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# From Waste to Warming: A Review of Solid Waste Mismanagement.

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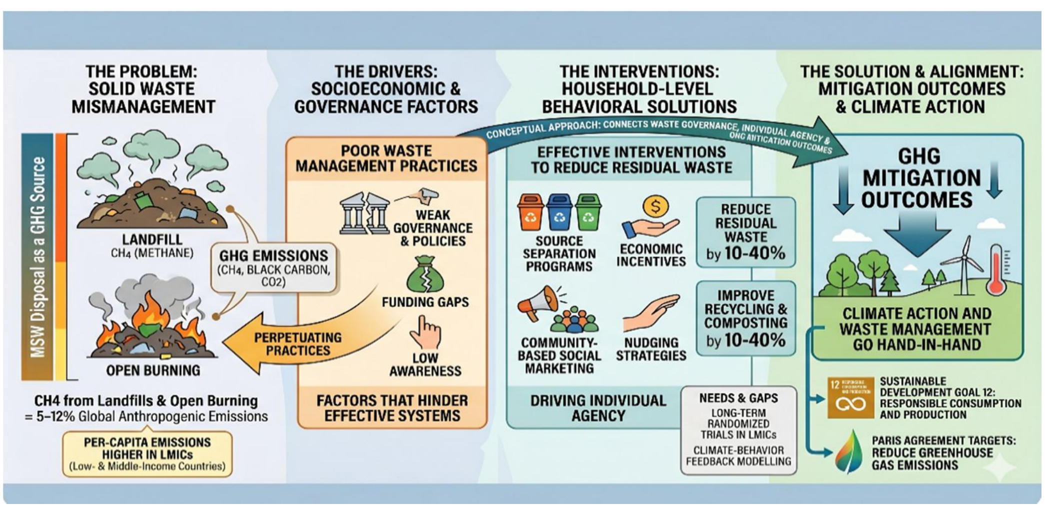
***Abstract:** Solid waste mismanagement is often an overlooked source of anthropogenic greenhouse gas (GHG) emissions. This narrative review collates evidence from peer-reviewed and Scopus-indexed literature to explore (i) the contribution of GHG emissions from MSW disposal, specifically landfill CH4 and open burning, (ii) how socioeconomic and governance factors perpetuate poor waste management practices, and (iii) how effective household-level behavioral interventions reduce waste generation and associated emissions. Based on a review of approximately 60 primary and review articles published from 2000 to 2024, the review reveals that methane gas emissions from landfills together with open burning account for 5–12% of global anthropogenic emissions, with much greater per-capita emissions in low-and middle-income countries (LMICs). Behavioral interventions, such as source separation programs, economic incentives, community-based social marketing, and nudging strategies, have been shown to reduce the amount of residual household waste by 10–40%, and the adoption of recycling and composting has been seen to improve by 10–40% when a multi-component intervention is used. The review highlights the need for more long-term randomized trials in LMIC settings and the lack of incorporation of climate-behavior feedback modelling, and suggests a conceptual approach that connects waste governance, individual agency, and GHG mitigation outcomes. Climate action and waste management go hand in hand and need to be strengthened to reach Sustainable Development Goal 12 (responsible consumption and production) and the targets of the Paris Agreement to reduce greenhouse gas emissions.*

***Keywords:** municipal solid waste; methane emissions; open burning; source separation; behavioural interventions; climate change mitigation; landfill gas; circular economy.*




## I. INTRODUCTION

The generation of municipal solid waste (MSW) has increased exponentially, reflecting urbanization and increasing consumption trends. The World Bank estimated that the global MSW generation was approximately 2.01 billion metric tons per year in 2016 and is estimated to reach 3.40 billion metric tons by 2050 under a similar business-as-usual scenario (Kaza et al., 2018). Many of these wastes are not properly handled and disposed of in open dumps, burned without energy recovery, and released into the environment, especially in cities in South and East Asia and municipalities in Sub-Saharan Africa. This mismanagement has far-reaching implications for the health and ecology of people and the environment, but more importantly, for the climate of the world.

The Intergovernmental Panel on Climate Change (IPCC, 2022) estimated that the waste industry accounts for approximately 5% of global anthropogenic greenhouse gas (GHG) emissions. Of these, CH4 is the largest and is the main component of methane arising from anaerobic decomposition in landfills, followed by $N_2O$ and $CO_2$ from open burning. Even relatively small mass-based emissions are of particular concern with respect to the near-term warming effects of methane because of its 100-year global warming potential ($GWP_{100}$), which is approximately 27–30 times that of $CO_2$ (Masson-Delmotte et al., 2021).

Although waste has not been as prominently considered in climate policy debates as energy, transport, or agriculture, it is an important climate impact. In addition, household behavior, a major determinant of waste generation, source separation, and recycling participation, has mostly been investigated in high-income country settings. There is a lack of translation of behavioral evidence across geographies, cultures, and institutional settings (Kollmuss & Agyeman, 2002; Steg & Vlek, 2009). This fills a critical knowledge gap, as LMICs contribute an increasing amount of waste to the world.

This review aims to answer three related research questions: (1) What is the quantitative contribution of solid waste mismanagement to GHG emissions globally and by region? (2) What influences waste mismanagement in terms of socioeconomic, institutional, and governance aspects? (3) What are the most effective household-level behavioral interventions that have proven to decrease waste generation and increase pro-environmental behaviors for climate mitigation? This review aims to answer these questions and create a cohesive body of evidence to guide policymakers and climate and waste researchers at the intersection of waste governance and climate change.

## II. METHODOLOGY

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) principles (Moher et al., 2009) were adapted for narrative synthesis used in this paper. The literature was retrieved via a search of Scopus, with additional searches in Web of Science and Google Scholar for cross-verification. The search strings included three conceptual domains: (i) waste management terms (municipal solid waste, landfill, open burning, waste mismanagement, and informal recycling); (ii) emissions terms (greenhouse gas emissions, methane, carbon dioxide, nitrous oxide, and landfill gas); and (iii) behavioral intervention terms (source separation, recycling behavior, nudge, community-based intervention, and waste reduction campaign).

The papers were shortlisted based on the following inclusion criteria: (a) published in peer-reviewed journals indexed in Scopus; (b) available in English between 2000 and 2024; (c) and (d) published papers provide empirical, modelling, or review-based evidence for at least one of the three research questions and are related to MSW or household waste, and not only to industrial or agricultural waste. Conference abstracts, grey literature, and duplicate studies were not included in this study. Of these, more than 800 titles were obtained, followed by an initial search whose results were screened by title and abstract, leaving 180 full texts of which approximately 60 were included for synthesis. Data extraction was structured in thematic matrices including the quantity of emissions, governance factors, and outcomes of interventions.

## III. SOLID WASTE MISMANAGEMENT AND GREENHOUSE GAS EMISSIONS

### A. *Global Scale of Waste Generation and Mismanagement*

The latest and most extensive global waste data from the World Bank's What a Waste 2.0 report (Kaza et al., 2018) showed that approximately 33% of all MSW is disposed of using environmentally unsound methods. In LMICs, the majority of waste is openly dumped: more than 90% of waste is dumped in uncontrolled open dumps or openly burned. In contrast, high-income countries have over 96% controlled landfills, waste-to-energy incineration, composting, and recycling facilities. This stark contrast is indicative of contrasting infrastructure investments, institutional capacity and regulatory enforcement.

South Asia and Sub-Saharan Africa have the highest proportion of mismanaged waste, by region, compared with the waste generated. Hoornweg and Bhada-Tata (2012) provided baseline information on the fact that cities in these regions spend 20–50% of their municipal budgets on waste management but do not collect 30–60% of the total solid waste generated. Most of the uncollected waste is found in informal settlements, and burning is the norm of disposal in such areas (Kumar et al., 2018). This leads to significant localized GHG emissions in addition to PM, black carbon, and toxic pollutants.

### B. *Landfill Methane: Magnitude and Mechanisms*

In most countries that have stopped dumping waste in open dumps, landfills are the largest source of GHG emissions from the waste sector. Methanogenic archaea decompose organic matter, mainly food waste, paper, and garden residue, in the absence of oxygen, resulting in methane production. Capturing and using landfills for energy has also been highly variable, ranging from over 60% in HICs with well-designed landfills with full-scale gas collection systems to essentially zero in many uncontrolled dump sites in LMICs (Lou & Nair 2009).

The contribution from the IPCC Fourth Assessment Report (Bogner et al., 2008) estimated that the global waste sector emitted approximately 1,460 Mt $CO_2$-eq in 2005, of which approximately 710 Mt was from landfill methane. More recent modelling by Thompson et al. (2019) indicated that national inventories are likely to underestimate global landfill CH4 emissions by up to 40% because of the lack of coverage of informal waste disposal sites and the underestimation of organic matter fractions in the waste streams of rapidly urbanizing countries.

The GHG profile of landfills is largely dependent on the composition of MSW. Waste streams high in food and organic waste, which are typical of cities in developing countries, produce proportionally higher CH4 emissions per tonne of waste deposited (Couth & Trois, 2010; food constitutes 50–70% of MSW, by mass, in developing country cities compared with 20–30% in HICs). This organic richness, coupled with warm tropical climates that promote microbial activity, leads to much higher CH4 emission factors in tropical LMICs than in temperate HICs. Couth and Trois (2010) demonstrated this dynamic in eight cities across Africa and found that the CH4 generation rate was 1.5–2.5 times higher than the default IPCC values.

### *C. Open Burning: An underrated emission source*

Open burning of solid waste is a major contributor of multiple GHGs and SLCPs; however, it is often not quantified and is common in Asia, Africa, and Latin America. Wiedinmyer et al. (2014) provided historic estimates of global waste burning, which resulted in an estimated annual $CO_2$-eq emission of approximately 29 Tg, with significant amounts of carbon and co-pollutants, such as dioxins and furans.

Open burning emits a mixture of products of incomplete combustion that differ in composition from landfill methane, which is dominated by a single compound. Black carbon, a component of soot, has a $GWP_{100}$ of the order of 900 or more per unit mass (Bond et al., 2013); however, its relatively short atmospheric lifetime means that it contributes mainly to the warming of the near term, rather than long-term accumulation. Paliwal et.al estimated that open waste burning emissions in India and estimated that the contribution of open burning is approximately 8-12% of the total black carbon emissions in India, which is a significant proportion considering the high waste generation in India and open burning practices in peri-urban and rural areas (Paliwal et al., 2016)

Open burning is not just a practice of the informal sector. There are many rural municipalities in Asia and Africa where open burning has been accepted or unofficially allowed as a waste management method, because affordable alternatives are not available (Kumar et al., 2017). This institutional aspect implies that open burning can only be addressed through the implementation of regulatory changes and infrastructure investments, as well as behavioral changes, as discussed in Section 5.

### *D. Informal Recycling, Composting, and Emission Offsets*

The informal waste sector is an important greenhouse gas (GHG) mitigation actor (sweepers, itinerant waste buyers, and small-scale recyclers), although its role is underutilized. In Brazil, waste pickers in cooperative recycling programs diverted millions of metric tons of recyclables annually from landfills, equivalent to hundreds of thousands of metric tons of CO2-eq. diverted, similar to the 20%–40% informal waste recovery rates documented in Asia, Africa, and Latin America (Wilson et al. 2009), but with waste pickers working under precarious conditions without recognition and institutional support.

The most effective GHG treatment for organic waste is composting and anaerobic digestion, after waste prevention. In a systematic review of life cycle assessment studies of organic waste management systems, Bernstad and la Cour Jansen (2012) reported that separate collection and biological treatment of food waste can result in net GHG savings between 200 and 800 kgCO2-eq/t compared with landfilling. However, high-quality source separation by households is required – a behavioral requirement that directly connects with the intervention evidence discussed in Section 5 – to attain these savings.

## IV. SOCIOECONOMIC AND GOVERNANCE DETERMINANTS OF WASTE MISMANAGEMENT

### *A. Income, Urbanization, and Infrastructure Deficit*

The deficit in income and infrastructure is the fourth of the four themes. The fourth of the four themes is the deficit in income and urbanization. The highest correlation of waste management quality from country to country is with income levels. Wilson et al. (2015) compiled data from 22 countries and reported a strong positive relationship between gross domestic product (GDP) per capita and the percentage of waste processed at controlled facilities. Most countries are unable to provide funding for the collection, transport, and treatment infrastructure below a threshold of approximately USD 5,000 per capita per year (purchasing power parity adjusted). This forms a vicious circle in which low -income results in low tax revenue for waste services, which leads to waste not being collected and inadequately treated, which has a negative impact on health and, therefore, economic productivity.

This infrastructure deficit is worsened by rapid urbanization. In sub-Saharan Africa, urban population growth is outpacing the administrative and fiscal capacity of urban municipalities to deliver services, in this case, waste collection (Turok and McGranahan, 2013). A large proportion of urban-dwelling residents in LMICs live in informal settlements, which are often not reached by formal waste collection services, either because of the physical characteristics of the road or because the residents' tenure is uncertain or unclear or because the residents reside in politically marginalized areas. Consequently, residents in slums practice open dumping or burning, resulting in high localized emissions.

### B. *Governance, Regulation and Enforcement*

Regulating waste requires not only a legislative component but also the capacity for monitoring, enforcement, and institutional accountability. Guerrero et al. (2013) performed a cross-national analysis of 17 cities and concluded that governance indicators (corruption control, rule of law, and regulatory quality) matter more than income alone; therefore, institutional capacity is an independent factor.

Since the 1990s, the decentralization of waste management responsibility to municipal governments has been a major policy direction, supported by international development banks. Marshall et al. (2013) reviewed the impacts of decentralization in LMICs and identified mixed outcomes because, although the local level is closer to the waste management challenge, local governments often lack the technical skills, finances, and political will to implement environmental standards. National-level frameworks and intergovernmental fiscal transfers continue to play an important role as complements to local autonomy.

### C. *Gender, Power and Waste Management*

Gender issues are often ignored in research and policy development related to household waste management (HWM). In most cultural contexts studied, women make key decisions regarding household waste management, including what is thrown away, how waste is sorted, and how it is disposed of (Gutberlet & Uddin, 2018). However, women remain underrepresented in formal waste governance institutions and are often denied access to the economic opportunities offered by recycling value chains. Dias (2016) reported that formally recognized waste-picker cooperatives with contracts with the local government were systematically marginalized by firms that started offering to pick up waste from the informal sector, particularly women-led cooperatives.

Acknowledging that women play a key role in household waste decisions is relevant for intervention design. Targeting women, who are often the final decision-makers, has yielded better results in terms of participation in source separation, and more consistent sorting behavior has been achieved compared to sex-neutral campaigns (Ojeda-Benitez et al., 2008). This highlights the need for sociodemographic segmentation in the design of behavioral interventions.

## V. HOUSEHOLD BEHAVIOURAL INTERVENTIONS AND WASTE REDUCTION

### A. *Theoretical Frameworks Underpinning Behavioural Change*

Household pro-environmental behavior has been examined under various theoretical perspectives, such as psychological, sociological, and economic approaches. The theory of planned behavior (TPB; Ajzen, 1991) proposes that attitude towards the behavior, subjective norms, and perceived behavioral control are all determinants of behavior. For recycling and waste sorting applications (Tonglet et al., 2004; Mannetti et al., 2004), positive attitudes towards environmental protection and high perceived behavioral control are found to be the strongest factors affecting participation. Perceptions of what others do and approve of (subjective norms) are important but contextually variable.

A complementary framework is provided by the value–belief–norm (VBN) theory (Stern, 2000), which views pro-environmental behavior as arising from biospheric values, which then leads to environmental beliefs and a sense of obligation. VBN has been used to describe the variation in household composting and source separation habits, with a higher value of biospheric norms invariably predicting a higher participation rate (Steg and Vlek, 2009). However, the translation of values into specific behavior is mediated by contextual factors such as infrastructure access, economic incentives, and social norms, indicating the need for multilevel intervention strategies.

Kollmuss and Agyeman (2002) noted the “mind the gap” problem, which refers to the fact that pro-environmental attitudes do not always translate into behavior. This attitude-behavior gap is due to competing values, habit strength, structural barriers, and cognitive limitations. To bridge this gap, interventions must change not only knowledge and attitudes but also the opportunity structures and social contexts in which behavior occurs.

### B. Economic Instruments: Pay-As-You-Throw and Deposit-Refund Schemes

Economic instruments induce price signals that embed the external costs of waste generation and disposal. Pay-as-you-throw (PAYT) schemes, in which households are charged for the volume or weight of unsorted (residual) waste they produce, provide a strong monetary incentive to reduce waste and promote source separation. Fullerton and Kinnaman (1996) provided the theoretical foundations that demonstrated the ability of PAYT to produce socially optimal levels of waste reduction when prices are set correctly. Empirically, Miranda et al. (1994) found that after the introduction of PAYT, there was a substantial decrease in the amount of residual waste collected in US municipalities, at 20–45%, with a corresponding increase in recycling capture rates. Similar results have been observed in Europe. Bel and Gradus (2016) conducted a meta-analysis of European PAYT programs, which yielded average waste reductions of 25–35% after the programs, with high inter-contextual variation. They pointed out that the size of the reduction is closely related to the price level, accessibility, and convenience of recycling facilities, and enforcement of anti-dumping regulations. Implementation is a critical challenge for PAYT in LMICs because the enforcement of such systems can result in a shift of waste into illegal dumping instead of waste reduction.

Among the best economic measures tested in the waste management arena are deposit-refund systems for beverage containers. Compliance rates for bottle and container deposit systems in other countries, such as Germany, the Nordic countries, and Canada, are high, in the range of 80%–98% for container return rates (Walls, 2011). The DRS mechanism incorporates the costs of litter and landfilling directly into the product price, provides an obvious incentive at the time of consumption, and utilizes loss aversion' (the human tendency to be driven more strongly by a lost deposit than by similar environmental arguments) (Thaler & Sunstein, 2008).

### C. Information and Education Campaigns

The most common waste management intervention is information provision, which was assumed in many public programs in which behavior was largely motivated by information gaps. However, empirical evidence on information-only interventions is limited. One of the first field experiments to show that descriptive social norms (information about what others do) are more effective than factual environmental information in changing household recycling behavior was conducted by Schultz et al. (1995**)**. Those who were asked to reflect on the recycling levels of their neighborhoods showed significantly greater changes in behavior than those asked to reflect on environmental benefits only.

This has been repeated and expanded upon in many subsequent studies. Thaler and Sunstein (2008) formalized these observations in their "nudge" theory, which showed that behavioral nudges could alter behavior without taking away options or financial incentives from the target.

There is promising evidence for the use of applications in waste management to achieve source separation compliance, with recycling being the "default" action and residual waste a "choice" that must be actively made. In pilot programs in several European cities, this approach has led to higher sorting rates (Thaler & Sunstein, 2008).

Community-based social marketing (CBSM; McKenzie-Mohr & Smith, 1999) is a structured approach to behavior change campaigns that incorporates social norm activation, commitment devices, and elimination of structural barriers. In Canada, Australia, and the UK, CBSM methods have been used to implement household composting programs that have boosted participation by 30%–50% over similar programs that only provide information (McKenzie-Mohr & Smith, 1999). The principles of CBSM include piloting the intervention with the target communities, targeting one high-priority behavior, and maintaining engagement through the use of prompts and feedback.

### D. Social Norms and Community-Based Approaches

Social norms have been extensively studied using empirical research since Schultz et al. (1995) published their seminal research on the role of social norms in influencing household waste behavior. Cialdini et al. (1990) identified two types of norms: descriptive norms, which refer to what people actually do, and injunctive norms, which refer to what people approve. They concluded that descriptive norms tend to be more influential on behavior than injunctive norms are. This distinction has practical consequences for campaigns because those that emphasize high levels of recycling or build participation in composting rely on descriptive norms and can have social contagion effects in the community.

Osbaldiston and Schott (2012) conducted a meta-analysis of pro-environmental behavior change interventions and concluded that interventions using social modelling, commitment, and prompts had the greatest effect sizes. In particular, public commitment to waste reduction targets (in which people make public pledges to take specific actions) led to a substantial boost in follow-through compared to private commitment or no commitment.

This is consistent with psychological consistency theory, which suggests that an individual's commitment to a given act becomes embedded in their consciousness, and they feel cognitive dissonance when they deviate from it, the motivation for compliance occurs.

Community-based waste management committees (CBOs) have been widely adopted as waste management committees in grassroots contexts in South and Southeast Asian countries, particularly for waste collection, composting, and recycling. Memon et al. (2003) reported CBO-led waste management programs in low-income urban neighborhoods in Asia and found that communities with active CBOs were able to improve the waste collection coverage rate (to the level of formal municipal services) at a much lower cost by mobilizing local social capital and creating accountability among peers. However, CBO sustainability depended on external technical and financial assistance and was susceptible to changes in leadership and political influence.

### *E. Nudging, Default Effects and Behavioural Architecture*

Since Thaler and Sunstein's (2008) groundbreaking synthesis, nudging has become a large field of behavioral policy research aimed at making pro-environmental behavior more convenient, visible, or the path of least resistance for consumers. In the waste domain, nudges work in several ways: making instructions for sorting easier to understand diminishes cognitive effort and errors; placing recycling bins in convenient locations boosts the capture rate; and visual cues, such as footpath markings directing people to recycling points, boost usage (Thaler & Sunstein, 2008).

Lehner et al. (2016) conducted a systematic review of nudging interventions for sustainable behavior (including waste management) and reported generally positive results with small to medium-sized effects. They warned that nudging evidence is predominantly from WEIRD (Western, Educated, Industrialized, Rich, and Democratic) communities and may not be directly applicable in LMIC settings, where root behaviors and cultural norms are significantly different. They recommended the co-design of nudge interventions with target communities as a prerequisite for contextual validity.

One of the strongest nudges is default effects, in which people tend to stay with the preferred choices. In the UK trials, opt-out composting programs with a caddy service offered to households by default reached 70–85% participation rates, while opt-in programs reached 20–40% participation rates (Thaler & Sunstein, 2008). This asymmetry is due to inertia and loss aversion, a tendency to avoid actively rejecting a service to which one has been assigned.

### *F. Multi-component and Integrated Interventions*

Several studies have found that single-component interventions have smaller, more temporary effects than multi-component interventions that include a combination of social, structural, informational, and economic norm components.

Abrahamse et al. (2005) conducted a systematic review of interventions for reducing household waste and concluded that multi-component programs had an average waste diversion rate of 20–40%, whereas single-component programs had an average rate of 5–10%.

The potential for infrastructure improvement (such as accessible recycling points), economic incentives (such as PAYT pricing), and social norm messaging to act together on multiple drivers of behavior suggests complementarity between mechanisms targeting different drivers.

The effects of waste reduction interventions that are part of larger sustainability programs (such as eco-neighborhood programs, zero-waste city campaigns, and extended producer responsibility [EPR] frameworks) can be shown to be amplified and more persistent (Guerrero et al., 2013). EPR creates a changing dynamic in the market, offering a redesign opportunity for manufacturers to focus on durability, recyclability, and minimal packaging, while simultaneously providing a cleaner disposal path for consumers. Behavioral change interactions between producers at the top and households at the bottom of the chain are an under-researched topic in the behavioral change literature.

## VI. CONNECTING HOUSEHOLD BEHAVIOUR TO GHG OUTCOMES: A CONCEPTUAL FRAMEWORK

Much of the literature on behavioral interventions overlooks system-level factors that link household waste behavior to greenhouse gas (GHG) emission outcomes.

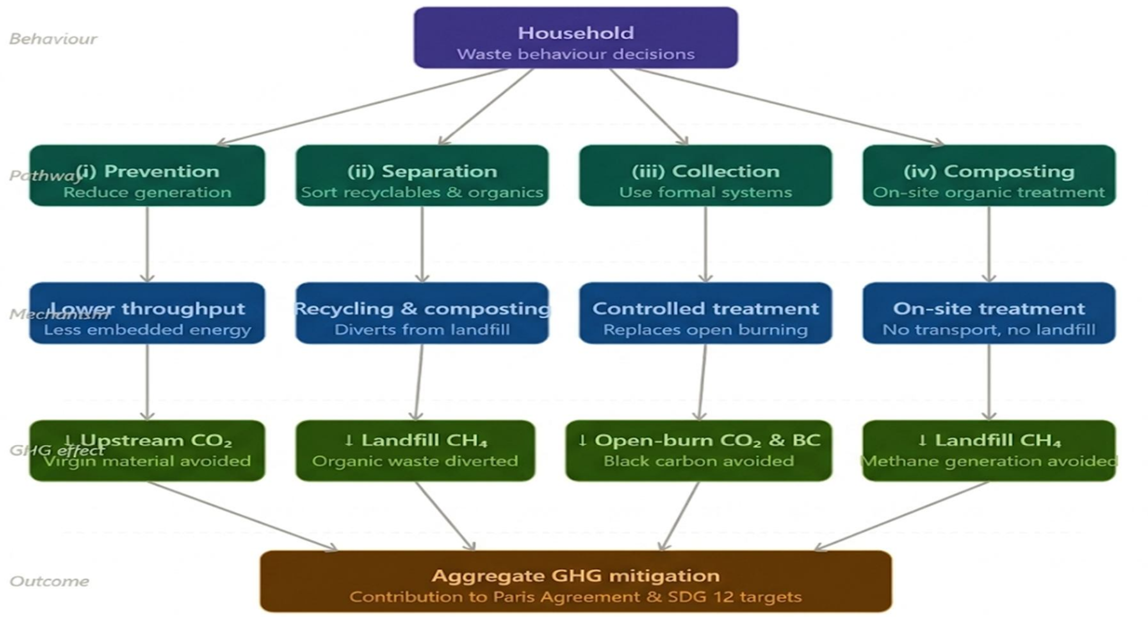



Fig1: Conceptual Framework for GHG mitigation (Self)

Figure 1 presents the conceptual framework proposed in this review, which involves four causal paths: (i) waste prevention, which decreases the amount of raw material throughput and embedded energy; (ii) source separation, which allows for high-quality recycling and composting, thereby substituting for raw material production and landfill methane emissions, respectively; (iii) participation in formal collection systems, which enables controlled treatment rather than informal dumping or burning; and (iv) adopting home composting, which treats organic waste on site, preventing landfill methane emissions.

There is significant uncertainty regarding the amount of GHG that can be saved for each pathway. Waste prevention is consistently found to have the highest climate benefit per tonne of waste avoided, followed by reuse, high-quality recycling, composting, incineration generating energy, and controlled landfilling with gas capture (Bernstad & la Cour Jansen, 2012). Open dumping and open burning are at the bottom of the list for climate outcomes. This hierarchy is consistent with the EU waste management hierarchy, which provides a regulatory structure based on evidence of environmental impact.

A major step needed to quantify the aggregate GHG benefits of household behavioral changes is to connect the observed changes in waste flows to emission factor databases. Defra (2023) provided emission conversion factors for waste management activities, such as landfilling, composting, anaerobic digestion, and recycling, for a range of waste materials. These factors allow for the estimation of the marginal GHG effect of waste diversion from various disposal scenarios. However, there is a gap between behavioral science and climate science literature because only a few studies reporting behavioral intervention outcomes include greenhouse gas (GHG) quantification.

This disconnection represents both a methodological gap and an opportunity. Future research that combines the behavioral design of the intervention with prospective GHG accounting may provide more policy-relevant evidence of the climate value of waste behavioral programs. A system-level analysis that takes individual behavior change to aggregate climate impact could be enabled by modelling the waste behavior of individual households with national waste flow and emission inventories, which has been used successfully in the energy sector (Dietz et al., 2009), but has not been applied to waste in general.

## VII. LOW- AND MIDDLE-INCOME COUNTRY CONTEXT: CHALLENGES AND OPPORTUNITIES

Most of the evidence of behavioral interventions from Section 5 comes from HIC settings, mainly in North America, Western Europe, and Australia. This geographical clustering is driven by the distribution of research funding and institutional capacity, not by the distribution of the waste management challenge; LMICs have the highest GHG emission pathways in the waste sector and the most mismanaged waste. This evidence gap is a high-priority research need.

Household behavioral interventions face unique challenges and opportunities in LMIC contexts. The availability of PAYT instruments is limited on the challenge side and may be too steep an opportunity cost for low-income households in terms of the time spent on source separation (Wilson et al., 2015). Structural barriers, such as informal housing with shared courtyards, lack of secure storage space, and unreliable collection schedules, also make it more difficult to implement consistent sorting behavior in high-income country (HIC) contexts. Participation in formal recycling schemes may be hindered by cultural norms regarding waste, such as stigma in dealing with waste and mistrust of the government waste collection service (Memon et al., 2003).

Regarding opportunities, some characteristics of LMIC urban contexts encourage waste management innovation at the community level. Community composting of organic waste is possible in informal settlements because waste is concentrated in one location, in contrast to suburban composting schemes in HICs, which are hampered by transportation costs. The informal recycling system can be formalized and enhanced without the need for mechanized facilities to replace it because the informal system offers the pre-existing infrastructure necessary to collect, sort, and recover materials (Gutberlet & Uddin, 2018). There is also a positive correlation between the amount of social capital in the community and the social cohesion present, and CBO-based waste management programs can tap into that social capital when it is more pronounced, especially in lower-income neighbourhoods, which are more interdependent. Even in low-income countries, mobile phone penetration is close to 80%, offering new tools for waste management behavioral interventions, such as reminders, social norm feedback, gamification, and digital deposit-refund schemes. The use of SMS messages to encourage adherence to waste collection points and improve waste sorting within households has been tested in pilot programs in Kenya, India, and the Philippines; however, the evidence is not yet strong. This field requires research on waste management behavior.

## VIII. POLICY IMPLICATIONS

The evidence summarized in this review has several inter-related implications for waste policy design. Waste management should be clearly included in national climate plans (Nationally Determined Contributions or NDCs) under the Paris Agreement, first. Only less than half of the NDCs submitted contain specific targets for the waste sector, and even fewer include legally binding regulations (IPCC, 2022). It takes political will and better GHG accounting systems that are able to measure emissions from informal waste disposal routes to make waste a headline mitigation sector.

Second, behavioral interventions are not replacements for infrastructure investments but should complement them. If recycling is not collected frequently, the accessibility of the collection point is low, or the treatment plant has limited capacity to treat recyclables, source separation campaigns will have limited impact. The order of investments is important; implementing PAYT or source separation systems before the necessary collection infrastructure is in place may have negative consequences such as illegal dumping and erosion of public trust (Guerrero et al., 2013).

Third, behavioral interventions should be targeted and designed to be relevant to the social, cultural, and institutional environments of the population of interest. Without being tailored to the local context, generic information campaigns are unlikely to cause a change in behavior in communities in LMIC. Participatory action research methodologies, which engage community members as co-creators of program design, provide a potential strategy for developing contextually appropriate and culturally relevant program designs (McKenzie-Mohr & Smith, 1999).

Fourth, EPR systems can be a systemic tool to reduce waste in addition to household behavioral initiatives. EPR places the producer on the hook for end-of-life product and packaging management, which encourages eco-design upstream and also provides funding for collection and recycling facilities to reduce the cost of pro-environmental behavior for consumers. The EU's Circular Economy Action Plan is the most comprehensive existing example of this approach, covering EPR for packaging, textiles, and electronics (Guerrero et al., 2013).

Fifth, there should be the institutionalization of gender-responsive design of waste policy. For waste sector programs, gender mainstreaming, such as gender-disaggregated monitoring, inclusion of women in leadership positions at waste management institutions, and provision of specific support for women-led waste cooperatives, can enhance social equity and program effectiveness, given the importance of women in household waste decision-making and their systematic underrepresentation in waste governance institutions (Dias, 2016).

## IX. RESEARCH GAPS AND FUTURE DIRECTIONS

This review highlights several evidence gaps in the literature. First, there is a lack of long-term and stringent assessments of household waste behavioral interventions in LMIC settings. The overwhelming majority of evidence from HICs has limited generalizability, and a significant proportion of the global waste challenge lacks a clear empirical basis for designing interventions. Community-based waste programs in African, SAAN, and SA-East Asian cities are a priority for research using randomized controlled trials or quasi-experimental designs.

Second, there is a lack of literature integrating evidence for behavioral interventions with GHG quantification. Although LCA studies have determined GHG emission factors for various waste treatment pathways with reasonable accuracy, few studies have quantified the GHG savings resulting from observed behavioral changes (e.g., metric tons of organic waste diverted from landfills) and reported them as primary outcomes. Adding GHG impact, in addition to waste diversion and participation in recycling, to future waste behavior trials would close the gap between the existing siloed behavioral and climate science literature.

Third, the mechanisms by which social norms influence household waste behavior in non-WEIRD populations remain unclear. Most norm-based intervention research has occurred in cultures and societies that value autonomy and have dominant frames that support it, most of which are individualistic, high-income societies. Other norm-setting mechanisms may be more relevant in other collectivist/community-based cultural settings, such as other community-based norms, for example, the norms within the family, or other norm carriers, such as religious or traditional leaders. Culturally comparative research designs are required to develop a more general understanding of the dynamics of social norms in relation to waste behavior.

Fourth, little is known about the interaction effects of various economic instruments and social norm interventions. Possible crowding-out effects, as predicted by economic theory, include the fact that the use of financial incentives to recycle can affect intrinsic pro-ecological motivation, such that the more people are paid for recycling, the less inclined they are to do so without pay, and the less likely they are to recycle if the pay stops (Frey & Jegen, 2001). The reverse is also true: the implementation of financial incentives can trigger an initial change in behavior that then becomes automatic and internalized, leading to lasting effects, even after the incentives are withdrawn. Future studies should be methodologically innovative by testing these interaction dynamics using adaptive designs that change the incentive and norm parts and/or the order of their presentation**.**

## X. CONCLUSION

Substantial and important GHG emissions are generated by the mismanagement of solid waste; 80% of solid waste emissions are methane from uncontrolled landfills and GHG emissions from open burning provide a climate forcing agent that would yield significant near-term GHG emission reductions for warming trajectories. The evidence presented here shows that when appropriately designed, contextualized, and supported by the right infrastructure and economic instruments, behavioral interventions within the household can yield significant waste reduction and source separation improvements and provide cascading GHG benefits by decreasing methane generation and eliminating higher-emission treatment options.

Actual policy and the extent of the research evidence, however, are not ambitious enough, or extensive enough, to meet the challenges of climate and waste crises. National climate mitigation plans continue to underrepresent the waste sector; there is a significant bias in the evidence base for behavioral interventions in HIC contexts; and there is minimal understanding of how waste behavior evidence can be integrated with GHG accounting. Adapting these shortcomings by investing in research, inter-jurisdictional collaboration, and linking waste management explicitly to the climate policy agenda is not only an academic need but also a necessity for achieving environmental sustainability globally.

Finally, changing household behavior is not a side effect of climate action; it is a cross-cutting issue that covers many different aspects of consumption, urban governance, social equity, and atmospheric chemistry. The potential to fully align the waste sector with climate science and climate policy is a huge opportunity to maximize co-benefits for climate, public health, and the circular economy, especially in fast-growing cities in the Global South, where the waste issue is most pressing and there is significant potential to leapfrog to more sustainable systems.

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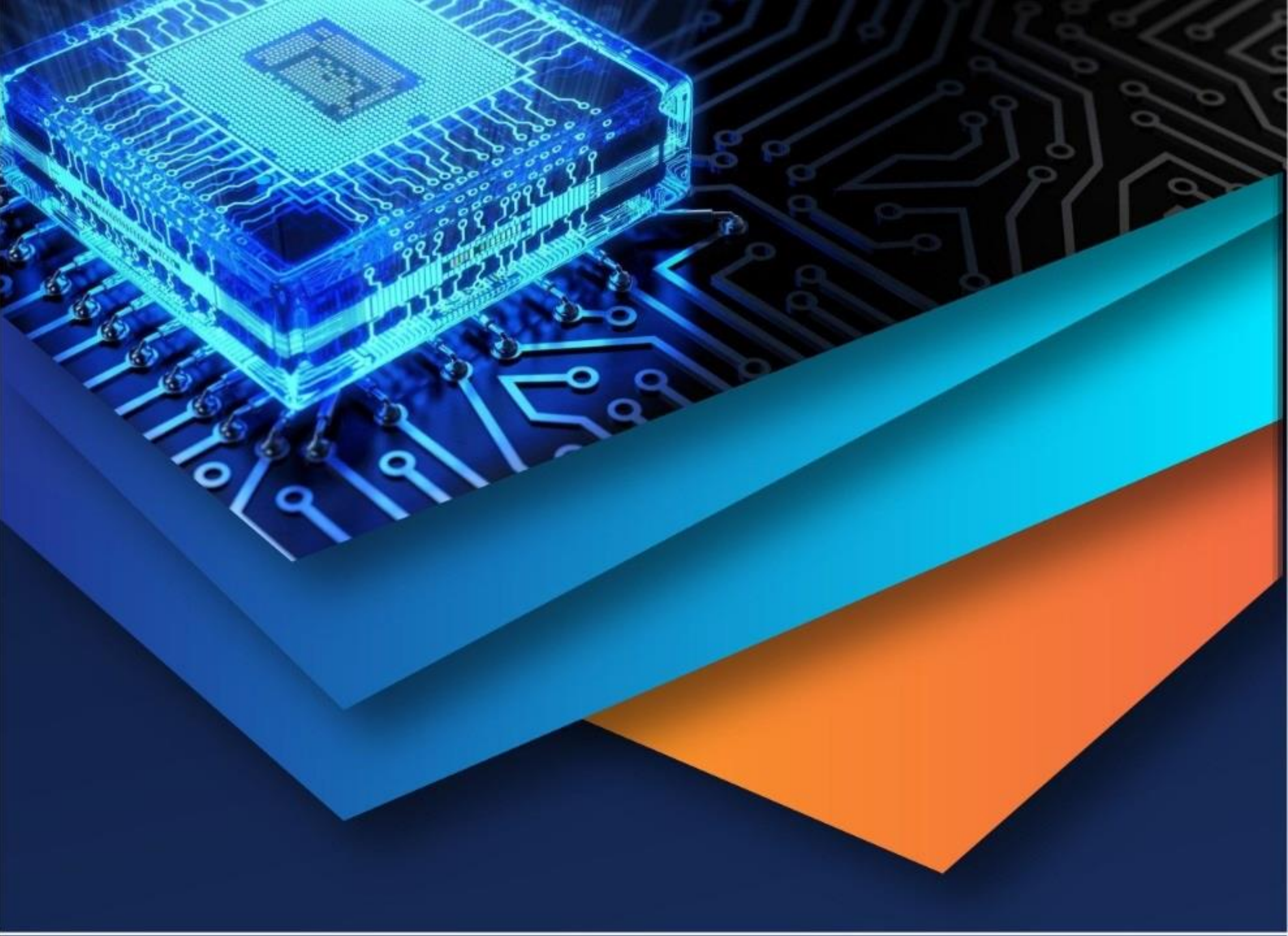

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