastic lumber used to produce plastic boats and furniture.	The Flipflopi Project Foundation	Kenya
The GIVO Project	Mechanical recycling of plastic waste collected from Lagos and Abuja neighbourhoods to produce plastic flakes/pellets.	GIVO Africa and the University of Warwick	Nigeria

This investigation employs a cradle-to-gate approach for the LCA, which includes waste collection and upstream transportation to the recycling facility, as well as the processing stages—namely recycling, which encompasses water and energy consumption and wastewater generation. This assessment concludes once the recycled product exits the facility's gate. It is important to note that this LCA boundary starts from waste collection and ends at the factory gate, excluding any downstream distribution of the recycled products. This approach aligns with standard 'cradle-to-gate' models, focusing on the environmental footprint from raw material collection to the recycling facility's processing phase, transforming plastic waste into resalable flakes or products. However, it excludes the usage phase and the end-of-life disposal or recycling of products. This exclusion is due to the nature of the project studies, which are in an emerging stage, with the initial products just beginning to be manufactured, and a lack of comprehensive data on these later stages.

The first case analyzed is the Ghana Clean-up Project, which aligns with the cradle-to-gate boundaries previously outlined. This project concentrates on collecting plastic waste from the environment and manufacturing plastic boards through mechanical recycling. The defined system boundaries for this analysis include the transportation of waste to the recycling facility by truck, along with the subsequent mechanical processing steps—sorting, crushing, washing, drying, and pressing—to produce the plastic boards (see Figure 5). These boundaries effectively span from the initial waste collection to the point where the processed product leaves the facility's gate, encompassing key operational stages and value addition within the SMEP project cases without extending to product distribution, usage, or end-of-life phases.

The selection of functional units in this study varied across the scenarios, reflecting the distinct output flows of each project. The functional unit for the Ghana Clean-up Project was defined as one square meter (m^2) of construction material, one centimeter (cm) thick, equating to 0.01 cubic meter (m^3) or 8.68 kilograms (kg) of plastic boards.

To assess the environmental benefits, the study employed the avoided burden approach, also known as the consequential, system expansion, or substitution approach. This method is the first in the hierarchy prescribed by ISO14044 for handling multifunctional processes in LCA, as discussed by Heijungs et al. (2021). The avoided burden approach considers the dual effects of recycling activities:

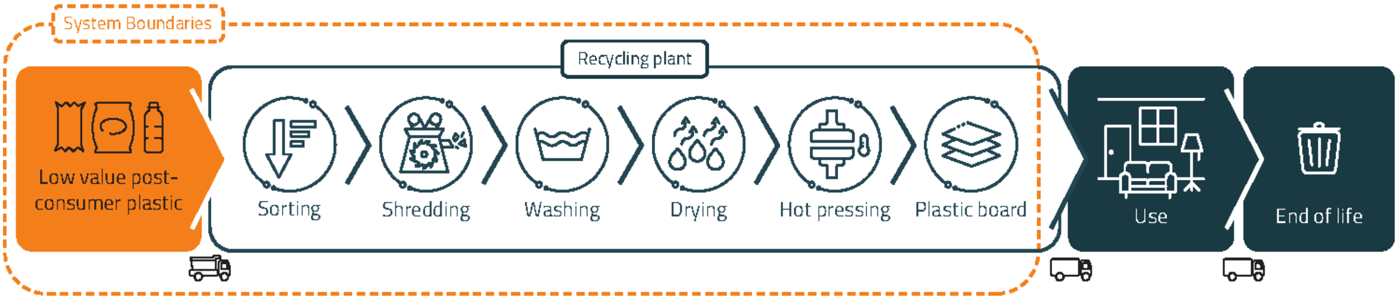
a. By averting the production of conventional market products that fulfill identical functions as the recycled outputs, reducing the demand for new raw materials and

b. By preventing the mismanagement of plastic waste, which would otherwise leave human-made systems and accumulate in the natural environment, this dual consideration includes the environmental impacts of recycling processes such as energy and water consumption and wastewater generation.

Consequently, the analysis for the Ghana Clean-up Project includes preventing the production of 0.01 m^3 of plywood per equivalent volume of plastic board produced, where 0.01 m^3 represents the volume for 1 m^2 of a board that is 1 cm thick.

↓ **Figure 5.** Ghana Clean-up Project’s system boundary

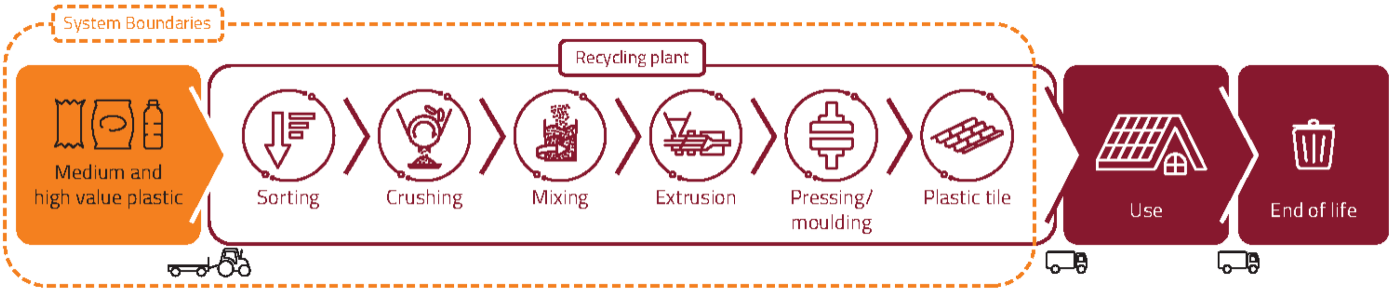
Source: Prepared by i17.



The second case examines the Chinhoyi University Project in Zimbabwe. This project involves gathering plastic waste from dumpsites, producers, and Community-Based Organisations (CBOs), which is then transported to the recycling facility using a tractor-trailer. The waste undergoes mechanical recycling to create plastic tiles, including an additional extrusion process (see Figure 6). In the case of the Chinhoyi University Project, the functional unit was established as 1 m^2 of roofing, corresponding to eight plastic tiles with a total weight of 3.2 kg. For this project, the environmental benefits include the avoided impacts of producing cement tiles or clay tiles, equivalent to 7 pieces weighing 4.6 kg and 4.4 kg, respectively.

↓ Figure 6. Chinhoyi University Project's system boundary

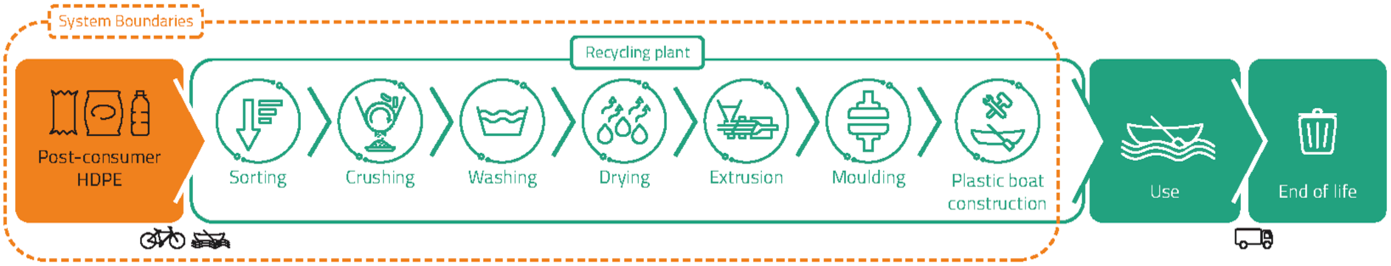
Source: Prepared by i17.



The third case examines the Flipflopi Project in Kenya, which employs mechanical recycling to convert plastic waste collected from households, local businesses, and peri-urban areas into plastic lumber. This recycled material is utilized to construct plastic boats and heritage furniture. The transportation of materials involves tractors with trailers and boats, followed by the processing steps of sorting, crushing, washing, drying, extrusion, and molding to produce the boats (see Figure 7). The project compares the environmental impacts of producing a boat from recycled plastic with that of a fiberglass boat. It is important to note that anti-fouling paint, which can release microplastics, is not used in these plastic boats, mitigating some potential environmental risks. However, depending on the types of plastics used, transforming this plastic waste into boats could still contribute to microplastic contamination in water bodies.[1] Moreover, the decision to compare recycled plastic boats with fiberglass boats, rather than wooden ones, was due to the need for life cycle inventory data for wooden boats, highlighting the localized nature and data limitations associated with wooden boat production.

↓ Figure 7. Flipflop Project's system boundary

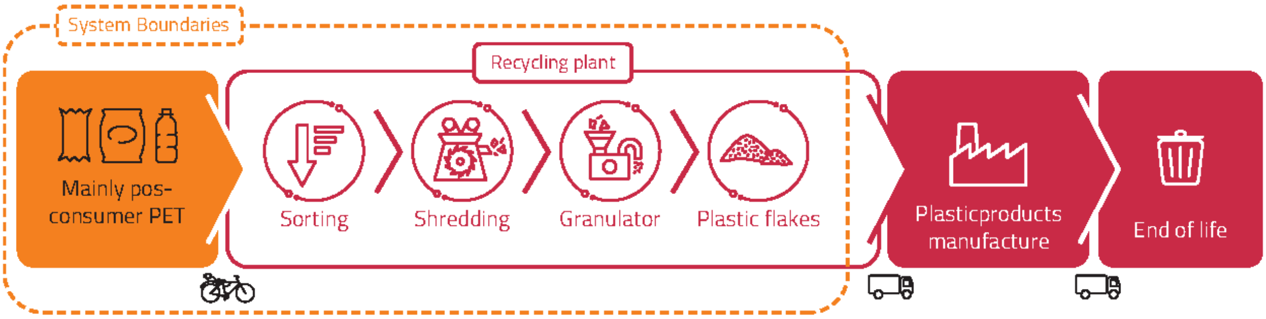
Source: Prepared by i17.



The fourth case examines the GIVO Project in Nigeria. Here, plastic waste collected from local neighborhoods is transported to the recycling facility using electric bicycles. The recycling center is independent of the national electric grid and powered by solar panels. The recycling process focuses on converting this waste into plastic flakes/pellets through mechanical recycling, specifically through crushing and granulating stages (see Figure 8). For the GIVO Project, the scenario considered the avoided production of one metric ton of virgin plastic flakes.

---

[1] This aspect was acknowledged in the results section (Section III.C), where precautions against plastic leakage are discussed.



↑ Figure 8. GIVO Project's system boundary

Source: Prepared by i17.

3.2. Life cycle inventories of the SMEP project cases

For the inventory compilation, primary data from the operational systems of the upcycled products were collected to represent the plastic recycling projects being examined (see Table 2). When primary data were unavailable, the analysis used comparable operational data from similar contexts within the respective countries. As for the background processes and the systems of the products being replaced, secondary data were carefully sourced from the Ecoinvent 3.9.1 (2022) database.

For the Ghana Clean-up Project, which is presently in the design phase for its plastic board production line, actual operational data needed to be more attainable. Consequently, the study adopted empirical data from a similar recycling facility in Hoi An, Vietnam, utilizing the same technology to produce plastic boards. This facility, established by Evergreen Labs, exemplifies innovative, cost-effective solutions for converting low-value plastic waste and currently processes approximately 40 tonnes of plastic waste monthly, significantly mitigating landfill and environmental pollution. This proxy approach facilitated the accurate estimation of resource utilization and emissions for this specific scenario (refer to Table 3 below). A detailed inventory breakdown for this scenario is provided in Table S.1, available in the supplementary materials at the end of this report.

The operational data for the Chinhoyi University Project's recycling facility in Zimbabwe, active since December 2022, included detailed electricity consumption metrics from an eight-hour operational shift. This data included the electricity mix sourced from the national grid, supplemented by diesel generators, which provide 15% of the electricity consumption in the facility, specifically to power the thermomolding process for plastic roof tiles. Water consumption metrics were derived by evaluating the volume and frequency of water usage, corresponding to producing eight tiles (each weighing 3.2 kg), adequately covering 1 m² of roofing area (see Table 3). Additional information is detailed in Table S.2 and the supplementary materials.

The materials recovery facility for the Flipflopi Project in Kenya, which has been operational since 2022, provided specific data regarding the resources required for boat construction. This pertinent information is briefly summarized in Table 3, with extended details in Table S.3 of the supplementary materials.

Lastly, data from the GIVO Project's recycling center in Nigeria, which has been operational since 2021, offered comprehensive insights into the material inputs and outputs within the defined system boundaries. This data, focused on producing one metric ton of plastic flakes as the reference flow for the life cycle assessment, is systematically compiled in Table 3 and further elaborated in Table S.4 of the supplementary materials.

Table 3. Life cycle inventories of SMEP project cases

	Ghana Clean-up Project	Chinhoyi University Project	The Flipflopi Project	The GIVO Project
Transport to the recycling plant	0.521 t*km (truck)	0.032 t*km (tractor with trailer)[a] 0.814 t*km (tractor with trailer)[b]	3.780 t*km (tractor) 1.050 t*km (Boat)	120 person*km (electric bicycle)
Sorting	0.001 t (PET)[c] 0.004 t (PE)[d] 0.004 t (PP)[e]	7.680 kg (HDPE) 1.920 kg (PET)	1,050 kg (HDPE)	1,188 t (PET) 0.010 t (HDPE) 0.002 t (PP)
Shredding (Energy consumption)	0.001 kWh	—	—	—
Crushing (Energy consumption)	—	0.710 kWh	96.574 kWh	275 kWh
Washing	0.005 m^3 (Water) 0.030 kWh (Energy) 0.005 m^3 (Wastewater)[f]	—	0.500 m3 (Water)	—
Drying (Energy consumption)	0.001 kWh	—	—	—
Mixing	—	0.363 kWh (Energy consumption) 17.920 kg (sand) 0.384 kg (kaolin)	—	—
Extrusion (Energy consumption)	—	1.511 kWh	394 kWh	—
Hot pressing/ moulding	0.003 kWh (Energy consumption)	0.604 kWh (Energy consumption) 0.917 L (Waterconsumption)g	200 m^3 (Water consumption)	—
Cutting (Energy consumption)	1.507E-04 kWh	—	—	—
Diesel generator (Energy consumption)	—	1.608 kWh	—	—
Boat construction	—	—	39.400 kWh (Energy consumption) 10 kg (Screws, nails)	—

	Ghana Clean-up Project	Chinhoyi University Project	The Flipflopi Project	The GIVO Project
Granulator (Energy consumption)	—	—	—	75 kWh
Recycled product	8.681 kg of plastic board (1 m2)	8 units of plastic tiles (1 m2 of roof covered)	1 boat unit (1,000 kg)	1 tonne of plastic flakes

↑ Source: Prepared by i17 based on information from the SMEP programme.

Notes:

[a] from Chinhonyi

[b] from surrounding towns

[c] rigid mono-materials, such as PET and plastic chairs, constitute 63% (PET – 10%)

[d] flexible mono-materials, such as carrier bags and sachets (20% - PE)

[e] multi-layer materials, such as cookie and chip wrappers (17% - PP)

[f] generated and recycled

[g] consumption for cooling (replacement water due to evaporation)

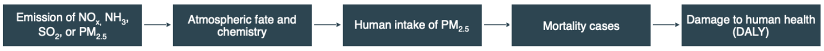
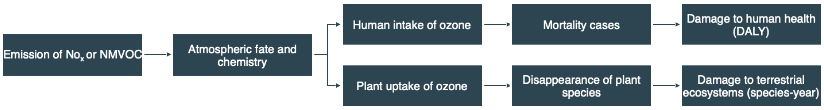
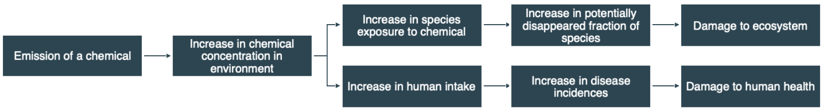
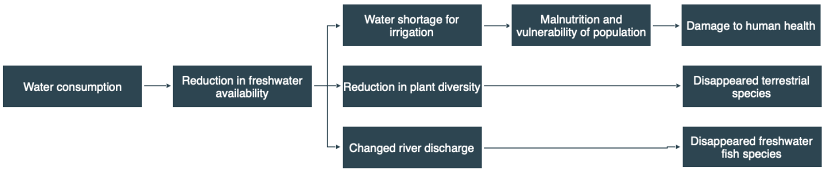
3.3. Impact assessment of the SMEP project cases

The ReCiPe 2016 methodology (Huijbregts et al., 2016) was utilized to systematically evaluate the environmental and health ramifications, encompassing both the positive and negative outcomes of the plastic recycling initiatives in the four case studies. Within this framework, eighteen midpoint LCA impact categories were identified, of which eight were deemed particularly pertinent to human health pathways. These categories include particulate matter formation, tropospheric ozone formation, ionizing radiation, stratospheric ozone depletion, human toxicity (carcinogenic and non-carcinogenic effects), global warming, and water consumption. The analysis concentrated on these specific categories, employing a hierarchical approach that aligns with the prevailing scientific consensus regarding the timing and probability of these impact mechanisms. It is important to note that these categories do not solely refer to health impacts due to workers' exposure, nor are they strictly localized to the activity sites. Instead, they refer to impacts spread across the environment, potentially affecting regional populations. However, some aspects, like particulate matter emissions, have a more intense effect on workers and local populations. Table 4 summarizes the selected health-impact categories. This table facilitates a clearer understanding of why these categories are critical and how they affect human health in the broader context.

Table 4. Impact categories from ReCiPe that affect the area of protection of human health

Impact category	Impact pathways	Characterization factors at midpoint level	Characterization factor at endpoint level
Climate change		Global warming potential (GWP), expressed in kg CO^2 equivalents, in a time horizon of 100 years	DALY
Stratospheric ozone depletion		Ozone Depleting Potential (ODP), expressed in kg CFC-11 equivalents, in a time horizon of 100 years	DALY

↑ Source: Source: Prepared by i17 based on Huijbregts et al. (2016).

Impact category	Impact pathways	Characterization factors at midpoint level	Characterization factor at endpoint level
Ionizing radiation		Ionizing Radiation Potential (IRP), expressed in kgBq Co-60 equivalents, in a time horizon of 100 years	DALY
Fine particulate matter formation		Particulate matter formation potentials (PMFP) expressed in primary PM2.5-equivalents	DALY
Photochemical ozone formation		Human health Ozone formation potentials (HOFP) expressed in NOx equivalents	DALY
Toxicity		Toxicity potential (TP), expressed in kg 1,4-dichlorobenzene equivalents, in a time horizon of 100 years	DALY
Water use		m^3 of water consumed per m^3 of water extracted	DALY

In human health, the ReCiPe approach incorporates the Disability-Adjusted Life Year (DALY) metric, quantifying the years of life lost and those living with disability (Deeney et al., 2023). This methodology applies DALYs consistent with established life cycle assessment (LCA) practices without weighting or age discounting. A specialized characterization model within ReCiPe translates the results from the life cycle inventory into DALYs, establishing them as the standard metric for evaluating impacts within this category. The specific emissions and associated impact categories are meticulously cataloged in Table S.6, provided in the supplementary materials. Moreover, the ReCiPe methodology offers regionalized characterization factors tailored to their specific geographical contexts, which are essential for the precise evaluation of the environmental impacts of emissions. These factors are important for accurately assessing the localized environmental impacts of emissions. Detailed information regarding these regionalized characterization factors is available in Table S.7, included within the supplementary materials.

3.4. Plastic leakage estimates of the SMEP project cases

The plastic emissions due to leakage were quantified using the established methodology of the Plastic Leak Project (Quantis, 2020). This methodological framework is specifically designed to calculate the volume of plastic that inadvertently exits the technosphere and enters the natural environment. It offers a structured approach for the detailed assessment of plastic leakage, enabling a more precise evaluation of its environmental repercussions.

The evaluation process of plastic leakage into natural settings is segmented into three methodical stages, as delineated by the Plastic Leak Project's guidelines (Quantis, 2020). The initial stage entails the computation of the Loss Rate (LR), which measures the fraction of waste mismanaged or lost due to ineffective waste management systems. Subsequently, the Release Rate (RelR) is determined, providing an estimate of the quantity of plastic directly entering an environmental domain. The concluding stage involves the calculation of the Redistribution Rate (RedR), which delineates the trajectory of plastic waste as it migrates from its initial point of environmental entry to subsequent locations. This methodology affords an in-depth insight into the pathways through which plastic waste transitions from anthropogenic domains into the broader natural environment.

In the Ghana Clean-up Project, all recycled plastics are designated as having Low Residual Value (LRV), with the total Mass of Plastic Waste (MPW) quantified at 8.681 kilograms, encompassing PET, PE, and PP. The MPW corresponds to post-consumer plastics collected and directed to the recycling process. This classification, collaboratively developed with the project team, is based on the waste's physical composition: 50% consists of small or detachable fragments (less than 5 cm), and the remaining 50% comprises medium-sized pieces (5-25 cm). This categorization is vital for defining the types of waste targeted for collection and recycling within the initiative.

The MPW represents the mass of plastic waste processed into recycled products for each project, as detailed in Table S.5, showing the reference flow used to assess the impact of the avoided product. The classification into categories such as Low, Medium, and High Residual Value reflects the market's valuation of the recycling potential of different types of plastic waste. Low Residual Value (LRV) is assigned to plastics with low recycling potential in the current market, Medium Residual Value to plastics with some recycling potential but challenges in collection and processing, and High Residual Value to plastics that are readily collectible and recyclable. This differentiation helps to outline the economic feasibility and environmental impact of recycling various types of waste across different projects.

The Chinhoyi University Project considers a total MPW of 9.60 kg[2], with the recycled plastic distributed as 10% small (less than 5 cm), 50% medium (5-25 cm), and 40% large (greater than 25 cm). The valuation estimates indicate that 60% of recycled plastic possesses a medium residual value, while 40% is assessed to have a high residual value. This precise classification is important to evaluate the value of recycled materials and their consequent environmental implications.

In the context of the Flipflopi Project, the MPW is reported to be 1,000 kg and composed of HDPE (high-density polyethylene). Of which, 60.04% are classified as medium-sized (5-25 cm) and 39.96% as large-sized (greater than 25 cm). All recycled plastics within this project are deemed to have low residual value, primarily due to the limited market demand and competitive recycling options available in the area (Lamu archipelago). The specific economic conditions and the availability of other recyclers influence the valuation of these materials as having low residual value.

The environmental attributes also play a critical role. HDPE, while recyclable, often competes with other materials that may be cheaper to procure or recycle, further justifying the low residual value assigned to the plastics used in this project.

Lastly, the GIVO Project processes a total MPW of 1,200 kg, consisting of PET, HDPE, and PP. This represents the daily input for the recycling operations, including 0.82% classified as small (less than 5 cm) and a predominant 99.18% as medium (5-25 cm). In terms of residual value, a mere 0.15% is estimated to hold a medium residual value, while a substantial 99.85% is categorized as having a high residual value. This significant proportion of high residual value highlights the recycled materials' strong economic and environmental potential within the project's scope.

The supplementary documents provide detailed explanations and the equations used for calculating the Loss Rate (LR), Release Rate (RelR), and Redistribution Rate (RedR), crucial metrics in assessing plastic leakage for each project. These terms are defined as follows:

- Loss Rate (LR): This metric measures the fraction of mismanaged or lost waste due to ineffective waste management systems. It quantifies the initial amount of waste that needs to be securely managed.

- Release Rate (RelR): This rate estimates the quantity of plastic directly entering an environmental domain, representing the immediate environmental impact of plastic leakage.

- Redistribution Rate (RedR): This rate delineates the trajectory of plastic waste as it moves from its initial point of environmental entry to other locations, showing how plastic spreads within the natural environment.

These stages are part of a comprehensive evaluation process of plastic leakage into natural settings, as outlined by the Plastic Leak Project's guidelines (Quantis, 2020). This process provides in-depth insights into how plastic waste transitions from human-made domains into the broader natural environment.

For the GIVO Project, a targeted sensitivity analysis was executed to evaluate the environmental repercussions of transitioning the recycling facility's electricity supply from renewable to conventional fossil-based sources. This scrutiny entailed a comparative evaluation of the environmental impacts associated with the current utilization of photovoltaic energy and the hypothetical adoption of local grid-based electricity in Nigeria, based on data from the Ecoinvent 3.9.1 (2022) database.

---

[2] The MPW of 9.60 kg does not represent the weight of a single product unit but the total input weight of plastic waste used in the recycling process to produce a specific output. This is differentiated from the previously mentioned metric of roofing tiles, where the water consumption was evaluated based on the production of eight tiles, each weighing 3.2 kg, collectively covering 1 m² of roofing area. The distinction lies in the MPW being the input for the entire recycling process, not the weight of individual finished products, as detailed in Table S.5.

Furthermore, the primary data's integrity and robustness were thoroughly examined using the Pedigree matrix approach formulated by Weidema and Wesnæs (1996). This evaluation framework systematically assesses data quality across five dimensions: reliability, completeness, temporal alignment, geographical relevance, and technological representativeness. It facilitates the estimation of uncertainties associated with material and energy flow data. The outcomes of this detailed evaluation, summarizing the data quality uncertainties, are systematically presented in Tables S.1, S.2, S.3, and S.4 within the supplementary materials.

4.

Results and Discussion

This report has investigated the role of recycling systems in selected case studies, considering their impacts in reducing plastic leakage, diminishing environmental pollution, and mitigating health impacts.

The LCA analysis using the DALY metric allows a better understanding of health implications arising from recycling initiatives, considering the efficacy of the product recycling system and the performance of local waste management practices in mitigating plastic leakage.

4.1. Health implications of recycling initiatives

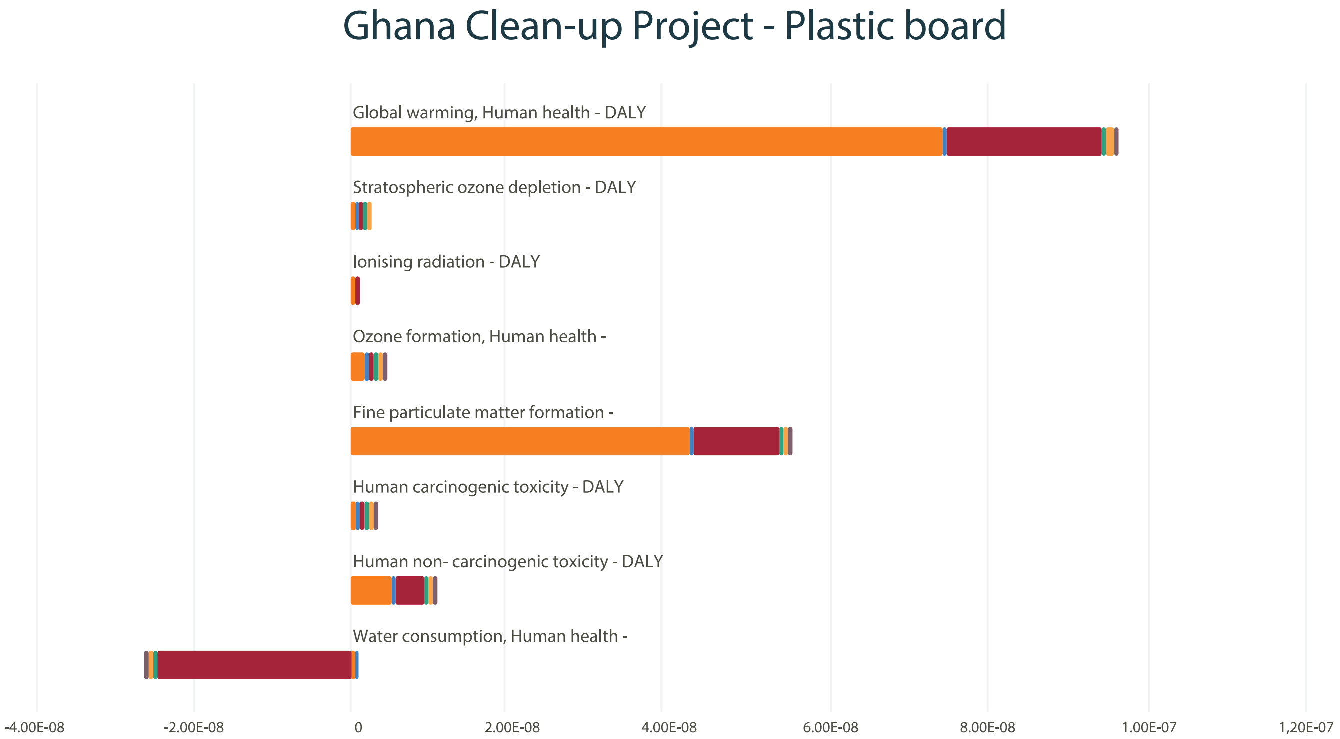
The environmental performance evaluation of each recycling project's production processes enabled identifying key categories contributing to health damage. Variations in the systems led to differences in the stages most associated with damage. Nonetheless, global warming potential and particulate matter formation were consistently identified as the predominant impact categories across all evaluated scenarios. Qin et al. (2022) have highlighted that mechanical recycling processes, marked by substantial energy requirements and particulate matter emissions, contribute significantly to environmental pollution. This aspect is particularly relevant to the observed health impacts across all projects, given each facility's universal application of mechanical recycling techniques.

In the Ghana Clean-up Project, waste transportation and washing stages were identified as significant contributors to the formation of fine particulate matter, accounting for 78.5% and 20.5% of the health impact, respectively. Emissions from the transportation stage were due to diesel combustion, whereas the adverse effects of the washing stage were largely attributed to electricity consumption. Despite a shift towards renewable energy in Ghana, a substantial portion, approximately 59%, of the nation's energy production is still dependent on fossil fuels, with oil and natural gas being the major contributors (Ghana Energy Commission, 2022). These stages of the project, especially those reliant on fossil fuel energy sources, impose considerable environmental burdens that significantly affect the overall DALYs associated with the project. As detailed in Table 4, global warming influences health through various pathways, such as increased heat-related illnesses, more frequent extreme weather conditions, and shifts in the distribution of disease vectors due to changing climates (De Schryver et al., 2009).

Conversely, in the Ghana Clean-up Project, water consumption unexpectedly positively affected the project's DALY. The washing stage, notably through the effective treatment of effluents, helped mitigate 18.20% of the total health impact. This finding is particularly relevant in sub-Saharan Africa, where challenges in wastewater management are prevalent. Uncontrolled effluent discharge often turns water bodies into breeding grounds for infectious agents, increasing the incidence of waterborne diseases (Onu et al., 2023). This highlights the critical role of efficient waste management practices at treatment facilities, especially regarding the quality of discharged effluents. Implementing such measures significantly influences DALY calculations, highlighting the importance of good wastewater management strategies that yield environmental and health gains. Figure 9 shows the distribution of process contributions across Intermediate impact categories impacting human health using DALY metrics. It may be noted that the sorting process has zero impact on DALY. This modeling decision is based on the scope of the LCA methodology used, which does not account for the impacts due to the direct exposure of workers during the sorting stage.

In the Chinhoyi University project analysis, global warming and fine particulate matter formation were the predominant contributors to human health impacts, accounting for 93.64% of the total DALY.

Ghana Clean-up Project - Plastic board	Global warming, Human health DALY	Stratospheric ozone depletion DALY	Ionising radiation DALY	Ozone formation, Human health DALY	Fine particulate matter formation DALY	Human carcinogenic toxicity	Human non-carcinogenic toxicity	Water consumption, Human health DALY
🟧 Transport to the recycling plant	7.44E-08	1.06E-11	1.64E-13	1.34E-09	4.24E-08	7.47E-10	4.97E-09	1.06E-10
■ Recycling plant - Sorting	0	0	0	0	0	0	0	0
🟦 Recycling plant - Shredding	2.66E-10	6.57E-14	1.62E-16	9.87E-13	7.69E-11	7.07E-13	1.39E-12	-7.64E-12
🟥 Recycling plant - Washing	1.95E-08	9.89E-12	3.21E-13	6.46E-11	1.11E-08	3.30E-10	3.61E-09	-2.48E-08
🟩 Recycling plant - Drying	2.23E-10	5.53E-14	1.36E-16	8.30E-13	6.47E-11	5.95E-13	1.17E-12	-6.42E-12
🟧 Recycling plant - Hot pressing	1.30E-09	3.23E-13	7.94E-16	4.84E-12	3.78E-10	3.47E-12	6.83E-12	-3.75E-11
🟪 Recycling plant - Cutting	6.64E-11	1.64E-14	4.04E-17	2.47E-13	1.92E-11	1.77E-13	3.48E-13	-1.91E-12



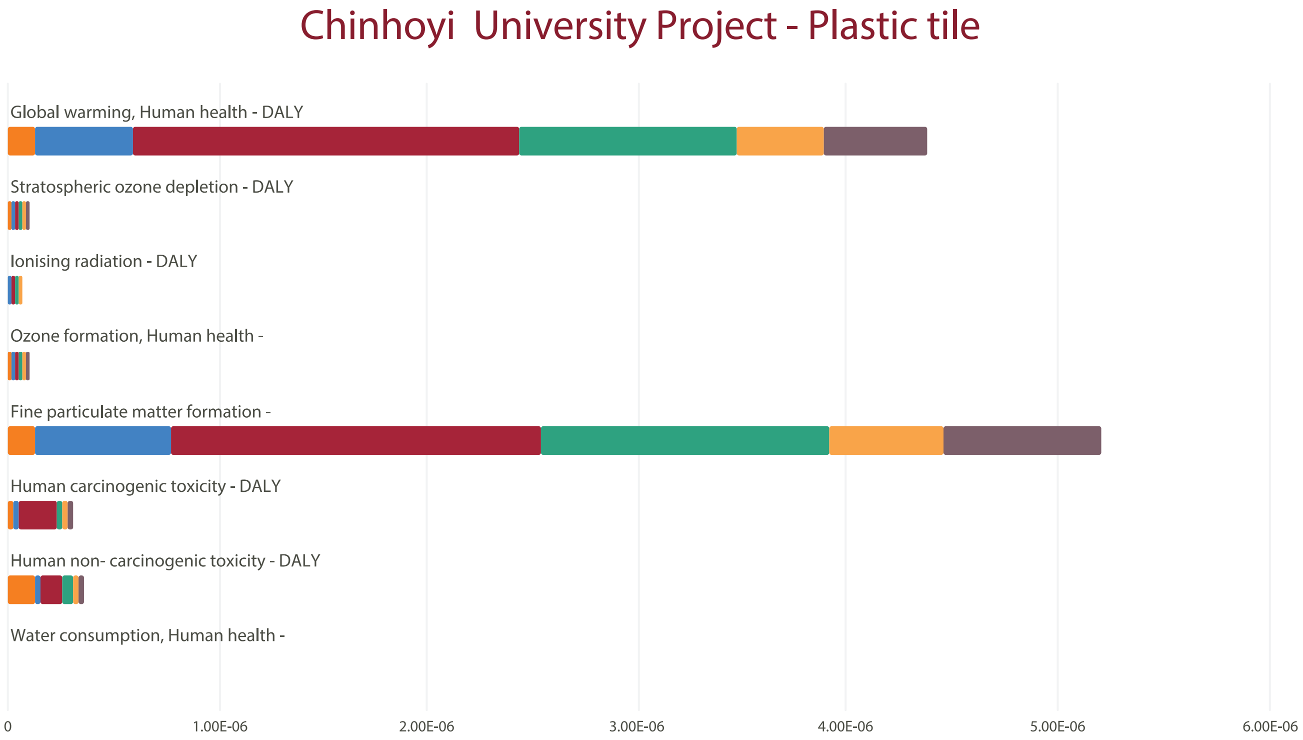
↑ Figure 9. Distribution of process contributions affecting human health (Ghana Clean-up Project)

Source: Prepared by i17.

Global warming affects health through various pathways, including an increase in heat-related illnesses, a rise in the frequency of extreme weather conditions, and changes in the distribution of disease vectors due to altered climatic conditions. The impact pathway is detailed in Table 4. For instance, increased temperatures can lead to higher incidences of diseases like malaria and heatstroke, affecting the overall health burden on populations. Similarly, fine particulate matter, predominantly arising from industrial processes, including the recycling activities at the project site, contributes significantly to respiratory and cardiovascular conditions. When inhaled, these particles can penetrate deep into lung passageways and enter the bloodstream, causing various health complications, particularly in densely populated areas or communities close to recycling facilities (De Schryver et al., 2009).

Within these impact categories, the energy-intensive processes of mixing and extrusion were pinpointed as the primary sources of environmental and health detriments. Specifically, the mixing process was attributed to 41.8% of the potential impacts of global warming, while extrusion was responsible for 23.3%. Regarding fine particulate matter formation, the mixing and extrusion stages contributed 34.0% and 26.0%, respectively. The reliance of Zimbabwe's energy sector on hydro and coal power, which meets only 40% of the country's energy needs, intensifies these effects (see Figure 10). The resulting energy deficit requires electricity imports from neighboring African countries, highlighting the nation's energy infrastructure's significant environmental and health ramifications of its recycling capabilities. It is crucial to understand that the health effects of the project’s activities are not confined to its surroundings. Instead, they extend to affect the regional populations, influenced by factors such as air and water quality that transcend local boundaries and are distributed across different scales and populations.

Chinhoyi University Project - Plastic tile	Global warming, Human health DALY	Stratospheric ozone depletion DALY	Ionising radiation DALY	Ozone formation, Human health DALY	Fine particulate matter formation DALY	Human carcinogenic toxicity	Human non-carcinogenic toxicity	Water consumption, Human health DALY
🟧 Transport to the recycling plant	1.36E-07	2.96E-11	1.99E-13	1.48E-09	1.44E-07	1.66E-10	1.54E-07	4.21E-11
⬛ Recycling plant - Sorting	0	0	0	0	0	0	0	0
🟦 Recycling plant - Crushing	4.82E-07	1.14E-10	5.26E-12	1.75E-09	6.39E-07	8.59E-09	2.54E-08	7.13E-10
🟥 Recycling plant - Mixing	1.84E-06	3.08E-10	1.87E-11	6.12E-09	1.78E-06	1.87E-07	1.01E-07	4.54E-08
🟩 Recycling plant - Extrusion	1.03E-06	2.42E-10	1.12E-11	3.73E-09	1.36E-06	1.83E-08	5.39E-08	1.52E-09
🟧 Recycling plant - Pressing	4.10E-07	9.66E-11	4.48E-12	1.49E-09	5.44E-07	7.31E-09	2.16E-08	6.10E-10
🟪 Recycling plant - Diesel generator	5.06E-07	2.17E-10	7.46E-13	8.09E-09	7.60E-07	5.64E-10	3.92E-09	1.62E-10



↑ Figure 10. Distribution of process contributions affecting human health (Chinhoyi University Project)

Source: Prepared by i17.

Lee and Yuan (2024) highlight the adverse effects of energy shortages on public health, noting that electricity deficits often result in adopting alternative energy sources, such as kerosene for lighting, which release harmful toxic compounds. This situation underscores recycling facilities' need to enhance energy efficiency and curtail energy consumption. The prevailing context of electricity scarcity implies that various sectors, including the recycling industry, must be improved to operate at full capacity. Consequently, these sectors might resort to alternative, less sustainable energy sources to maintain essential operations, potentially heightening health risks for surrounding populations. Thus, improving energy efficiency and adopting renewable and low-particulate emission sources within recycling operations is environmentally beneficial and crucial for safeguarding public health.

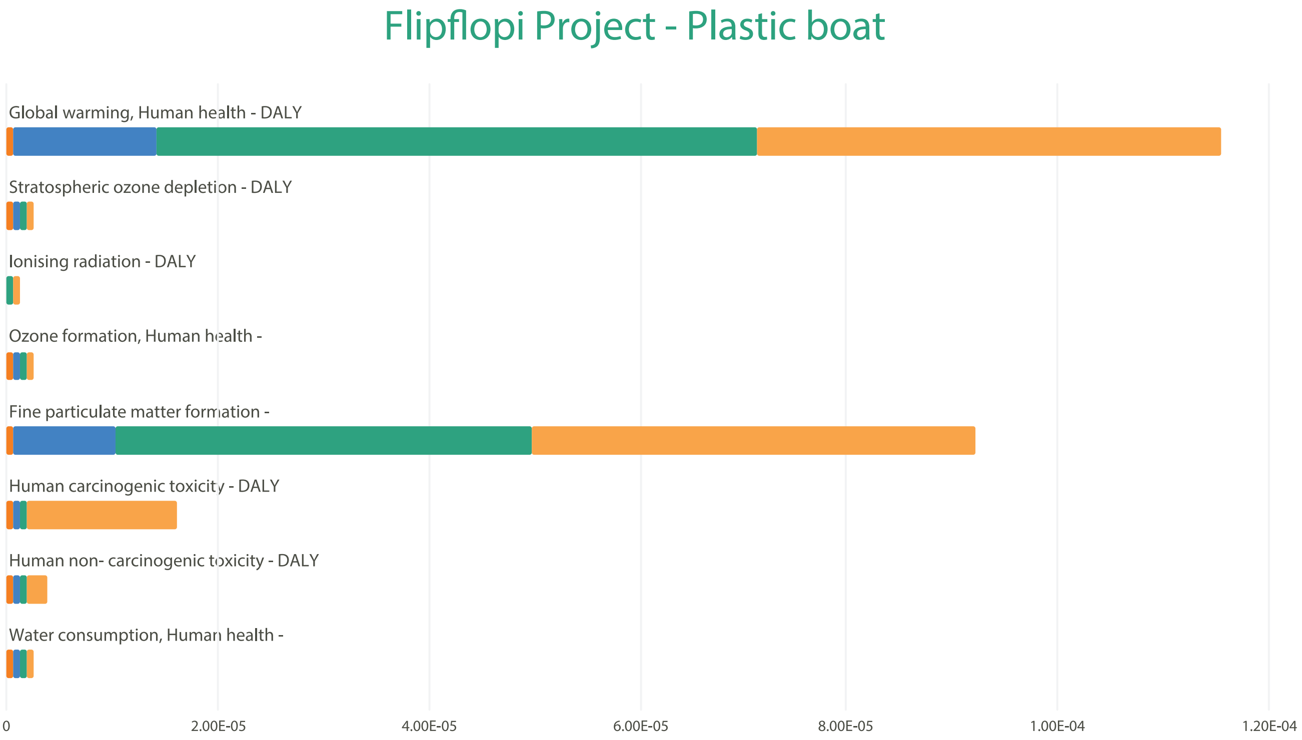
In the assessment of the Flipflopi Project, the predominant health impact categories identified were global warming, fine particulate matter formation, and carcinogenic toxicity, collectively accounting for 98.24% of the DALYs. The boat-building phase was pinpointed as the primary source of health impacts across these categories, mainly due to the extensive electricity required and the utilization of metal screws and nails in the manufacturing process. Specifically, the energy-intensive plastic extrusion process contributed significantly to the global warming category (49.5%) and to fine particulate matter formation (42.7%). In terms of Human Carcinogenic Toxicity, the boat construction phase, mainly through the use of materials such as metal screws and nails, was linked to 97.0% of the health impacts observed. The primary concern here stems from the emission of heavy metals during the steel rolling process, an essential manufacturing step for boat components. This activity's resultant waste and sludge are potential sources of environmental heavy metal contamination, representing a critical risk to human health (see Figure 11).

Kumar et al. (2023) have highlighted the considerable environmental hazard of metallurgical waste, including its role as a significant source of heavy metal pollution. Once introduced into the ecosystem, these heavy metals can be absorbed through inhalation of dust or fumes, ingestion via contaminated water or food, or direct contact with contaminated soil or surfaces. This risk of exposure transcends occupational environments, affecting entire communities, especially where waste and emissions management practices are deficient or non-existent.

↓ Figure 11. Distribution of process contributions affecting human health (Flipflop Project)

Source: Prepared by i17.

Flipflopi Project - Plastic boat	Global warming, Human health DALY	Stratospheric ozone depletion DALY	Ionising radiation DALY	Ozone formation, Human health DALY	Fine particulate matter formation DALY	Human carcinogenic toxicity	Human non-carcinogenic toxicity	Water consumption, Human health DALY
🟧 Transport to the material recovery facility	6.18E-07	1.34E-10	9.02E-13	6.77E-09	6.61E-07	8.46E-10	6.88E-07	1.91E-10
⬛ Material recovery facility - Sorting	0	0	0	0	0	0	0	0
🟦 Material recovery facility - Crushing	1.40E-05	7.01E-09	1.66E-11	4.33E-08	9.67E-06	8.77E-08	1.71E-07	4.13E-08
🟥 Material recovery facility - Washing	0	0	0	0	0	0	0	0
🟩 Material recovery facility - Extrusion/moulding	5.72E-05	2.86E-08	6.79E-11	1.77E-07	3.95E-05	3.58E-07	6.98E-07	1.68E-07
🟧 Material recovery facility - Boat construction	4.38E-05	7.20E-09	1.29E-09	9.52E-08	4.25E-05	1.47E-05	1.60E-06	2.57E-07



In the evaluation of the GIVO Project, the recycling process analysis indicated that global warming and fine particulate matter formation were the predominant factors contributing to 99.44% of the total DALYs. The sorting phase was the major contributor to these impacts, accounting for approximately 96.6 ^{2} 4.52% of the health-related consequences (see Figure 12). Mohammed et al. (2023) have emphasized that the sorting stage poses considerable challenges in recycling efforts, often associated with emissions due to the mishandling of residual plastic waste and the use of diesel-powered machinery in substandard landfills, further exacerbating health impacts as detailed by Sun et al. (2023).

A distinctive feature of the GIVO Project is its reliance on photovoltaic electricity from solar energy and the use of electric bicycles to transport waste to the facility. These sustainable practices significantly enhance the project's environmental performance and reduce the health impacts typically associated with traditional fossil fuel-based transportation methods. In contrast to other scenarios where the transportation phase significantly contributed to health detriments due to reliance on fossil fuels, the GIVO Project demonstrates a marked reduction in these adverse effects.

Furthermore, the project underscores the significant influence of energy-sourcing decisions. Utilizing grid electricity in Nigeria, predominantly from fossil fuels, would increase health-related damages. Specifically, the DALY could rise by 6.9 times, indicating a significant increase in health impacts due to the heavy reliance on natural gas for power generation in Nigeria, as reported by Chanchangi et al. (2023). This scenario highlights the vital role of sustainable energy solutions in recycling operations. Adopting photovoltaic energy systems aligns with environmental sustainability goals and is crucial in mitigating the health impacts of fossil fuel-based energy sources.

↓ **Figure 12.** Distribution of process contributions affecting human health (GIVO Project)

Source: Prepared by i17.

GIVO Project - Plastic Flakes	Global warming, Human health DALY	Stratospheric ozone depletion DALY	Ionising radiation DALY	Ozone formation, Human health DALY	Fine particulate matter formation DALY	Human carcinogenic toxicity	Human non-carcinogenic toxicity	Water consumption, Human health DALY
🟧 Transport to the recycling centre	7.64E-08	2.05E-11	4.17E-12	1.46E-10	1.05E-07	9.03E-09	5.79E-09	2.08E-10
⬛ Recycling centre - Sorting	3.33E-05	1.83E-10	1.45E-12	9.86E-09	1.52E-06	2.37E-08	1.51E-07	3.50E-10
🟦 Recycling centre - Shredding	1.08E-09	9.17E-13	8.99E-14	2.44E-12	1.35E-09	4.67E-11	6.65E-10	-2.46E-09
🟥 Recycling centre - Granulator	2.95E-10	2.50E-13	2.45E-14	6.65E-13	3.67E-10	1.27E-11	1.81E-10	-6.72E-10

The analysis revealed that emissions, especially greenhouse gases and particulate matter, were the primary contributors to health impacts across all evaluated recycling projects. This outcome accentuates the need for comprehensive management strategies within these initiatives, focusing on emission reduction techniques and adopting sustainable practices. The findings stress integrating environmental and health considerations into recycling projects' planning and development phases. Consequently, there is a call to action for future measures towards more accountable and efficient project management, ensuring that environmental safeguarding and public health welfare are prioritized in operational agendas.

4.2. Impact on the Product Recycling System

Analyzing the recycled products system highlights the significant role of recycling in reducing environmental and health impacts. This reduction is primarily achieved by decreasing the manufacturing of new products and lowering reliance on virgin raw materials, often linked to substantial fossil fuel consumption. This approach resulted in a net negative health impact in all examined scenarios, as elaborated in Table 5, remembering that one DALY represents the loss of the equivalent of one year of full health. This outcome is particularly significant considering increasing global plastic production and consumption forecasts. According to Tenhunen-Lunkka et al. (2023), plastic production is expected to generate around 1.34 Gt of CO2eq emissions by 2030, potentially rising to 2.80 Gt by 2050. These figures highlight the urgent need to adopt circular economy practices to secure future sustainability. This reinforces the critical role of recycling in mitigating environmental and health impacts.

Table 5. Impact on human health in DALYs

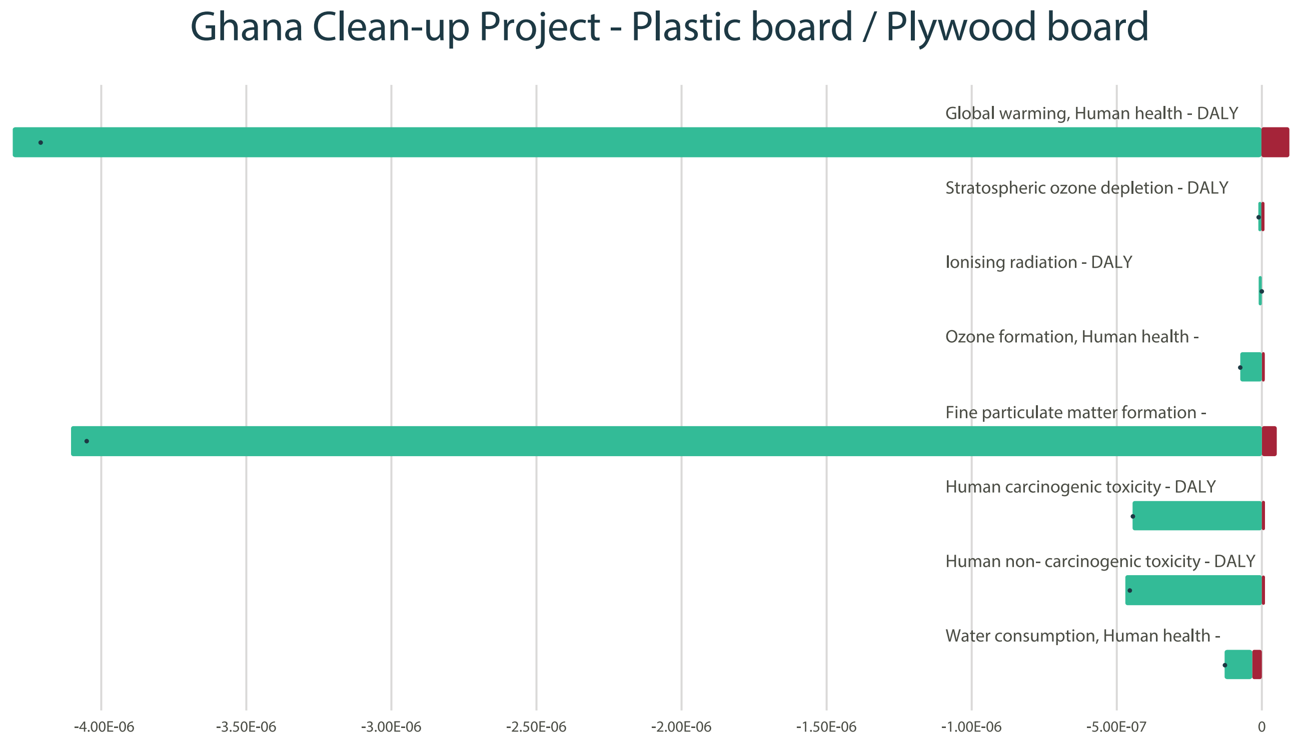
Ghana Clean-up Project		Chinhonyi University Project		The Flipflopi Project		The GIVO Project	
Plastic board	1.36E-07 DALY	**Plastic tile**	1.03E-05 DALY	**Plastic boat**	2.27E-04 DALY	**Recycled plastic flakes**	3.52E-05 DALY
Avoided impact (plywood board)	-9.47E-06 DALY	**Avoided impact (cement or clay tiles)**	-1.16E-05 DALY Cement tile -1.53E-05 DALY Clay tile	**Avoided impact (fiberglass boat)**	-2.59E-02 DALY	**Avoided impact (virgin plastic flakes)**	-4.81E-03 DALY
Net impact	-9.34E-06 DALY	**Net impact**	-1.31E-06 DALY Cement tile -4.98E-06 DALY Clay tile	**Net impact**	-2.57E-02 DALY	**Net impact**	-4.78E-03 DALY

↓ Source: Prepared by i17 based on information from the SMEP programme.

The Ghana Clean-up Project exemplifies the environmental advantages of substituting traditional manufacturing processes with recycling practices. By transforming plastic waste into plastic boards, the initiative eliminates the need for urea-based resins, such as urea formaldehyde, commonly used in plywood production. This substitution significantly reduces the electricity demand typically associated with manufacturing plywood boards, thereby positively influencing the global warming impact category, as depicted in Figure 13. Additionally, there is a decrease in fine particulate matter formation, a pollutant primarily emitted during standard plywood production processes. By redirecting plastic waste from landfills to recycling sites, the project achieves an 98.6% reduction in environmental impacts compared to conventional plywood production, underscoring the substantial benefits of recycling in terms of emission reduction and resource conservation.

As a result, using recycled plastics in board production instead of plywood reduces environmental harm and enhances the end product's mechanical and physical properties. Research by Ashori et al. (2023) indicates that boards manufactured from recycled plastics exhibit superior qualities to traditional resin-bonded plywood, including reduced water absorption and swelling, increased

Ghana Clean-up Project - Plastic board	Global warming. Human health DALY	Stratospheric ozone depletion DALY	Ionising radiation DALY	Ozone formation. Human health DALY	Fine particulate matter formation DALY	Human carcinogenic toxicity	Human non-carcinogenic toxicity	Water consumption. Human health DALY
🟥 Plastic board (1 m² = 0.01 m³)	9.58E-08	2,10E-11	4,86E-13	1,41E-09	5,41E-08	1,08E-09	8,58E-09	-2,48E-08
🟩 Avoided impact (plywood board - 0.01 m³)	-4.30E-06	-2.31E-09	-1.70E-11	-7.55E-08	-4.10E-06	-4.43E-07	-4.57E-07	-1.03E-07
● Net impact	-4,20E-06	-2,29E-09	-1,65E-11	-7,41E-08	-4,04E-06	-4,42E-07	-4,49E-07	-1,27E-07



↑ **Figure 13.** Comparative Analysis of Human Health Impact Categories in DALYs: Recycled Products vs Avoided Conventional Product Production (Ghana Clean-up Project)

Source: Prepared by i17.

bending resistance, and improved tensile and shear strength. Additionally, these recycled boards show greater resistance to screw withdrawal. These improvements are crucial for the progress of recycling initiatives, demonstrating that recycled materials can surpass traditional materials in both environmental and functional performance. This progress supports the shift away from conventional, unsustainable materials and encourages the broader adoption of recycling practices, aligning with global sustainability goals.

The Chinhoyi University Project assessed the environmental benefits of manufacturing plastic roof tiles from recycled materials against traditional clay and cement tiles production. The analysis revealed that recycling reduced environmental impacts: 11.3% less than cement tiles and 32.6% less than clay tiles. Significant environmental concerns for clay tiles include global warming and fine particulate matter formation, as illustrated in Figure 14. These impacts largely stem from the direct emissions associated with the clay tile manufacturing process. The project successfully avoids these detrimental emissions by utilizing recycled plastic waste for tile production, showcasing the environmental advantages of substituting conventional materials like clay with recycled alternatives. This approach not only reduces harmful emissions but also emphasizes the role of recycling in fostering sustainable construction methodologies.

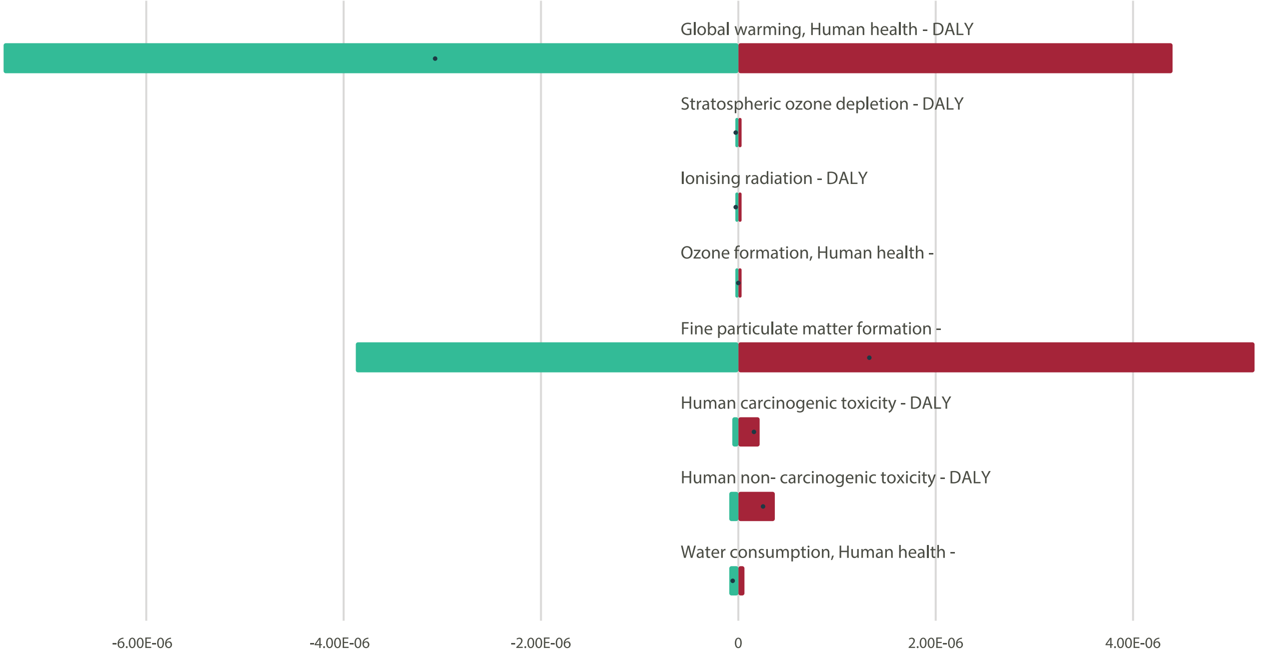
In cement tile production, the environmental benefits are mainly due to avoiding clinker production, a significant source of health and environmental impacts in this sector. The clinkerization process, responsible for a substantial portion of emissions in cement manufacturing, typically requires the combustion of fossil fuels to reach the necessary high temperatures, contributing to 85-90% of the total emissions (Kusuma et al., 2022). This stage is notably problematic due to its substantial greenhouse gas emissions and other atmospheric pollutants (Antunes et al., 2022). The shift towards sustainable alternatives, such as the recycled plastic roof tiles produced in the Chinhoyi University Project, is crucial for reducing the environmental footprint associated with traditional roofing materials.

↓ **Figure 14.** Comparative Analysis of Human Health Impact Categories in DALYs: Recycled Products vs Avoided Conventional Product Production (Chinhoyi University Project)

Source: Prepared by i17.

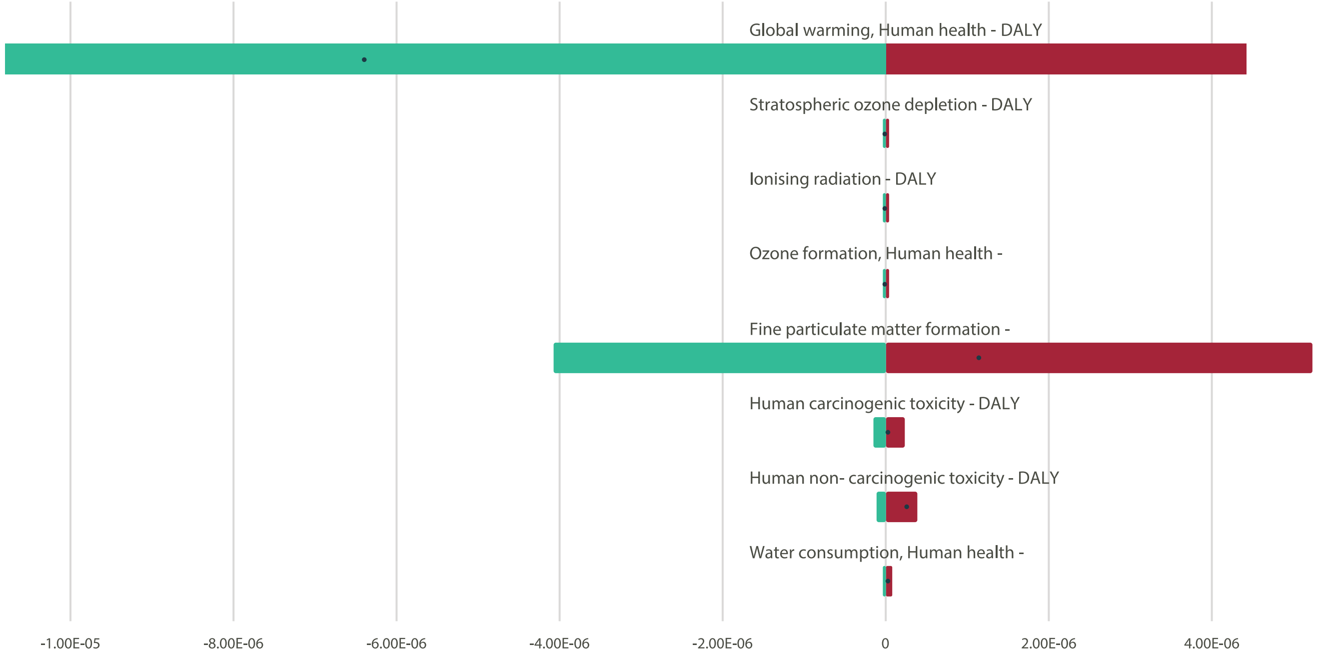
Chinhoyi University Project - Plastic tile / Cement tile	Global warming. Human health DALY	Stratospheric ozone depletion DALY	Ionising radiation DALY	Ozone formation. Human health DALY	Fine particulate matter formation DALY	Human carcinogenic toxicity	Human non-carcinogenic toxicity	Water consumption. Human health DALY
🟥 Plastic tile (8 units or 1 m² of roof covered)	4,40E-06	1,01E-09	4,06E-11	2,27E-08	5,23E-06	2,22E-07	3,59E-07	-4,85E-08
🟩 Avoided impact (cement tile - 7 units or 1 m² of roof covered)	-7,44E-06	-3,27E-10	-4,93E-11	-1,72E-08	-3,88E-06	-5,61E-08	-1,02E-07	-8,84E-08
● Net impact	-3,05E-06	6,79E-10	-8,66E-12	5,51E-09	1,35E-06	1,66E-07	2,58E-07	-3,99E-08

Chinhoyi University Project - Plastic tile / Cement tile



Chinhoyi University Project - Plastic tile / Clay tile	Global warming. Human health DALY	Stratospheric ozone depletion DALY	Ionising radiation DALY	Ozone formation. Human health DALY	Fine particulate matter formation DALY	Human carcinogenic toxicity	Human non-carcinogenic toxicity	Water consumption. Human health DALY
🟥 Plastic tile (8 units or 1 m² of roof covered)	4.40E-06	1.01E-09	4.06E-11	2.27E-08	5.23E-06	2.22E-07	3.59E-07	-4.85E-08
🟩 Avoided impact (clay tile - 7 units or 1 m² of roof covered)	-1.08E-05	-5.81E-10	-2.83E-11	-2.35E-08	-4.11E-06	-1.87E-07	-1.15E-07	-9.00E-09
● Net impact	-6.41E-06	4.25E-10	1.24E-11	-8.15E-10	1.12E-06	3.48E-08	2.44E-07	3.95E-08

Chinhoyi University Project - Plastic tile / Clay tile



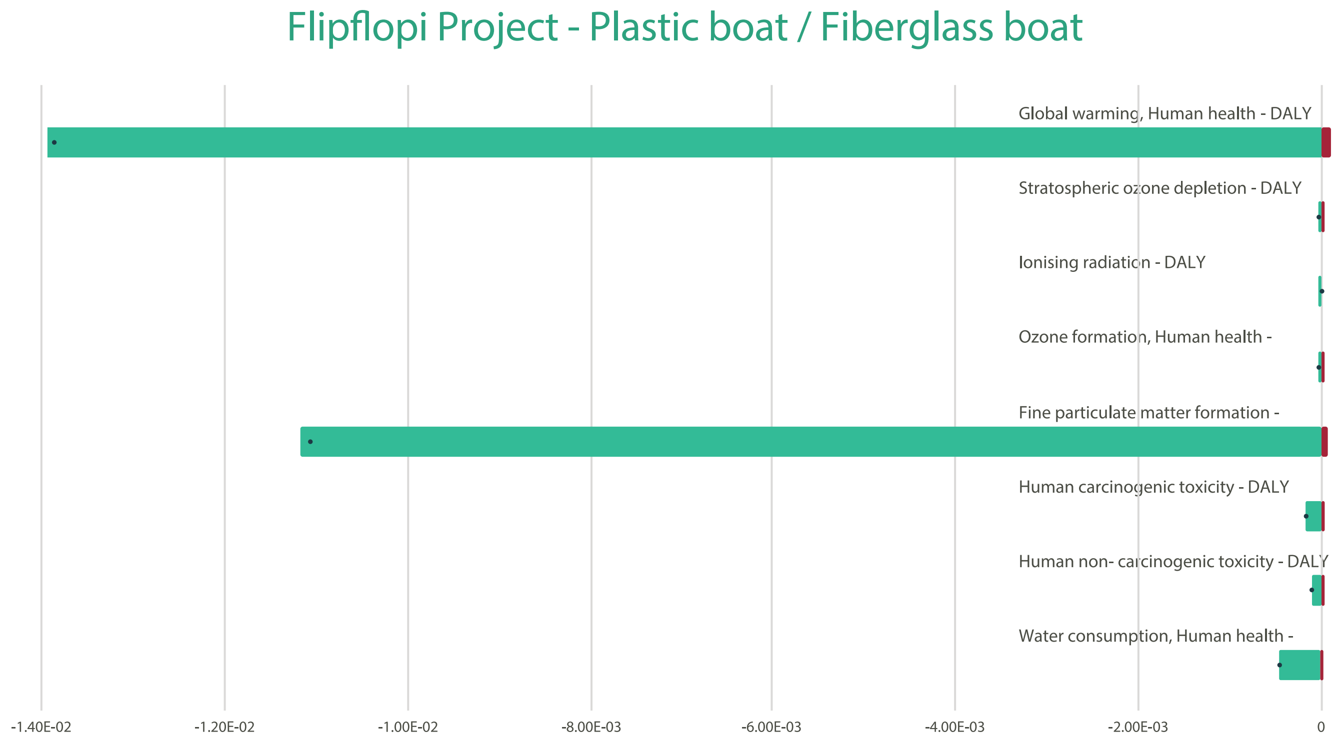
The analysis showed that replacing clay tiles with recycled plastic roof tiles offers more health benefits than replacing cement tiles. In a comparative LCA conducted by Souza et al. (2015), ceramic (i.e., clay) and concrete roof tiles were analyzed within the Brazilian context. Generally, the cement in concrete tiles was found to have a higher environmental impact. However, focusing specifically on human health, the findings suggested that ceramic tiles might pose a greater health risk than concrete ones. It is crucial to note that while overall environmental impacts may favor one material, particular concerns, such as human health, may yield different conclusions.

The Flipflopi Project showcases considerable environmental advantages in boat manufacturing through its innovative recycling approach. By repurposing plastic waste into boats, the initiative realizes a remarkable 99.1% decrease in environmental harm compared to the conventional production of fiberglass boats. This significant reduction is mainly due to eliminating glass-filled nylon production, an essential environmental detriment in traditional boat manufacturing. However, it should be clarified that standard fiberglass boats are predominantly constructed using polyester rather than nylon. This distinction represents a methodological limitation within our analysis, stemming from the absence of a specific inventory for the precise material composition typically used in fiberglass boats. Despite this, the positive environmental impact of the recycling process remains significant, especially in diminishing global warming potential and particulate matter emissions, as illustrated in Figure 15.

↓ Figure 15. Comparative Analysis of Human Health Impact Categories in DALYs: Recycled Products vs Avoided Conventional Product Production (Flipflop Project)

Source: Prepared by i17.

Flipflopi Project - Plastic boat	Global warming. Human health DALY	Stratospheric ozone depletion DALY	Ionising radiation DALY	Ozone formation. Human health DALY	Fine particulate matter formation DALY	Human carcinogenic toxicity	Human non-carcinogenic toxicity	Water consumption. Human health DALY
🟥 Plastic boat (1 unit)	1.16E-04	4.29E-08	1.38E-09	3.22E-07	9.23E-05	1.51E-05	3.16E-06	4.67E-07
🟩 Avoided impact (fiberglass boat - 1 unit)	-1.40E-02	-7.89E-06	-3.76E-07	-2.74E-05	-1.12E-02	-1.89E-04	-1.24E-04	-4.43E-04
● Net impact	-1.39E-02	-7.85E-06	-3.74E-07	-2.71E-05	-1.11E-02	-1.74E-04	-1.21E-04	-4.42E-04



Moreover, the Flipflopi Project contributes additional environmental benefits by circumventing the adverse effects of end-of-life disposal of fiberglass boats. Conventionally, these boats are relegated to landfills due to the prohibitive costs and logistical challenges of recycling fiberglass materials. Senavirathna et al. (2022) emphasize that landfill disposal of fiberglass boats releases numerous harmful particles into the environment. Over time, as these materials break down, they can release particles that infiltrate and persist within the food chain, adversely affecting aquatic life. Research by Ciocan et al. (2020) has demonstrated the detrimental impact of dust from glass-reinforced plastic fragments, a common byproduct of ship waste, on marine organisms such as mussels and water fleas. These observations highlight the extensive ecological benefits of recycling initiatives like the Flipflopi Project, which extend beyond conventional waste reduction to include the prevention of environmental and health hazards associated with traditional disposal practices of materials like fiberglass.

In the GIVO Project, substituting virgin plastic flake production with a recycling process has demonstrated a significant net positive effect on human health, resulting in a 99.3% reduction in adverse impacts. This aligns with trends seen in other case studies, where the production of virgin plastic flakes predominantly contributes to health issues through global warming and particulate matter formation. Key factors exacerbating these health impacts include the production processes for xylene, which is essential for synthesizing terephthalic acid, and ethylene, along with heat generation, particularly impacting fine particulate matter formation. These stages are significant sources of emissions, contributing notably to the overall health risks of producing virgin plastic flakes. The GIVO Project circumvents these harmful emissions by recycling plastic waste, showcasing the substantial environmental and health advantages of utilizing recycled materials over virgin counterparts (see Figure 16).

Ganesan et al. (2023) underscore the benefits of using recycled materials, noting that products like the plastic flakes produced in the GIVO Project can significantly lower the carbon footprint and enhance public health outcomes. They point out that recycling processes generally demand less energy and fewer additives compared to conventional manufacturing, which is known to account for up to 4% of global fossil fuel consumption, leading to significant emissions. In contrast, adopting recycling results in inherently more sustainable products, characterized by significantly reduced emissions, as highlighted by Nanda and Berruti (2021). This transition towards recycling not only fosters environmental sustainability but also plays a vital role in diminishing the health hazards associated with the consumption and emissions of fossil fuels, thereby reinforcing the value of integrating recycled materials into product manufacturing.

↓ Figure 16. Comparative Analysis of Human Health Impact Categories in DALYs: Recycled Products vs Avoided Conventional Product Production (GIVO Project)

Source: Prepared by i17.

GIVO Project - Palstic Flakes	Global warming. Human health DALY	Stratospheric ozone depletion DALY	Ionising radiation DALY	Ozone formation. Human health DALY	Fine particulate matter formation DALY	Human carcinogenic toxicity	Human non-carcinogenic toxicity	Water consumption. Human health DALY
🟥 Recycled plastic flake (1 tonne)	3.34E-05	2,05E-10	5.73E-12	1.00E-08	1.63E-06	3.28E-08	1.57E-07	-2.58E-09
🟩 Avoided impact (virgin plastic flake - 1 tonne)	-2.77E-03	-1,05E-05	-5.29E-08	-5.10E-06	-1.87E-03	-5.07E-05	-5.86E-05	-4.81E-05
● Net impact	-2.74E-03	-1,05E-05	-5.29E-08	-5.09E-06	-1.87E-03	-5.06E-05	-5.85E-05	-4.81E-05

The contrast between conventional manufacturing and recycling becomes even more pronounced when evaluating potential changes in the energy source for the GIVO Project. For instance, replacing photovoltaic electricity with grid electricity, as depicted in Figure 16, would increase environmental damage. However, even with this hypothetical increase, recycling remains a substantially better option than the production of virgin plastic flakes, with an overall reduction in impact of 85.3%. This finding is consistent with research by Zhang et al. (2020), who found that replacing coal-based energy with a mixed source, including solar power, could reduce the environmental impacts associated with global warming by up to 31%. These findings highlight the critical role of sustainable energy solutions in enhancing the environmental efficacy of recycling processes, thereby maintaining the superiority of recycling over traditional production methods in reducing emissions and promoting environmental health.

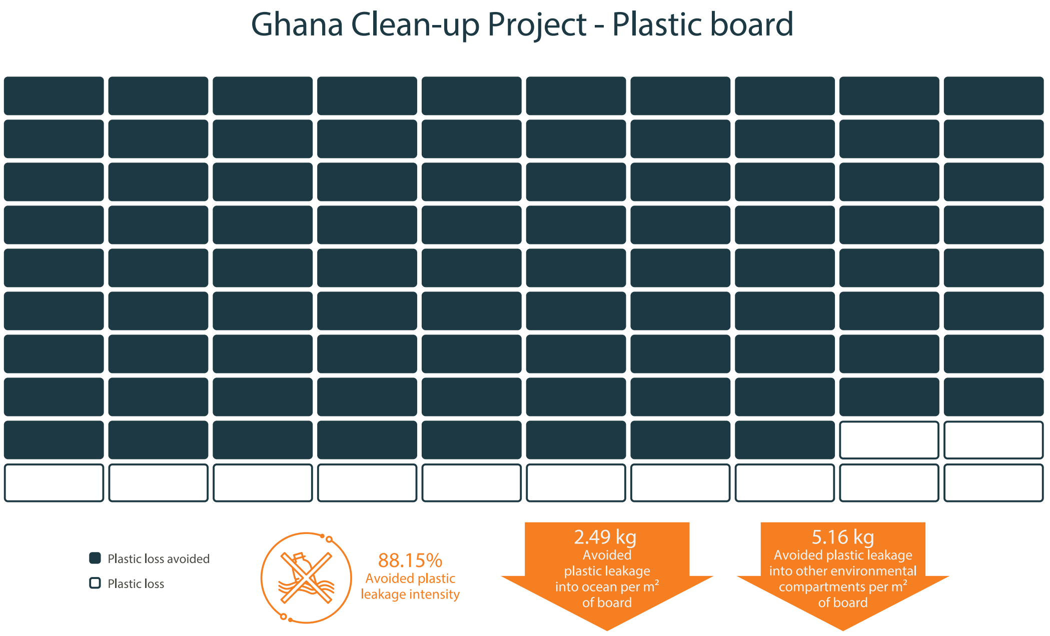
The insights derived from these case studies unequivocally underscore the vital role of plastic recycling in mitigating the adverse health and environmental impacts associated with traditional plastic production. Recycling offers a significant reduction in the environmental footprint of the plastics industry by eliminating the need for virgin plastic production, typically characterized by intensive resource use and high levels of pollutant emissions. Deeney et al. (2023) emphasize the essential contribution of recycling to sustainable waste management practices. This is particularly pertinent in developing regions, such as Africa, where the detrimental effects of plastic pollution exacerbate existing socioeconomic challenges (Rossouw et al., 2023). By curtailing pollutant emissions by avoiding virgin material production, recycling initiatives contribute to improved air quality and endorse a pathway toward sustainable development, which is crucial for these areas' economic and environmental well-being (Onu et al., 2023). Hence, adopting and prioritizing sustainable practices like plastic recycling is imperative for fostering a healthier, more equitable, and environmentally sustainable future.

4.3. Estimate performance of avoiding plastic leakage through recycling

This report presents the plastic leakage inventory for each project (see Tables S.12 to S.15), utilizing the data on plastic waste and the calculated rates of loss, release, and redistribution, as detailed in Tables S.8 to S.11 of supplementary material. This supplementary material underscores the critical role of recovering and recycling plastic waste in minimizing environmental leakage.

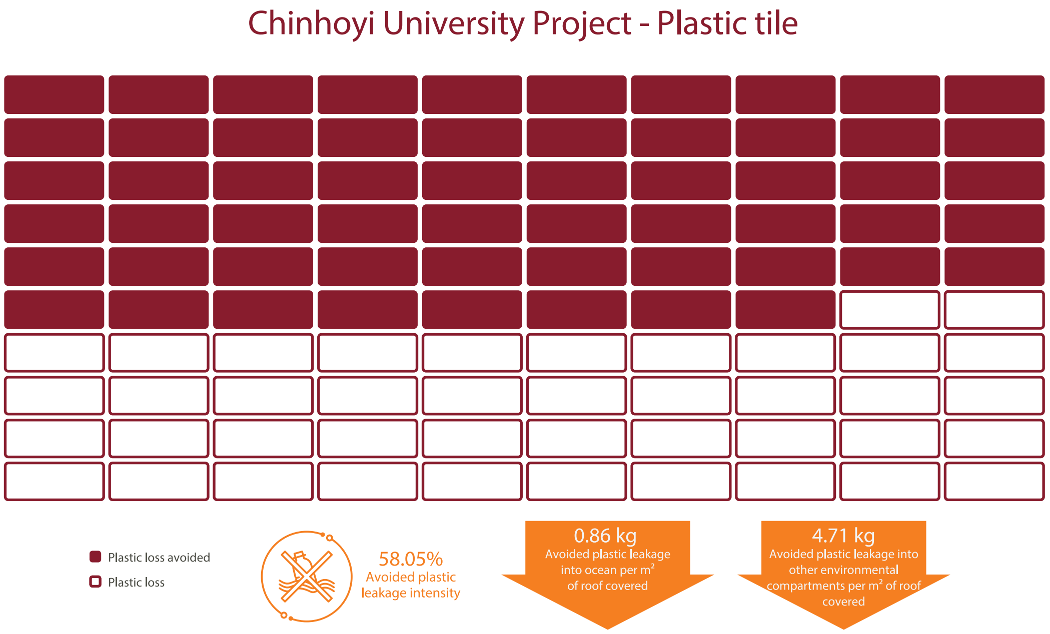
The Ghana Clean-up Project scenario analysis reveals a notable decrease in potential plastic leakage (see Figure 17). Without this recycling initiative, it is estimated that approximately 88.15% of the plastic waste intended for recycling facilities would likely end up leaking into the environment. The project effectively prevents 2.49 kg of macroplastic per square meter of produced plastic sheeting from entering the oceans and prevents 5.16 kg from dispersing into other environmental areas. These beneficial results stem from the project's focus on recycling low-value post-consumer plastics, which should be addressed in collection and recycling efforts due to their negligible economic value. Ji et al. (2023b) highlight that low-value recyclable materials represent a substantial fraction of the total waste produced, posing significant recycling challenges due to their low density, small size, and voluminous nature. Ordinarily, these materials are destined for landfill disposal or incineration or become part of environmental leakage. The insights from this project underscore the critical importance of recycling low-value materials and confronting the economic and technological hurdles associated with processing this type of waste.

In the Chinhoyi University Project, the recycling initiative has resulted in a 58.05% reduction in plastic leakage, as illustrated in Figure 18. For each square meter of roofing made from recycled plastic tiles, the project averts the leakage of 0.86 kg of plastic into the oceans. It prevents 4.71 kg from contaminating other environmental compartments. A notable aspect of this project is the focus on recycling materials that possess high and medium residual values, which are more likely to be collected by waste pickers, with an Informal Collection Rate (InfCollR) averaging around 84 ² 14%, depending on the size of the particles. This collection rate contributes to the scenario's relatively high but improved leakage avoidance figures. Despite these challenges, recycling efforts have reduced plastic waste's environmental mismanagement by half. This progress is particularly



← **Figure 17.** Plastic leakage avoided by plastic recycling (Ghana Clean-up Project)

Source: Prepared by i17.



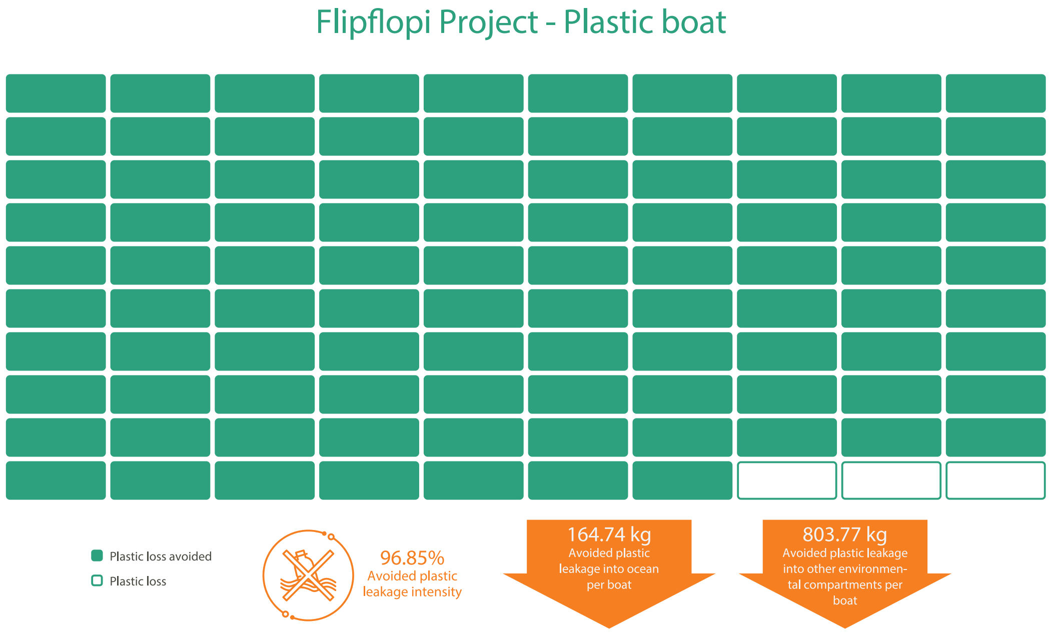
← **Figure 18.** Plastic leakage avoided by plastic recycling (Chinhoyi University Project)

Source: Prepared by i17.

noteworthy in Zimbabwe, where challenges in solid waste management are prevalent (Nhubu and Muzenda, 2019). The project's ability to decrease plastic leakage significantly highlights the potential impact of recycling initiatives on reducing environmental pollution, even amidst complex waste management landscapes.

The Flipflopi Project has exhibited exceptional efficacy in mitigating plastic leakage, achieving an impressive 96.85% reduction in environmental losses, as depicted in Figure 19. For every boat produced from recycled plastic waste, the initiative prevents 164.74 kg of plastic from contaminating the ocean and 803.77 kg from infiltrating other environmental zones on the land. This significant decrease in leakage primarily results from the project's strategic focus on repurposing low-value waste. This practice parallels the approach of the Ghana Clean-up Project, which similarly targets waste typically overlooked due to its minimal economic return and high likelihood of environmental dispersion.

Maddalene et al. (2023) explored the circularity of plastic in a study spanning six cities across various nations, including India, Indonesia, Malaysia, Panama, and Vietnam. Their research highlighted that low-value plastic packaging, especially from fast-moving consumer goods, poses substantial hurdles for formal and informal waste management systems, mainly due to challenges in collecting and adding value to the collected materials. The findings underscore the importance of improving collection systems to curb plastic leakage significantly. Moreover, integrating economic incentives into recycling and recovery operations enhances their effectiveness. By establishing recycling initiatives as economically viable business models, a sustainable value chain for recycled materials can be developed, promoting enduring environmental stewardship, as Onungwe et al. (2023) suggested. This strategy not only aids in reducing plastic leakage but also supports the advancement of sustainable recycling practices.

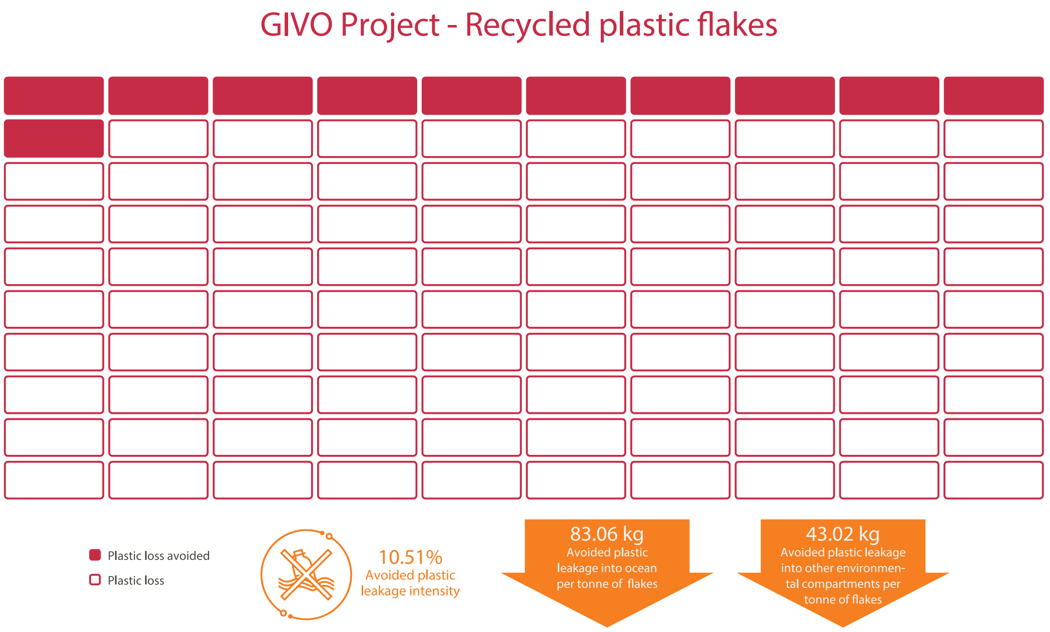


← **Figure 19.** Plastic leakage avoided by plastic recycling (Flipflop Project)

Source: Prepared by i17.

Leakage rates in recycling initiatives are profoundly affected by each country's unique environmental and infrastructural conditions, as detailed by the Plastic Leak Project (Quantis, 2020). Unlike the scenario in Kenya, the GIVO Project in Nigeria showed lesser effectiveness in curbing plastic waste leakage, avoiding only 10.51% of potential environmental losses through the production of recycled plastic flakes (see Figure 20). This lower efficiency is attributed to Nigeria's significant loss rate of 68.23%. Moreover, the project primarily processes high-value waste, which has high local demand by various recyclers, resulting in lower rates of leakage avoidance. Despite these challenges, the project notably reduces environmental pollution by preventing 86.03 kg of plastic per metric ton of recycled flakes from entering the oceans and 43.02 kg from infiltrating other environmental zones. This effort is crucial in the context of global plastic pollution challenges. Seyyedi et al. (2023) state that over 150 million tonnes of plastic waste pollute aquatic ecosystems worldwide, significantly impacting ecosystems and human health. Although the GIVO Project's impact may seem modest compared to other case studies, it remains essential in the broader fight against global plastic pollution.

The findings highlight the urgent necessity to improve plastic recycling and collection systems to tackle the critical environmental issue of plastic leakage. The starting point typically involves low collection rates in the countries examined, especially for low-value plastics. Enhancing recycling infrastructures presents a significant opportunity to protect ecosystems and biodiversity, lower greenhouse gas emissions, diminish pollution, and foster positive outcomes for human health. A primary strategy should involve integrating more low-value waste into the recycling process, as its underutilization markedly contributes to environmental leakage. Substantial investments in recycling and collection frameworks are essential to protect the environment and human health. Hence, they contribute to developing more environmentally aware and responsible communities.



← Figure 20. Plastic leakage avoided by plastic recycling (GIVO Project)

Source: Prepared by i17.

5.

Key Considerations and Recommendations from SMEP Target Countries

Utilizing the Disability-Adjusted Life Year (DALY) metric alongside the ReCiPe methodology, which integrates regional and demographic factors, this study quantifies the health benefits of recycling practices. This analytical approach shows the potential life years saved, showcasing the significant health benefits of recycling, especially in reducing the impacts of global warming and particulate matter. Despite these benefits, current recycling rates for plastic waste could be much higher in the studied countries: 10% in Ghana, 15% in Zimbabwe, 8% in Kenya, and 10% in Nigeria, which is concerning given their high levels of waste generation.

Recycling mitigates health risks associated with environmental pollutants and contributes to tangible life-year gains, as evidenced by the reduction in DALYs for each ton of recycled plastic. The data, underpinned by the ReCiPe framework, illustrate that recycling substantially diminishes the disease burdens related to environmental degradation. A comparative analysis between scenarios incorporating recycling and those without delineates the vital contribution of recycling to public health improvement. Table 6 provides an in-depth examination of the health benefits of increased recycling efforts, presenting a persuasive case for the international advancement of recycling programs.

Expanding on this, enhancing recycling infrastructure and public awareness can significantly improve public health. By increasing recycling rates, countries can contribute to the global effort to combat climate change and reduce the prevalence of pollution-related diseases. Therefore, policymakers, stakeholders, and communities must invest in and support recycling initiatives, recognizing their environmental and public health benefits. The findings advocate for a concerted global effort to elevate recycling practices, aligning them with sustainable development goals and public health objectives.

Table 6. Impact on human health in DALYs

Country	Project	Final Product	Life gained per 1 thousand tonnes of waste plastic recycled	Contribution per Impact Category								
			Total (days)	Total (DALY)	Global warming, Human health	Strato-spheric ozone depletion	Ionising radiation	Ozone formation, Human health	Fine particulate matter formation	Human carcino-genic toxicity	Human non-car-cinogenic toxicity	Water con-sumption, Human health
Ghana	**Ghana Clean-up Project**	**Plastic board**	1 year	1.076E+00	4.840E-01	2.639E-04	1.906E-06	8.533E-03	4.658E-01	5.088E-02	5.167E-02	1.467E-02
Kenya	**Flipflopi Project**	**Plastic boat**	24 years	2.45E+01	1.32E+01	7.00E-03	3.57E-04	2.60E-02	1.06E+01	1.66E-01	1.15E-01	4.21E-01
Nigeria	**GIVO Project**	**Recycled plastic flakes**	4 years	3.98E+00	2.28E+00	9.00E-03	4.41E-05	4.00E-03	1.56E+00	4.20E-02	4.90E-02	4.00E-02

↓ Source: Prepared by i17 based on information from the SMEP programme.

Country	Project	Final Product	Life gained per 1 thousand tonnes of waste plastic recycled		Contribution per Impact Category							
			Total (days)	Total (DALY)	Global warming, Human health	Strato-spheric ozone depletion	Ionising radiation	Ozone formation, Human health	Fine particulate matter formation	Human carcino-genic toxicity	Human non-car-cinogenic toxicity	Water con-sumption, Human health
Zimbabwe	**Chinhonyi University Project**	**Plastic board**	50 days	1.36E-01	3.18E-01	-7.07E-05	9.02E-07	-1.00E-03	-1.41E-01	-1.70E-02	-2.70E-02	4.00E-03
		Plastic tiles replacing clay titles	189 days	5.19E-01	6.68E-01	-4.42E-05	-1.29E-06	8.49E-05	-1.17E-01	-4.00E-03	-2.50E-02	-4.00E-03

Table 6 demonstrates that positive values signify a decrease in life years lost, highlighting the health advantages of using recycled products. In contrast, negative values indicate a reduction in life expectancy, underscoring areas where improvements in recycling methods are necessary to mitigate adverse health effects. This granular analysis aids in formulating targeted interventions to amplify the health benefits of recycling activities.

The aggregation of impact categories delineates the contribution of each category to the overall reduction in DALYs. This evaluation employs the absolute sum method, assessing the deviation of impact values from a zero baseline, indicative of no impact. This technique facilitates a thorough examination of the health implications of recycling, acknowledging both its beneficial and detrimental effects.

The report identifies key health risks linked to global warming and particulate matter formation and calls for targeted interventions. It also exposes the variation in plastic leakage prevention, which ranges from 10.51% to 96.85%, a discrepancy influenced by distinct waste management practices, the economic value of post-consumer plastics, and the specific characteristics of waste in the analyzed regions. These insights underscore the necessity for tailored methodologies to measure the health effects of plastic leakage, providing a more detailed evaluation of these impacts.

5.1. Recommendations

Ongoing research and investment in recycling initiatives are essential for fostering the development of global plastic circular economies, emphasizing the role of trade in services to enhance plastic recycling and management and deploying systems that reduce plastic usage. These initiatives can mitigate environmental and health impacts throughout their lifecycles. Lisiecki et al. (2023) argue that the effectiveness of current circular economy strategies for plastics may be constrained without implementing new regulations and shifts in plastic demand and consumption habits. This underscores the importance of broadening initiatives like those examined in this study to realize the intended environmental and health benefits and ensure the sustainable management of plastic resources.

Integrating innovative recycling methods with supportive policies and shifts in consumer behavior is crucial for enhancing the efficacy of circular economy efforts, thereby contributing to more sustainable and responsible management of plastic resources in alignment with global sustainability objectives. Acknowledging that discussions persist about which recycling methods can be considered environmentally sound is important. The environmental impact of different recycling processes varies, including their impacts on human health. If such impacts are not included in the scope of an assessment, this exclusion must be clearly stated. Before making any recommendations, it is essential to consider and evaluate the impacts of the recycling processes, ensuring that the methods adopted improve recycling efficacy and align with health benefits for workers and communities.

Deeney et al. (2023) highlight that achieving the SDGs within the waste sector hinges on the ongoing refinement of circular economy policies. This refinement should be grounded in comprehensive analyses that consider co-benefits and compensation strategies, utilizing a range of economic, environmental, health, and social metrics. Regular updates and revisions of these strategies are necessary to accommodate new technological developments, ensuring their applicability and effectiveness across various contexts. This approach should tackle technical and economic challenges and incorporate environmental and health considerations, making circular economy initiatives more versatile and impactful in fostering sustainable development.

Future research should also prioritize the collection phases of recycling processes, acknowledging the considerable health risks waste pickers face due to unsafe working conditions. Undas et al. (2023) highlight that the absence of protective gear and prolonged exposure to hazardous environments exacerbate these workers' susceptibility to respiratory, dermatological, and other chronic health conditions—this critical aspect of the recycling process warrants further investigation. Moreover, to comprehensively evaluate the impacts of recycling initiatives, studies should extend to the usage and disposal phases of products derived from recycled plastics. Complete life cycle assessments are imperative for thoroughly examining recycling practices' environmental, health, and social ramifications, ensuring that a full spectrum of impacts informs policy and operational decisions.

Additionally, future research should encompass the effects of plastic waste that is openly burned or discarded in unregulated dumps or precarious landfills. For instance, before establishing the materials recovery facility on Lamu Island in Kenya, a significant amount of plastic waste was either burned (63%) or repurposed as cooking fuel (24%) due to the scarcity of firewood. Following the implementation of the Flipflopi project, local surveys reported a 22% decrease in plastic waste disposal at local dumpsites, signifying the project's positive influence on waste management practices.

This study adopts an avoided burden approach, concentrating on macroplastic leakage from lost or poorly managed waste, underlining the need to devise methods for quantifying the impacts of both macroplastic and microplastic leakage on human health. Such advancements would allow for a more exhaustive evaluation of plastic leakage, addressing a notable gap in understanding the effects of plastics on human health. Furthermore, there is a pressing requirement for the standardization of impact assessment methodologies to enable direct comparisons of waste reduction strategies, aiding policymakers, researchers, and practitioners in assessing the efficacy of different measures in reducing plastic waste's environmental and health consequences. Establishing consistent metrics and methods is vital for progressing towards a unified and effective approach to combating plastic pollution.

To access the SMEP Trade and Pollution Dashboard, use this QRcode or this link: https://bit.ly/SMEP_UNCTAD

References

Akan, O.D., Udofia, G.E., Okeke, E.S., Mgbechidinma, C.L., Okoye, C.O., Zoclanclounon, Y.A.B., Atakpa, E.O., Adebanjo, O.O., 2021. Plastic waste: Status, degradation and microbial management options for Africa. J Environ Manage 292, 112758. https://doi.org/10.1016/j.jenvman.2021.112758

Akuoko, I.S.G., Vandenberg, J., Falman, J.C., Otsuka, K., Lau, G.K., Skrobe, M., An, S., Faustman, E.M., Ota, Y., 2023. Rethinking plastic realities in Ghana: A call for a well-being approach to understanding human-plastics entanglements for more equitable plastics governance. Mar Policy 158, 105856. https://doi.org/https://doi.org/10.1016/j.marpol.2023.105856

Ali, S.S., Abdelkarim, E.A., Elsamahy, T., Al-Tohamy, R., Li, F., Kornaros, M., Zuorro, A., Zhu, D., Sun, J., 2023. Bioplastic production in terms of life cycle assessment: A state-of-the-art review. Environmental Science and Ecotechnology 15, 100254. https://doi.org/10.1016/j.ese.2023.100254

Afon, A., 2012. A survey of operational characteristics, socioeconomic and health effects of scavenging activity in Lagos, Nigeria. Waste Management & Research 30, 664–671. https://doi.org/10.1177/0734242X12444894

Angnunavuri, P.N., Attiogbe, F., Mensah, B., 2023. Particulate plastics in drinking water and potential human health effects: Current knowledge for management of freshwater plastic materials in Africa. Environmental Pollution 316, 120714. https://doi.org/10.1016/j.envpol.2022.120714

Antunes, M., Santos, R.L., Pereira, J., Rocha, P., Horta, R.B., Colaço, R., 2022. Alternative clinker technologies for reducing carbon emissions in cement industry: A critical review. Materials 15. https://doi.org/10.3390/ma15010209

Ashori, A., Ayrilmis, N., Heydari, V., 2023. Enhancing interfacial adhesion through coupling agent incorporation in plywood/ plastic waste composite materials. Int J Adhes Adhes 127, 103513. https://doi.org/10.1016/j.ijadhadh.2023.103513

Chanchangi, Y.N., Adu, F., Ghosh, A., Sundaram, S., Mallick, T.K., 2023. Nigeria's energy review: Focusing on solar energy potential and penetration, Environment, Development and Sustainability. Springer Netherlands. https://doi.org/10.1007/s10668-022-02308-4

Ciocan, C., Kristova, P., Annels, C., Derjean, M., Hopkinson, L., 2020. Glass reinforced plastic (GRP) a new emerging contaminant - First evidence of GRP impact on aquatic organisms. Mar Pollut Bull 160. https://doi.org/10.1016/j.marpolbul.2020.111559

Cook, E., Derks, M., Velis, C.A., 2023. Plastic waste reprocessing for circular economy: A systematic scoping review of risks to occupational and public health from legacy substances and extrusion. Science of the Total Environment. https://doi.org/10.1016/j.scitotenv.2022.160385

Dada, O., 2022. What You Should Know About the Life of a Waste Picker in Lagos. https://www.globalcitizen.org/en/content/waste-picking-pickers-lagos-health-well-being/?gad^{2} source=1&gclid=Cj0KCQiA84CvBhCaARIsAMkAvkL8s-joh05pIlK4Fa5epaeC4S-kynl-oBFgXXgUG7QLAadU7JnOCGIaAkjhEALw^{2} wcB

Dada, O.T., Faniran, G.B., Ojo, D.B., Taiwo, A.O., 2023. Waste pickers' perception of occupational hazards and well-being in a Nigerian megacity. International Journal of Environmental Studies 80, 933–947. https://doi.org/10.1080/00207233.2022.2055344

Daraskevich, S., Foley, K., Palosky, J., Rozear, A., Sagna, M.L., 2023. Redefining Waste: Developing a Plastic Recycling Economy in Ghana.

Deeney, M., Green, R., Yan, X., Dooley, C., Yates, J., Rolker, H.B., Kadiyala, S., 2023. Human health effects of recycling and reusing food sector consumer plastics: A systematic review and meta-analysis of life cycle assessments. J Clean Prod 397, 136567. https://doi.org/10.1016/j.jclepro.2023.136567

De Schryver, A.M., K.W. Brakkee, M.J. Goedkoop, M.A. Huijbregts, 2009. Characterization factors for global warming in life cycle assessment based on damages to humans and ecosystems. Environ. Sci. Technol., 43 (6) (2009), pp. 1689-1695. https://doi.org/10.1021/es800456m

Dibia, S., Wala, K., Onwuzurike, U., Anabaraonye, B., Arinze, C., 2023. The impacts of plastic pollution on public health in Nigeria.

Di Maria, F., Sisani, F., Contini, S., Ghosh, S.K., Mersky, R.L., 2020. Is the policy of the European Union in waste management sustainable? An assessment of the Italian context. Waste Management 103, 437–448. https://doi.org/10.1016/j.wasman.2020.01.005

Duane, B., Ashley, P., Saget, S., Richards, D., Pasdeki-Clewer, E., Lyne, A., 2020. Incorporating sustainability into assessment of oral health interventions. Br Dent J 229, 310–314. https://doi.org/10.1038/s41415-020-1993-9

Ecoinvent, 2022. Life Cycle Inventory Database Ecoinvent Version 3.9.1. Zürich, Switzerland.

Ellen MacArthur Foundation, World Economic Forum, McKinsey&Co, 2016. The New Plastic Economy: Rethinking the Future of Plastics. Ellen MacArthur Foundation 1–120.

GAIA, 2021. Strengthening Waste Picker Organising in Africa. Global Alliance for Incinerator Alternatives (GAIA). Available online at: www.no-burn.org/Strengthening-Waste-Picker-Organising-in-Africa

Gall, M., Wiener, M., Chagas de Oliveira, C., Lang, R.W., Hansen, E.G., 2020. Building a circular plastics economy with informal waste pickers: Recyclate quality, business model, and societal impacts. Resour Conserv Recycl 156, 104685. https://doi.org/https://doi.org/10.1016/j.resconrec.2020.104685

Ganesan, A., Preetha, H., Subathara, S., Bhowmik, S., 2023. Comparative analysis of carbon emission from products of virgin plastics and recycled plastics and their environmental benefits. International Journal of Environmental Science and Technology 20, 6713–6722. https://doi.org/10.1007/s13762-022-04337-y

Ghana Energy Commission, 2022. National Energy Statistics 2000-2022 edition.

Gutberlet, J., Uddin, S.M.N., 2017. Household waste and health risks affecting waste pickers and the environment in low- and middle-income countries. Int J Occup Environ Health 23, 299–310. https://doi.org/10.1080/10773525.2018.1484996

Hashim, M., Njogu, P., Kinyua, R., Korir, R., 2020. Awareness of scavenging waste pickers on occupational hazards in selected dumpsites in Nairobi metropolis, Kenya. IOSR Journal of Humanities And Social Science 25, 38–46.

Intauno, K., Poshai, L., 2023. Examining the Occupational Safety and Health Hazards encountered by Municipal Waste Collectors in Murewa Rural District Council, Zimbabwe. International Journal of Law and Public Policy 5, 59–71.

Jerie, S., 2016. Occupational Risks Associated with Solid Waste Management in the Informal Sector of Gweru, Zimbabwe. J Environ Public Health 2016. https://doi.org/10.1155/2016/9024160

Jerie, S., Tevera, D., 2014. Solid Waste Management Practices in the Informal Sector of Gweru, Zimbabwe. Journal of Waste Management 2014, 148248. https://doi.org/10.1155/2014/148248

Heinrich Böll Foundation, 2019. Plastic Atlas Facts and figures about the world of synthetic polymers, 2019. Berlin, Germany.

Holland, C., 2021. Opportunities beg for exporting more waste plastic to South African recyclers. Economist Namibia. https://economist.com.na/64328/special-focus/opportunities-beg-for-exporting-more-waste-plastic-to-south-african-recyclers/

Horodytska, O., Kiritsis, D., Fullana, A., 2020. Upcycling of printed plastic films: LCA analysis and effects on the circular economy. J Clean Prod 268, 1–12. https://doi.org/10.1016/j.jclepro.2020.122138

Huijbregts, M., Steinmann, Z.J.N., Elshout, P.M.F.M., Stam, G., Verones, F., Vieira, M.D.M., Zijp, M., van Zelm, R., 2016. ReCiPe 2016. National Institute for Public Health and the Environment, Netherlands 194.

ISO 14040, 2006. Environmental management – life cycle assessment – Principles and framework. International Organisation for Standardisation (ISO), International Organisation for Standardisation (ISO). Environmental management - Life cycle assessment - Principles and framework. Geneva, Switzerland.

ISO 14044, 2006. Environmental management – life cycle assessment – requirements and guidelines. International Organisation for Standardisation (ISO), The International Standards Organisation (ISO). The International Journal of Life Cycle Assessment. Geneva, Switzerland.

Jambeck, J., Hardestyb, B., Brooksa, A., Friendc, T., Telekic, K., Fabresd, J., Beaudoind, Y., Bambae, A., Francisf, J., Ribbinkg, A., Baletag, T., Bouwmanh, H., Knoxi, J., Wilcox, C., 2018. Challenges and emerging solutions to the land-based plastic waste issue in Africa. Marine Policy, 96, 256–263. https://doi.org/10.1016/j.marpol.2017.10.041

Ji, T., Fang, H., Zhang, R., Yang, J., Fan, L., Hu, Y., Cai, Z., 2023a. Low-value recyclable waste identification based on NIR feature analysis and RGB-NIR fusion. Infrared Phys Technol 131, 104693. https://doi.org/10.1016/j.infrared.2023.104693

Ji, T., Fang, H., Zhang, R., Yang, J., Fan, L., Li, J., 2023b. Automatic sorting of low-value recyclable waste: a comparative experimental study. Clean Technol Environ Policy 25, 949–961. https://doi.org/10.1007/s10098-022-02418-7

Kaza, S., Yao, L.C., Bhada-Tata, P., Van Woerden, F., 2018. What a Waste 2.0; What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050: A Global Snapshot of Solid Waste Management to 2050. Urban Development; Washington, DC: World Bank. https://openknowledge.worldbank.org/entities/publication/d3f9d.

Kehinde, O., Ramonu, O.J., Babaremu, K.O., Justin, L.D., 2020. Plastic wastes: environmental hazard and instrument for wealth creation in Nigeria. Heliyon 6. https://doi.org/10.1016/J.HELIYON.2020.E05131

Kibria, M.G., Masuk, N.I., Safayet, R., Nguyen, H.Q., Mourshed, M., 2023. Plastic Waste: Challenges and Opportunities to Mitigate Pollution and Effective Management, International Journal of Environmental Research. Springer International Publishing. https://doi.org/10.1007/s41742-023-00507-z

Kimani, S.K., 2021. Exposure to Pollutants and Health of Women Waste Pickers at Dandora Dumpsite in Nairobi, Kenya. International Journal of Innovative Research & Development 10.

Kumar, V., Tyagi, S.K., Kumar, K., Parmar, R.S., 2023. Heavy Metal-Induced Pollution in the Environment through Waste Disposal. International Journal of Research Publication and Reviews 4, 1205–1210.

Kusuma, R.T., Hiremath, R.B., Rajesh, P., Kumar, B., Renukappa, S., 2022. Sustainable transition towards biomass-based cement industry: A review. Renewable and Sustainable Energy Reviews. https://doi.org/10.1016/j.rser.2022.112503

Kwarteng, I.K., Kontic, D., Bizjak, T., Kontic, B., 2020. Assessing the Role of Waste Pickers in the Recycling Industry in Accra Metropolis. Journal of Geoscience and Environment Protection 8.

Landrigan, P.J., Raps, H., Cropper, M., Bald, C., Brunner, M., Canonizado, E.M., Charles, D., Chiles, T.C., Donohue, M.J., Enck, J., Fenichel, P., Fleming, L.E., Ferrier-Pages, C., Fordham, R., Gozt, A., Griffin, C., Hahn, M.E., Haryanto, B., Hixson, R., Ianelli, H., James, B.D., Kumar, P., Laborde, A., Law, K.L., Martin, K., Mu, J., Mulders, Y., Mustapha, A., Niu, J., Pahl, S., Park, Y., Pedrotti, M.L., Pitt, J.A., Ruchirawat, M., Seewoo, B.J., Spring, M., Stegeman, J.J., Suk, W., Symeonides, C., Takada, H., Thompson, R.C., Vicini, A., Wang, Z., Whitman, E., Wirth, D., Wolff, M., Yousuf, A.K., Dunlop, S., 2023. The Minderoo-Monaco Commission on Plastics and Human Health. Ann Glob Health 89. https://doi.org/10.5334/aogh.4331

Lee, C.C., Yuan, Z., 2024. Impact of energy poverty on public health: A non-linear study from an international perspective. World Dev 174, 106444. https://doi.org/10.1016/j.worlddev.2023.106444

Linnenkoper, K., 2023. Struggling recycling efforts in Zimbabwe to 'leave no one behind. Recycling International.

Lisiecki, M., Damgaard, A., Ragaert, K., Astrup, T.F., 2023. Circular economy initiatives are no guarantee for increased plastic circularity: A framework for the systematic comparison of initiatives. Resour Conserv Recycl 197, 107072. https://doi.org/10.1016/j.resconrec.2023.107072

Ma, Y., Liu, H., Wu, J., Yuan, L., Wang, Y., Du, X., Wang, R., Marwa, P., Petlulu, P., Chen, X., Zhang, H., 2019. The adverse health effects of bisphenol A and related toxicity mechanisms. Environmental Research, 176. https://doi.org/10.1016/j.envres.2019.108575

Maddalene, T., Youngblood, K., Abas, A., Browder, K., Cecchini, E., Finder, S., Gaidhani, S., Handayani, W., Hoang, N.X., Jaiswal, K., Martin, E., Menon, S., O'Brien, Q., Roy, P., Septiarani, B., Trung, N.H., Voltmer, C., Werner, M., Wong, R., Jambeck, J.R., 2023. Circularity in cities: A comparative tool to inform prevention of plastic pollution. Resour Conserv Recycl 198, 107156. https://doi.org/10.1016/j.resconrec.2023.107156

Machemedze, R., Kadungure, A., 2021. Propelling virtuous and breaking vicious cycles: Responding to health and climate risks for informal residents and workers in two areas of Zimbabwe. Harare, Zimbabwe.

Maia de Souza, D., Lafontaine, M., Charron-Doucet, F., Chappert, B., Kicak, K., Duarte, F., Lima, L., 2016. Comparative life cycle assessment of ceramic brick, concrete brick and cast-in-place reinforced concrete exterior walls. J Clean Prod 137, 70–82. https://doi.org/10.1016/j.jclepro.2016.07.069

Makwara, E.C., Snodia, S., 2013. Confronting the reckless gambling with people's health and lives: urban solid waste management in Zimbabwe. European Journal of Sustainable Development 2.

Mangold, H., von Vacano, B., 2022. The Frontier of Plastics Recycling: Rethinking Waste as a Resource for High-Value Applications. Macromol Chem Phys 223, 1–17. https://doi.org/10.1002/macp.202100488

Mazhandu, Z.S., Muzenda, E., Belaid, M. et al. Comparative assessment of life cycle impacts of various plastic waste management scenarios in Johannesburg, South Africa. Int J Life Cycle Assess 28, 536–553 (2023). https://doi.org/10.1007/s11367-023-02151-3

Mensah, H., Julian Nalumu, D., 2024. Transforming waste-picking landscape in Ghana: from survival to sustainable enterprise. Local Environ 29, 206–223. https://doi.org/10.1080/13549839.2023.2280223

Millán-Estepa, Á., Díez-Martínez, E., Ladrón-de-Guevara-Muñoz, M.C., De-Cózar-Macías, Ó.D., Blázquez-Parra, E.B., Ladrón-de-Guevara-López, I., 2023. Implementation of a Sustainable Washing System Applied to Waste Recycling, in: Gerbino, S., Lanzotti, A., Martorelli, M., Mirálbes Buil, R., Rizzi, C., Roucoules, L. (Eds.), . Springer International Publishing, Cham, pp. 110–121. https://doi.org/10.1007/978-3-031-15928-2_10

Mohammed, M.A., Abdulhasan, M.J., Kumar, N.M., Abdulkareem, K.H., Mostafa, S.A., Maashi, M.S., Khalid, L.S., Abdulaali, H.S., Chopra, S.S., 2023. Automated waste-sorting and recycling classification using artificial neural network and features fusion: a digital-enabled circular economy vision for smart cities. Multimed Tools Appl 82, 39617–39632. https://doi.org/10.1007/s11042-021-11537-0

Mudu, P., Nartey, B.A., Kanhai, G., Spadaro, J. V, Fobil, J., 2021. Solid waste management and health in Accra, Ghana.

Nanda, S., Berruti, F., 2021. Thermochemical conversion of plastic waste to fuels: a review. Environ Chem Lett 19, 123–148. https://doi.org/10.1007/s10311-020-01094-7

Nemadire, S., Mapurazi, S., Nyamadzawo, G., 2017. Formalising informal solid waste recycling at the Pomona dumpsite in Harare, Zimbabwe. Nat Resour Forum 41, 167–178. https://doi.org/https://doi.org/10.1111/1477-8947.12130

Nhubu, T., Muzenda, E., 2019. Determination of the least impactful municipal solid waste management option in Harare, Zimbabwe. Processes 7. https://doi.org/10.3390/pr7110785

Nuripuoh, J.G., Duwiejuah, A.B., Bakobie, N., 2022. Awareness and health risk protection behaviours of scavengers in the Gbalahi landfill site, Ghana, in the era of sustainable development. Discover Sustainability 3, 1. https://doi.org/10.1007/s43621-021-00070-7

OECD, 2022. Plastic waste by end-of-life fate and region - projections. https://doi.org/https://doi.org/https://doi.org/10.1787/e4e8c086-en

Ogunkoya, J., Abiodun, O., Sodeinde, K., Bamidele, E., Sotunsa, J., Ladele, A., Emeruwa, G., Ogunyemi, O., 2022. Respiratory Symptoms and Spirometry Profile of Plastic Factory Workers in Ogun State, Southwest Nigeria. Occupational Diseases and Environmental Medicine.

Onu, M.A., Ayeleru, O.O., Oboirien, B., Olubambi, P.A., 2023. Challenges of wastewater generation and management in sub-Saharan Africa: A Review. Environmental Challenges 11, 100686. https://doi.org/10.1016/j.envc.2023.100686

Onungwe, I., Hunt, D.V.L., Jefferson, I., 2023. Transition and Implementation of Circular Economy in Municipal Solid Waste Management System in Nigeria: A Systematic Review of the Literature. Sustainability (Switzerland) 15. https://doi.org/10.3390/su151612602

Owusu-Sekyere, E., 2014. Scavenging for wealth or death? Exploring the health risk associated with waste scavenging in Kumasi, Ghana. Ghana Journal of Geography 6.

Peninah, K., Kelonye, F.B., Araka, G.O., 2022. Occupational Hazards among the Solid Waste Workers in Eldoret Central Business District, Kenya. Journal of Research Innovation and Implications in Education 6, 357–367.

Qin, Y., Liu, Y., Wang, J., Lu, Y., Xu, Z., 2022. Emission of PAHs, PCBs, PBDEs and heavy metals in air, water and soil around a waste plastic recycling factory in an industrial park, Eastern China. Chemosphere 294, 133734. https://doi.org/10.1016/j.chemosphere.2022.133734

Quantis, 2020. Plastic Leak Project: Methodological Guidelines.

Raufu, Y.O., Olayinka, A.S., Raimi, M.O., Olawale, S.H., Olabisi, O.L., 2023. Assessment of occupational risks of waste scavenging in Ilorin metropolis. AfricArXiv.

Rodrigues Gonçalves, M., Nogueira Cruvinel, V.R., Verpaele, S., Bashash, M., Pintas Marques, C., Urbano, M.R., Paoliello, M.M.B., Aschner, M., da Silva Santos, V., 2024. Metal levels in waste pickers in Brasilia, Brazil: hair and nail as exposure matrices. J Toxicol Environ Health A 87, 77–90. https://doi.org/10.1080/15287394.2023.2276372

Rossouw, R., Gihring, K., Crowe Pettersson, K., Kasner, S.-A., 2023. Plastic bans and phase-outs: Benefits for South Africa. Cape Town, South Africa.

Senavirathna, G.R.U., Galappaththi, U.I.K., Ranjan, M.T.T., 2022. A review of end-life management options for marine structures: State of the art, industrial voids, research gaps and strategies for sustainability. Clean Eng Technol 8. https://doi.org/10.1016/j.clet.2022.100489

Seyyedi, S. Reza, Kowsari, E., Ramakrishna, S., Gheibi, M., Chinnappan, A., 2023. Marine plastics, circular economy, and artificial intelligence: A comprehensive review of challenges, solutions, and policies. J Environ Manage 345, 118591. https://doi.org/10.1016/j.jenvman.2023.118591

Shomuyiwa, D.O., Onukansi, F.O., Ivanova, M., Lucero² Prisno, D.E., 2023. The Plastic treaty: What is in it for Africa? Public Health Challenges 2, 2–5. https://doi.org/10.1002/puh2.83

Smith, E., Bilec, M.M., Khanna, V., 2023. Evaluating the Global Plastic Waste Management System with Markov Chain Material Flow Analysis. ACS Sustain Chem Eng 11, 2055–2065. https://doi.org/10.1021/acssuschemeng.2c04270

Soares, B.B., Sousa, L.F. de, Santos, M.A. dos, 2021. Evaluation of occupational safety conditions in a waste plastic recycling plant in Brazil. Independent Journal of Management & Production 12.

Souza, D.; Lafontaine, M.; Charron-Doucet, F.; Bengoa, X.; Chappert, B.; Duarte, Lima, L., 2015. Comparative Life Cycle Assessment of ceramic versus concrete roof tiles in the Brazilian context. J Clean Prod 89, 165-173. http://dx.doi.org/10.1016/j.jclepro.2014.11.029

Srivastav, A., Xenos, S., 2020. Environmental Assessment of Kayak using MFA & LCA. A case study at Melker of Sweden.

Sun, Y., Wang, D., Li, X., Chen, Y., Guo, H., 2023. Public attitudes toward the whole life cycle management of plastics: A text-mining study in China. Science of the Total Environment 859, 159981. https://doi.org/10.1016/j.scitotenv.2022.159981

Taiwo, A.O., 2022. A dumpsite is no place for a child: study shows Nigeria's young waste pickers are at risk. https://theconversation.com/a-dumpsite-is-no-place-for-a-child-study-shows-nigerias-young-waste-pickers-are-at-risk-192619

Taiwo, A.O., Dada, O.T., Ayoola, A.S., Faniran, G.B., 2022. Socio-Economic, Health and Environmental Aspects of Child Waste Picking Activity at Africa's Largest Dumpsite. Am J Environ Sci 18, 69–80.

Tenhunen-Lunkka, A., Rommens, T., Vanderreydt, I., Mortensen, L., 2023. Greenhouse Gas Emission Reduction Potential of European Union's Circularity Related Targets for Plastics, Circular Economy and Sustainability. Springer International Publishing. https://doi.org/10.1007/s43615-022-00192-8

Tiwari, R., Azad, N., Dutta, D., Yadav, B.R., Kumar, S., 2023. A critical review and future perspective of plastic waste recycling. Science of the Total Environment 881, 163433. https://doi.org/10.1016/j.scitotenv.2023.163433

Tsakona, Maria; Elaine Baker, Ieva Rucevska, Thomas Maes, Lars Rosendahl Appelquist, Miles Macmillan-Lawler, Peter Harris, Karen Raubenheimer, Romain Langeard, Heidi Savelli-Soderberg, Kei Ohno Woodall, Jost Dittkrist, Tabea Anna Zwimpfer, Ruta Aidis, Clever Mafuta, Tina Schoolmeester, 2021. Drowning in Plastics –Marine Litter and Plastic Waste Vital Graphics, UN environment programme.

Undas, A.K., Groenen, M., Peters, R.J.B., van Leeuwen, S.P.J., 2023. Safety of recycled plastics and textiles: Review on the detection, identification and safety assessment of contaminants. Chemosphere 312, 137175. https://doi.org/10.1016/j.chemosphere.2022.137175

UNEP, 2022. Resolution 5/14. End plastic pollution: Towards an international legally binding instrument. United Nations Environment Programme 1–6.

UNEP, 2023. Chemicals in plastics: a technical report. United Nations Environment Programme and Secretariat of the Basel, Rotterdam and Stockholm Conventions. Geneva

UNCTAD, 2021. Challenges and opportunities for single-use plastic subistitutes: Insights from Kenya.

UNCTAD, 2024. UNCTADstat. Plastics trade by partner, annual (experimental). Available https://unctadstat.unctad.org/datacentre/dataviewer/US.PlasticsTradebyPartner

United Nations, 2015. Transforming our world: the 2030 Agenda for Sustainable Development Preamble. https://doi.org/10.1201/b20466-7

Vlasopoulos, A., Malinauskaite, J., ² abnie² ska-Góra, A., Jouhara, H., 2023. Life cycle assessment of plastic waste and energy recovery. Energy 277. https://doi.org/10.1016/j.energy.2023.127576

Wagner, M., Monclús, L., Arp, H., Groh, K., Løseth, M., Muncke, J., Wang, Z., Wolf, R., Zimmermann, L., 2024. State of the science on plastic chemicals - Identifying and addressing chemicals and polymers of concern, http://dx.doi.org/10.5281/zenodo.10701706.

Weidema, B.P., Wesnæs, M.S., 1996. Data quality management for life cycle inventories-an example of using data quality indicators. J Clean Prod 4, 167–174. https://doi.org/10.1016/S0959-6526(96)00043-1

Wenga, T., Chinyama, S.R., Gwenzi, W., Jamro, I.A., 2023. Quantification of bio-wastes availability for bioenergy production in Zimbabwe. Sci Afr 20. https://doi.org/10.1016/j.sciaf.2023.e01634

WHO, 2024. Heath and Environment. https://www.who.int/europe/health-topics/environmental-health/#tab=tab²1

World Economic Forum, 2023. Data benefits Ghana's fight against plastic pollution. https://www.weforum.org/impact/data-benefits-ghana-fight-against-plastic-pollution/

Yalwaji, B., John-Nwagwu, H., T.O. Sogbanmu, T., 2022. Plastic pollution in the environment in Nigeria: A rapid systematic review of the sources, distribution, research gaps and policy needs, Scientific African,16. https://doi.org/10.1016/j.sciaf.2022.e01220

Zhang, R., Ma, X., Shen, X., Zhai, Y., Zhang, T., Ji, C., Hong, J., 2020. PET bottles recycling in China: An LCA coupled with LCC case study of blanket production made of waste PET bottles. J Environ Manage 260, 110062. https://doi.org/10.1016/j.jenvman.2019.110062

Zimbabwe Environmental Law Association, 2023. Proper Plastic Waste Management Is Critical.

Annex 1

Determination of the Loss Rate (LR), Release Rate (RelR), and Redistribution Rate (RedR)

1. Loss Rate (LR)

Calculating the Loss Rate (*LR*) in this study is critical in understanding the extent of plastic leakage into the environment. The *LR* encompasses several key aspects of waste management inefficiencies, including:

- *Directly lost waste (LR_dirpat):* Represents waste that escapes collection and management systems directly into the environment.
- *Uncollected waste (LR_uncol):* Waste is never collected due to waste management infrastructure or practice gaps.
- *Poorly managed waste (LR_porrman):* Waste collected but not managed or treated according to environmental protection standards, leading to potential leakage.

The *LR* is quantitatively assessed through a structured equation that combines these components to provide a comprehensive measure of waste loss:

$$LR = LRdirpat + LRuncol + LRporrman$$

Eq. (1)

Further, the study adopts a detailed approach to account for various pathways through which waste can enter the environment, including littering, fly-tipping, dumping, and inadequate landfilling practices. This is encapsulated in the following equation, which refines the calculation of LR by incorporating the probability of littering and the inefficiencies in waste management practices:

$$LR = Littering + (1 - Littering) \cdot (LRdirpat + Flytipping + Dumping + Landfill) = Littering + (1 - Littering) \cdot (Unspecified\ landfills + Open\ dump + Unaccounted\ for) = Littering + (1 - Littering) \cdot (Unspecified\ landfills + Open\ dump + Unaccounted\ for)$$

Eq.(2)

The regionalized loss rates applied in this analysis are derived from comprehensive national statistics, as outlined by the World Bank and detailed in the methodology by Quantis (2020). This ensures that the LR calculations are grounded in context-specific data, enhancing the accuracy and relevance of the study's findings. The specific loss rates for each region and nation under investigation are presented in the supplementary material (Tables S.8 to S.11), offering a detailed view of the variability in waste management practices and their environmental implications across different geographical contexts.

2. Release rate (RelR) and Redistribution rate (RedR)

The Release Rate (*RelR*) quantifies the proportion of product waste, including macroplastics, that enters oceans (*RelRocean*), freshwater systems (*RelRfrw*), and terrestrial environments (*RelRterenv*). These rates are determined by expert analysis and comprehensive research (Quantis, 2020). This approach ensures a robust foundation for understanding the pathways through which plastic waste is released into the environment. The supplementary material meticulously compiles the specific data supporting these release rates (Tables S.8 to S.11).

An essential aspect of the *RelR* calculation is accounting for waste that, despite poor management, does not end up directly in the environment. This includes materials collected by informal waste pickers (*InfCollR*), which may be redirected toward recycling or reuse channels. The fraction of waste undergoing such informal collection is calculated using the following equation, offering insight into the diverse outcomes of waste management practices:

$$InfCollR = 1 - (RelRocean + RelRfrw + RelRterenv) \quad \text{Eq.(3)}$$

The Redistribution Rate (*RedR*) calculation assumes that all plastics released into freshwater and oceans converge in the oceanic environment. Conversely, plastics released into terrestrial environments are considered to remain within that specific environment. This implies that the *RedR* is assumed to be 100% for plastics entering aquatic systems, as detailed in the methodology by Quantis (2020). This assumption is critical for understanding plastic waste's final destination and long-term environmental impacts.

3. Leakage

The calculation of macroplastics leakage (*Leak_macro*) in each country's life cycle stage (stage *X*) combines the Mass of Plastic Waste (MPW) with country-specific Loss Rates (*LR*) and Release Rates (*RelR*) across different environments, adjusted by Redistribution Rates (*RedR*), as detailed in Equations 4 and 5. This approach quantifies macroplastic leakage to assess environmental impacts comprehensively.

$$Leak_{macro_{lifecyclestageX\ ocean}} = \sum (MPW_{lifecyclestageX} \bullet LR_{countryY} \bullet \left(RelR_{ocean} + RelR_{frw}\right) \bullet RedR)$$

Eq.(4)

$$Leak\_macro_{lifecyclestageX\ otheterenv} = \sum (MPW_{lifecyclestageX} \bullet LR_{countryY} \bullet (RelR_{terenv}) \bullet RedR)$$

Eq.(5)

Annex 1: Supplementary Tables

Table S.1 Inventory of plastic recycling to produce plastic board (RF = 1m^2) – Ghana Clean-up Project.

Stages	Flow	Amount	Database - Ecoinvent	Reference period	Pedigree matrix	σ^2
Transport to the recycling plant	Transport by truck	0.521 t*km	transport, freight, lorry 3.5-7.5 metric ton, EURO2	2017-2022	(3;1;1;1;1)	2.01
Recycling plant - Sorting	rigid mono-materials, such as PET and plastic chairs that constitute the largest share of 63%; (PET	0.001 t	Waste polyethylene terephthalate, for recycling, unsorted {GLO}| waste polyethylene terephthalate, for recycling, unsorted, Recycled Content cut-off |	2022	(3;1;1;1;1)	1.11
	flexible mono-materials, such as carrier bags and sachets (20% - PE)	0.004 t	Waste polyethylene, for recycling, unsorted {GLO}| waste polyethylene, for recycling, unsorted, Recycled Content cut-off |	2022	(3;1;1;1;1)	1.11
	multi-layer materials, such as cookie and chip wrappers (17% - PP)	0.004 t	Waste polypropylene, for recycling, unsorted {GLO}| waste polyethylene terephthalate, for recycling, unsorted,	2022	(3;1;1;1;1)	1.11
Recycling plant (Shredding	Energy consumption	0.001 kWh	Electricity, medium voltage {GH}| market for electricity, medium	2022	(2;1;1;3;2)	1.09
Recycling plant (Washing)	Water consumption (m^3)	0.005 m^3	Tap water {RoW}| market for tap water | Cut-off, U	2012 - 2022	(2;1;1;3;2)	1.09
	Wastewater generated and recycled (m^3)	0.005 m^3	Wastewater, average {RoW}| treatment of wastewater, average, wastewater treatment |	2010 - 2022	(2;1;1;3;2)	1.09
	Energy consumption	0.030 kWh	Electricity, medium voltage {GH}| market for electricity, medium	2022	(2;1;1;3;2)	1.09
Recycling plant (Drying)	Energy consumption	0.001 kWh	Electricity, medium voltage {GH}| market for electricity, medium	2022	(2;1;1;3;2)	1.09
Recycling plant (Hot pressing)	Energy consumption	0.003 kWh	Electricity, medium voltage {GH}| market for electricity, medium	2022	(2;1;1;3;2)	1.09

Recycling plant (Cutting)	Energy consumption	1.507E-04 kWh	Electricity, medium voltage {GH}| market for electricity, medium	2022	(2;1;1;3;2)	1.09
Recycled product	Amount of Plastic Board produced	8.681 kg (1.000 m²)	-	-	-	-

Table S.2. Inventory of plastic recycling to produce plastic tile (RF = 1 m²) – Chinhoyi University Project.

Stages	Flow	Amount	Database - Ecoinvent	Reference period	Pedigree matrix	σ²
Transport to the recycling plant (from Chinhonyi)	Transport by tractor with trailer	0,032 t*km	Transport, tractor and trailer, agricultural {RoW}| transport, tractor and trailer, agricultural | Cut-off,	1991 -2022	(2;1;1;1;1)	1.07
Transport to the recycling plant (from surrounding towns)	Transport by tractor with trailer	0.814 t*km	Transport, tractor and trailer, agricultural {RoW}| transport, tractor and trailer, agricultural | Cut-off, U	1991 -2022	(2;1;1;1;1)	1.07
Recycling plant - Sorting	HDPE	7.680 t	Waste polyethylene, for recycling, unsorted {GLO}| waste polyethylene, for recycling, unsorted, Recycled Content cut-off |	2022 -2022	(2;1;1;1;1)	1.07
	PET	1.920 t	Waste polyethylene terephthalate, for recycling, unsorted {GLO}| waste polyethylene terephthalate, for recycling, unsorted, Recycled Content cut-off |	2022 - 2022	(2;1;1;1;1)	1.07
Recycling plant – Crushing	Energy consumption	0.710 kWh	Electricity, medium voltage {ZW}| market for electricity, medium voltage | Cut-off, U	2022	(2;1;1;1;1)	1.06
Recycling plant - Mixing	Energy consumption	0.363 kWh	Electricity, medium voltage {ZW}| market for electricity, medium voltage | Cut-off, U	2014 - 2022	(2;1;1;1;1)	1.07
	Sand	17.920 kg	Sand {RoW} market for sand Cut-off	2011 - 2022	(2;1;1;1;1)	1.07
	Kaolin	0.384 kg	Kaolin {GLO}| market for kaolin | Cut-off, U	2011 - 2022	(2;1;1;1;1)	1.07
Recycling plant – Extrusion	Energy consumption	1.511 kWh	Electricity, medium voltage {ZW}| market for electricity, medium voltage | Cut-off, U	2014 -2022	(2;1;1;1;1)	1.06
	Energy consumption	0.604 kWh	Electricity, medium voltage {ZW}| market for electricity, medium voltage | Cut-off, U	2014 - 2022	(2;1;1;1;1)	1.06

Recycling plant –Pressing/ moulding	Water consumption for cooling (replacement water,	0.917 l	Water, cooling, unspecified natural origin, ZW	-	(2;1;1;1; 1)	1.07
Recycling plant – Diesel generator	Energy consumption	1.608 kWh	Diesel, burned in diesel-electric generating set, 18.5kW {GLO}| diesel, burned in diesel-electric generating set, 18.5kW |	2010 - 2022	(2;1;1;1; 1)	1.06
Recycled product	Amount of Plastic Tiles produced	8.000 units (1 m^2 of roof covered)	-	-	-	-

Table S.3. Inventory of plastic recycling to produce plastic boats (RF = 1 unit) – The Flipflopi Project.

Stages	Flow	Amount	Database - Ecoinvent	Reference period	Pedigree matrix	σ²
Transport to the material recovery facility	Transport by tractor	3.780 t*km	Transport, tractor and trailer, agricultural {RoW}| transport, tractor and trailer, agricultural | Cut-off, U	1991 -2022	(2;1;1;1;1)	2.00
Transport to the material recovery facility	Transport by boat	1.050 t*km	Transport, freight, sea, container ship | transport, freight, sea, container ship | Cut-off,	2007 -2022	(2;1;1;1;1)	1.07
Material recovery facility - Sorting	HDPE	1,050 kg	Waste polyethylene, for recycling, unsorted {GLO}| waste polyethylene, for recycling, unsorted, Recycled Content cut-	2022 -2022	(2;1;1;1;1)	1.07
Material recovery facility – Crushing	Energy consumption	96.574 kWh	Electricity, medium voltage {KE}| market for electricity, medium voltage | Cut-off, U	2014 -2022	(2;1;1;1;1)	1.06
Material recovery facility - Washing	Water consumpti	0.500 m³	Water, well, KE	-	(2;1;1;1;1)	1.07
Material recovery facility – Extrusion	Energy consumption	394.000 kWh	Electricity, medium voltage {KE}| market for electricity, medium voltage | Cut-off, U	2014 -2022	(2;1;1;1;1)	1.06
Material recovery facility –Moulding	Water consumpti	200.000 m³	Water, well, KE	-	(2;1;1;1;1)	1.07
	Energy consumption	39.400 kWh	Electricity, medium voltage {KE}| market for electricity, medium voltage | Cut-off, U	2014 - 2022	(2;1;1;1;1)	1.06

Material recovery facility – Boat construction	Screws, nails	10.000 kg	market for steel, unalloyed | steel, unalloyed | Cut-off, U / market for wire drawing, steel | wire drawing, steel | Cut-off, U / market for metal working, average for steel product manufacturing | metal working, average for	2011-2022	(2;1;1;1;1)	1.07
Recycled product	Boat produced	1.000 units (1,000.000 kg)	-	-	-	-

Table S.4. Inventory of plastic recycling to produce plastic flakes (RF = 1 tonne) – The GIVO Project.

Stages	Flow	Amount	Database - Ecoinvent	Reference period	Pedigree matrix	σ²
Transport to the GIVO Center	Transport by electric bicycle	120.000 person*km	Transport, passenger, electric bicycle {RoW}| transport, passenger, electric bicycle | Cut-off, U	2005-2022	(2;1;1;1;1)	1.07
GIVO Center (Sorting)	PET	1,188 t	Waste polyethylene terephthalate, for recycling, unsorted {GLO}| waste polyethylene terephthalate, for recycling, unsorted, Recycled Content cut-off |	2022-2022	(2;1;1;1;1)	1.07
	HDPE	0.010	Waste polyethylene, for recycling, sorted {GLO}| waste polyethylene, for recycling, sorted, Recycled Content cut-off | Cut-off, U	2022-2022	(2;1;1;1;1)	1.07
	PP	0.002	Waste polypropylene, for recycling, unsorted {GLO}| waste polyethylene terephthalate, for recycling, unsorted, Recycled Content cut-off | Cut-off, U	2021-2021	(2;1;1;1;1)	1.07
GIVO Center (Shredding)	Energy consumption	275.000 kWh	Electricity, low voltage {RoW}| electricity production, photovoltaic, 3kWp flat-roof installation,	2008-2022	(2;1;1;1;1)	1.07
GIVO Center (Granulator)	Energy consumption	75.000 kWh	Electricity, low voltage {RoW}| electricity production, photovoltaic, 3kWp flat-roof installation,	2008-2022	(2;1;1;1;1)	1.07
Recycled product	Plastic flakes	1 tonne	-	-	-	-

Table S.5. Reference flows used to assess the impact of the avoided product.

	Avoided	Database[a]
Ghana Clean-up Project	Plywood board (0.001 m3)	(Ecoinvent, 2022)
Chinhoyi University Project	Cement tile (7 units)	(Ecoinvent, 2022)
	Roof tile (7 units)	(Ecoinvent, 2022)
The Flipflopi Project	Fibreglass boat (1 unit)	Inventory data from: (Srivastav and Xenos, 2020)
The GIVO Project	Virgin plastic flakes (1 tonne)	(Ecoinvent, 2022)

[a] The energy, water and emissions demands of the reference flows were adapted according to the inventories of the countries under study.

Table S.6 Emissions and related impact categories with regionalized characterization factors provided by ReCiPe methodology (Huijbregts et al., 2016).

Emissions	Midpoint impact categories
NO_2	Ozone Formation, human health / Fine Particulate Matter Formation
NO	Ozone Formation, human health / Fine Particulate Matter Formation
NO_x	Ozone Formation, human health / Fine Particulate Matter Formation
NMVOC	Ozone Formation, human health
Ammonia	Fine Particulate Matter Formation
SO_2	Fine Particulate Matter Formation
SO_x	Fine Particulate Matter Formation
SO_3	Fine Particulate Matter Formation
Water, cooling, unspecified natural origin	Water consumption
Water	Water consumption
Water, lake	Water consumption
Water, river	Water consumption
Water, turbine use, unspecified natural origin	Water consumption
Water, unspecified natural origin	Water consumption
Water, well	Water consumption

Table S.7 Regionalized characterization factors for human health were used in the study (Huijbregts et al., 2016).

Ozone formation – Human health		
Environmental compartment	Substance	Characterisation factor (kg)
Air	Nitrogen dioxide, GH	2.4E-06 kg
Air	Nitrogen monoxide, GH	3.68E-06 kg
Air	Nitrogen oxides, GH	2.4E-06 kg
Air	NMVOC, non-methane volatile organic compounds, GH	1.1E-07 kg
Air	Nitrogen dioxide, ZW	9.7E-07 kg
Air	Nitrogen monoxide, ZW	1.49E-06 kg
Air	Nitrogen oxides, ZW	9.7E-07 kg
Air	NMVOC, non-methane volatile organic compounds, ZW	4.3E-08 kg
Air	Nitrogen dioxide, KE	9.7E-07 kg
Air	Nitrogen monoxide, KE	1.49E-06 kg
Air	Nitrogen oxides, KE	9.7E-07 kg
Air	NMVOC, non-methane volatile organic compounds, KE	4.3E-08 kg

Fine particulate matter formation		
Environmental compartment	Substance	Characterisation factor (kg)
Air	Ammonia, GH	0.000015
Air	Nitrogen dioxide, GH	3.2E-06
Air	Nitrogen monoxide, GH	4.91E-06
Air	Nitrogen oxides, GH	3.2E-06
Air	Sulfur dioxide, GH	0.000093
Air	Sulfur oxides, GH	0.000093
Air	Sulfur trioxide, GH	7.44E-05
Air	Ammonia, ZW	7.9E-06
Air	Nitrogen dioxide, ZW	2.7E-06
Air	Nitrogen monoxide, ZW	4.14E-06
Air	Nitrogen oxides, ZW	2.7E-06
Air	Sulfur dioxide, ZW	0.00011
Air	Sulfur oxides, ZW	0.00011

Air	Sulfur trioxide, ZW	0.000088
Air	Ammonia, KE	7.9E-06
Air	Nitrogen dioxide, KE	2.7E-06
Air	Nitrogen monoxide, KE	4.14E-06
Air	Nitrogen oxides, KE	2.7E-06
Air	Sulfur dioxide, KE	0.00011
Air	Sulfur oxides, KE	0.00011
Air	Sulfur trioxide, KE	0.000088
Air	Ammonia, NG	0.000015
Air	Nitrogen dioxide, NG	3.2E-06
Air	Nitrogen monoxide, NG	4.91E-06
Air	Nitrogen oxides, NG	3.2E-06
Air	Sulfur dioxide, NG	0.000093
Air	Sulfur oxides, NG	0.000093
Air	Sulfur trioxide, NG	7.44E-05

Water consumption

Environmental compartment	Substance	Characterisation factor (m^3)
Raw	Water, cooling, unspecified natural origin, GH	9.28E-07
Water	Water, GH	-9.3E-07
Water (ocean)	Water, GH	0
Raw	Water, lake, GH	9.28E-07
Raw	Water, river, GH	9.28E-07
Raw	Water, turbine use, unspecified natural origin, GH	9.28E-07
Raw	Water, unspecified natural origin, GH	9.28E-07
Raw	Water, well, GH	9.28E-07
Raw	Water, cooling, unspecified natural origin, ZW	3.37E-09
Raw	Water, lake, ZW	3.37E-09
Raw	Water, river, ZW	3.37E-09
Raw	Water, turbine use, unspecified natural origin, ZW	3.37E-09
Raw	Water, unspecified natural origin, ZW	3.37E-09
Raw	Water, well, ZW	3.37E-09

Water	Water, ZW	-3.4E-09
Water (ocean)	Water, ZW	0
Raw	Water, cooling, unspecified natural origin, KE	0
Water	Water, KE	0
Water (ocean)	Water, KE	0
Raw	Water, lake, KE	0
Raw	Water, river, KE	0
Raw	Water, turbine use, unspecified natural origin, KE	0
Raw	Water, unspecified natural origin, KE	0
Raw	Water, well, KE	0
Raw	Water, cooling, unspecified natural origin, NG	0
Raw	Water, lake, NG	0
Water	Water, NG	0
Water (ocean)	Water, NG	0
Raw	Water, river, NG	0
Raw	Water, turbine use, unspecified natural origin, NG	0
Raw	Water, unspecified natural origin, NG	0
Raw	Water, well, NG	0

Table S.8. Loss, release, and redistribution rates used to calculate plastic leakage – plastic recycling to produce plastic board (RF = 1m^2) – Ghana Clean-up Project.

Loss rate (littering) for small size or detachable, on-the-go*	5.000%
Loss rate (littering) for medium-size, on-the-go*	2.000%
Loss rate to be applied on the share that is not littered - Ghana (LRdirpat+Flytipping+Dumping+Landfill)	87.716%
Initial release rate, ocean, and freshwater ($RelR_{ocean}$+$RelR_{frw}$), low residual value, small size	40.000%
Initial release rate, other terrestrial environment ($RelR_{terenv}$), low residual value, small size	60.000%
Initial release rate, ocean, and freshwater ($RelR_{ocean}$+$RelR_{frw}$), low residual value, medium size	25.000%
Initial release rate, other terrestrial environment ($RelR_{terenv}$), low residual value, medium size	75.000%
Collected by waste pickers (InfCollR), low residual value	0.000%
Redistribution rate to the ocean ($RedR_{ocean}$)	100% of macroplastics released into ocean and freshwater
Redistribution rate to another terrestrial environment ($RedR_{terenv}$)	100% of macroplastics released into another terrestrial environment

*Without a better understanding, the on-the-go littering rate for low residual value plastic waste is assumed because waste is recovered from the environment and dump sites.

Table S.9. Loss, release, and redistribution rates used to calculate plastic leakage – plastic recycling to produce plastic tile – Chinhonyi University Project.

Loss rate (littering) for small size or detachable, on-the-go*	5.000%
Loss rate (littering) for medium-size, on-the-go*	2.000%
Loss rate (littering) for large size, on-the-go*	1.000%
Loss rate to be applied on the share that is not littered - Zimbabwe (LRdirpat+Flytipping+Dumping+Landfill)	89.776%
Initial release rate, ocean, and freshwater ($RelR_{ocean}$+$RelR_{frw}$), medium residual value, small size	25.000%
Initial release rate, other terrestrial environment ($RelR_{terenv}$), medium residual value, small size	75.000%
Initial release rate, ocean, and freshwater ($RelR_{ocean}$+$RelR_{frw}$), medium residual value, medium size	15.000%
Initial release rate, other terrestrial environment ($RelR_{terenv}$), medium residual value, medium size	85.000%
Initial release rate, ocean, and freshwater ($RelR_{ocean}$+$RelR_{frw}$), medium residual value, large size	5.000%
Initial release rate, other terrestrial environment ($RelR_{terenv}$), medium residual value, large size	95.000%
Initial release rate, ocean, and freshwater ($RelR_{ocean}$+$RelR_{frw}$), high residual value, small size	15.000%
Initial release rate, other terrestrial environment ($RelR_{terenv}$), high residual value, small size	15.000%
Initial release rate, ocean, and freshwater ($RelR_{ocean}$+$RelR_{frw}$), high residual value, medium size	10.000%
Initial release rate, other terrestrial environment ($RelR_{terenv}$), high residual value, medium size	5.000%
Initial release rate, ocean, and freshwater ($RelR_{ocean}$+$RelR_{frw}$), high residual value, large size	1.000%
Initial release rate, other terrestrial environment ($RelR_{terenv}$), high residual value, large size	1.000%
Collected by waste pickers (InfCollR), medium residual value	0.000%
Collected by waste pickers (InfCollR), high residual value, small size	70.000%
Collected by waste pickers (InfCollR), high residual value, small size	85.000%
Collected by waste pickers (InfCollR), high residual value, small size	98.000%
Redistribution rate to the ocean ($RedR_{ocean}$)	100% of macroplastics released into ocean and freshwater
Redistribution rate to another terrestrial environment ($RedR_{terenv}$)	100% of macroplastics released into another terrestrial environment

*On-the-go littering rate for low residual value plastic waste is assumed without a better understanding because waste is recovered from community-based organizations, individual plastic pickers, and major plastic waste producers such as retail shops, institutions, and supermarkets.

Table S.10. Loss, release, and redistribution rates used to calculate plastic leakage – plastic recycling to produce plastic boats – The Flipflopi Project.

Loss rate (littering) for medium-size, on-the-go*	2.000%
Loss rate (littering) for large size, on-the-go*	1.000%
Loss rate to be applied on the share that is not littered - Kenya (LRdirpat+Flytipping+Dumping+Landfill)	96.800%
Initial release rate, ocean, and freshwater ($RelR_{ocean}$+$RelR_{frw}$), low residual value, medium size	25.000%
Initial release rate, other terrestrial environment ($RelR_{terenv}$), low residual value, medium size	75.000%
Initial release rate, ocean, and freshwater ($RelR_{ocean}$+$RelR_{frw}$), low residual value, large size	5.000%
Initial release rate, other terrestrial environment ($RelR_{terenv}$), low residual value, large size	95.000%
Collected by waste pickers (InfCollR), low residual value	0.000%
Redistribution rate to the ocean ($RedR_{ocean}$)	100% of macroplastics released into ocean and freshwater
Redistribution rate to another terrestrial environment ($RedR_{terenv}$)	100% of macroplastics released into another terrestrial environment

*On-the-go littering rate for low residual value plastic waste is assumed, without a better understanding, because waste is recovered from households, local businesses, peri-urban areas, dumpsites, beach clean-ups, and mangrove clean-ups.

Table S.11. Loss, release, and redistribution rates used to calculate plastic leakage – plastic recycling to produce plastic flakes – The GIVO Project.

Loss rate (littering) for small size, on-the-go*	5.000%
Loss rate (littering) for medium-size, on-the-go*	2.000%
Loss rate to be applied on the share that is not littered - Nigeria (LRdirpat+Flytipping+Dumping+Landfill)	68.235%
Initial release rate, ocean, and freshwater (RelRocean+RelRfrw), medium residual value, small size	25.000%
Initial release rate, other terrestrial environment (RelRterenv), medium residual value, small size	75.000%
Initial release rate, ocean, and freshwater (RelRocean+RelRfrw), medium residual value, medium size	15.000%
Initial release rate, other terrestrial environment (RelRterenv), medium residual value, medium size	85.000%
Initial release rate, ocean, and freshwater (RelRocean+RelRfrw), high residual value, small size	15.000%
Initial release rate, other terrestrial environment (RelRterenv), high residual value, small size	15.000%
Initial release rate, ocean, and freshwater (RelRocean+RelRfrw), high residual value, medium size	10.000%
Initial release rate, other terrestrial environment (RelRterenv), high residual value, medium size	5.000%
Collected by waste pickers (InfCollR), medium residual value	0.000%
Collected by waste pickers (InfCollR), high residual value, small size	70.000%
Collected by waste pickers (InfCollR), high residual value, medium size	85.000%
Collected by waste pickers (InfCollR), high residual value, large size	98.000%
Redistribution rate to the ocean (RedRocean)	100% of macroplastics released into ocean and freshwater
Redistribution rate to another terrestrial environment (RedRterenv)	100% of macroplastics released into another terrestrial environment

**The on-the-go littering rate for low residual value plastic waste is assumed without a better understanding because waste is recovered from the neighborhood, including households and businesses.*

Table S.12. Plastic leakage inventory - plastic recycling to produce plastic board (RF = 1m²) – Ghana Clean-up Project.

	Plastic waste (t)	Waste littered (t)	Waste not littered but lost	Waste initially released to ocean and	Waste initially released to the	Waste redistributed to the ocean (kg)	Waste redistributed to the terrestrial
Post-consumer LVP collected and directed to the recycling	0.009						
Small size or detachable (< 5cm)	0.004	2.170 E-04	0.004	0.002	0.002	1.534	2.300
Medium Size (5-25cm)	0.004	8.681 E-05	0.004	0.001	0.003	0.954	2.863
Large Size	0	0	0	0	0	0	0
Total	0.009	3.038 E-04	0.007	0.002	0.005	2.488	5.164

Table S.13. Plastic leakage inventory - plastic recycling to produce plastic tile (RF = 1 m^2 of roof covered) – The Chinhoyi University Project.

	Plastic waste (kg)	Waste littered (kg)	Waste not littered but lost (kg)	Waste initially released to ocean and freshwater	Waste initially released to the terrestrial	Waste redistributed to the ocean (kg)	Waste redistributed to the terrestrial environment
Post-consumer LVP collected and directed	9.600						
Small size or detachable (< 5cm)	0.960	0.048	0.819	0.182	0.442	0.182	0.442
Medium Size (5-25cm)	4.800	0.096	4.223	0.561	2.289	0.561	2.289
Large Size (>25cm)	3.840	0.038	3.413	0.117	1.981	0.117	1.981
Total	9.600	0.182	8.455	0.861	4.712	0.861	4.712

Table S.14. Plastic leakage inventory - plastic recycling to produce plastic boats (RF = 1 unit) – The Flipflopi Project.

	Plastic waste (kg)	Waste littered (kg)	Waste not littered but lost (kg)	Waste initially released to ocean and	Waste initially released to the terrestrial environment (kg)	Waste redistributed to the ocean (kg)	Waste redistributed to the terrestrial environmen
Post-consumer LVP collected and	1,000.000						
Small size or detachable (< 5cm)	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Medium Size (5-25cm)	600.402	12.008	569.565	145.393	436.180	145.393	436.180
Large Size (>25cm)	399.598	3.996	382.943	19.347	367.592	19.347	367.592
Total	1,000.0	16.004	952.508	164.740	803.772	164.740	803.772

Table S.15. Plastic leakage inventory - plastic recycling to produce plastic flakes (RF = 1 tonne) – The GIVO Project.

	Plastic waste (kg)	Waste littered (kg)	Waste not littered but lost (kg)	Waste initially released to ocean and freshwater (kg)	Waste initially released to the terrestrial environment	Waste redistributed to the ocean (kg)	Waste redistributed to the terrestrial environment (kg)
Post-consumer LVP collected and directed to the recycling	1,200.000						
Small size or detachable (< 5cm)	9.840	0.492	6.379	1.032	1.037	1.032	1.037
Medium Size (5-25cm)	1,190.160	23.803	795.862	82.029	41.979	82.029	41.979
Large Size	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Total	1,200.00	24.295	802.24	83.060	43.016	83.060	43.016