Potentials for future reductions of global GHG and air pollutant emissions from circular municipal waste management systems

Adriana Gomez Sanabria (gomezsa@iiasa.ac.at)
International Institute for Applied Systems Analysis https://orcid.org/0000-0002-2317-3946
Gregor Kiesewetter
International Institute for Applied Systems Analysis (IIASA)
Zbigniew Klimont
International Institute for Applied Systems Analysis https://orcid.org/0000-0003-2630-198X
Wolfgang Schöpp
International Institute for Applied Systems Analysis (IIASA)
Helmult Haberl
University of Natural resources and Life Sciences

Article

Keywords: Municipal waste, greenhouse gases, air pollution, methane, SDGs

Posted Date: June 22nd, 2021

DOI: https://doi.org/10.21203/rs.3.rs-512870/v1

Version of Record: A version of this preprint was published at Nature Communications on January 10th, 2022. See the published version at https://doi.org/10.1038/s41467-021-27624-7.

Potentials for future reductions of global GHG and air pollutant emissions from circular municipal waste management systems

Adriana Gómez-Sanabria*[a,b], Gregor Kiesewetter[a], Zbigniew Klimont[a], Wolfgang Schoepp[a] & Helmut Haberl[b]

[a] Pollution Management Research Group, Energy, Climate and Environment Program, International Institute for Applied Systems Analysis, Laxenburg, Austria

[b] Institute of Social Ecology, University of Natural Resources and Life Sciences, Vienna, Austria

Contributions

AGS designed the study, performed the projections, emission simulations and analysis, and prepared the manuscript. GK performed the ambient air pollution concentration calculations. ZK provided expert guidance and contributed to the revision of the manuscript. WS prepared and imported the IAE-WEO activity drivers and provided methodological advice. HH participated in the development of the research and contributed to writing the manuscript. All authors were involved in the discussion during the process.

Corresponding author

Correspondence to: Adriana Gómez-Sanabria. Email: gomezsa@iiasa.ac.at

AGS: ORCID: 0000-0002-2317-39

HH: ORCID: 0000-0003-2104-5446

Abstract

Recent trajectories of production and consumption patterns have resulted in massively rising quantities of municipal solid waste (MSW). In combination with the large global quantities of mismanaged MSW these increases cause detrimental effects on the environment and climate. Few analyses of the potential environmental co-benefits resulting from the implementation of circular MSW management systems exist. To our knowledge, no global study of possible future scenarios of MSW generation, composition, management, and associated burdens is available that explicitly considers the important differences between urban and rural settings. To help filling this gap, we here develop a systematic approach for evaluating the benefits of implementing circular MSW management systems in terms of their potentials to reduce greenhouse gas emissions (GHG) and air pollution. We also analyse their role in the pursuit of the Sustainable Development Goals (SDGs). Building on the Shared Socioeconomic Pathways (SSPs), we build two sets of global scenarios until 2050, namely baseline and mitigation scenarios. In these scenarios, we assess trajectories of future MSW generation and the impact of MSW management strategies on methane (CH_4), carbon dioxide (CO_2) and air pollutant emissions. We estimate that future MSW generation could increase to at least 3.7 Gt/yr and at most to 4.3 Gt/yr by 2050, depending on the respective SSP storyline. In 2050, we show that the adoption of mitigation strategies in the sustainability-oriented scenario yields earlier, and major, co-benefits compared to scenarios in which inequalities are reduced but that are focused solely on technical solutions. In 2050, the GHG emissions in the sustainability-oriented scenario amount to 182 Gg CO_{2eq}/yr of CH_4, to be released while CO_2, particulate matter, and air pollutants from open burning of MSW can be virtually eliminated, indicating that this source of ambient air pollution can be entirely eradicated before 2050. We conclude that significant potentials exist to reduce GHG, and air pollution if circular MSW management systems are implemented. We also demonstrate that the 6.3 target of the SDG 6 can only be achieved through more ambitious sustainability-oriented scenarios that limit MSW generation and improve management.

Key words: Municipal waste, greenhouse gases, air pollution, methane, SDGs

Introduction

Global quantities of municipal solid waste (MSW) generation have grown massively over the last decades, not only due to population growth but also as a result of economic growth and the consequent changes in production and consumption patterns[1,2]. Estimates suggest that the world population generated 1.9 Gt/yr of MSW in 2015 and is expected to generate about 3.5 Gt/yr of MSW in 2050[3]. High-income countries (in terms of the World Bank income classification) generate more waste per capita per year than low-income countries: they are responsible for 34% of the amount of MSW generated each year, even though they account for just 16% of the global population[4]. These large quantities of MSW generated each year necessitate the implementation of appropriate management systems if the additional associated environmental and health impacts should be avoided that would emerge in the absence of suitable treatment facilities[5]. High-income countries can deploy policies and instruments to cope with the rising MSW flows and hence have cleaner and better-organized waste management systems. Examples include the EU Waste Framework Directive 2008/98/EC[6], the 3R's strategy in Japan [7] and the Resource Conservation and Recovery Act 1976[8], 1986 in the United States. However, high-income countries are still mostly not successful in reducing the amount of MSW generated each year[9]. By contrast, low-income countries often lack suitable management systems, which results from the shortage of funds, poor planning, poor implementation of law and lack of technology and expertise [4,10,11]. Additionally, the outsourcing of resource-intensive production and waste exports from high-income to low-income countries exacerbates the environmental problems resulting from inadequate waste management in many of these countries[12]. Often, open burning, littering and poorly managed landfills are the main ways of waste disposal in low-income countries[4]. Open waste burning results in the release of toxic pollutants, e.g., particulate matter (PM), black carbon (BC), organic carbon (OC), carbon oxide (CO), sulphur dioxide (SO_2), among others, and greenhouse gases (GHG) including carbon dioxide (CO_2) as well as smaller amounts of methane (CH_4)[13–15]. Litter harms wildlife and ecosystems, especially marine life. Global marine litter is currently recognized as one of the biggest sources of ocean's pollution[16,17]. Decomposition of organic matter in landfills can result in the release of CH_4[18], a greenhouse gas that is 28 times more potent per kg emitted than CO_2 in a 100 year timeframe[19], and is also a precursor of tropospheric ozone which alters background ozone concentration and therefore impacts human health[20–22]. In addition to the negative impacts on the environment and climate, these unsustainable practices have well documented adverse effects on human health[23–25]. BC and OC, which are components of $PM_{2.5}$, are associated with pulmonary disease, heart disease and acute lower respiratory infection[26–29]. While reducing air pollution has positive health effects, the impact on the climate system is more difficult to assess. Given the complex interaction between air pollutants and GHGs in the atmosphere, polices that aim at reducing both air pollution and GHG emissions at the same time may succeed to reduce some GHG emission at the expense of reducing cooling effects from specific pollutants such as BC[30].

In the past years, research on waste has gone beyond disposal of wastes to assess the linkages between waste and resource use, climate change, air and water pollution. In that context, various studies have looked at emissions from landfills when assessing sectoral and regional contributions to GHG emissions and abatement potentials[31–34]. Further assessments include the annual National Inventory Submissions of all Parties included in the Annex I of the Convention to the UNFCCC which comprise all reporting on GHG emissions and removals[1]. Current estimates are that landfills contribute about 15% to global anthropogenic CH_4 emissions[31]. Other studies show that open burning of MSW is an important contributor to particulate matter and air pollutant emissions[14,35,36], specifically, it contributes 11% to total global $PM_{2.5}$ emissions and 6-7% to total global BC emissions [35,36]. BC from open burning of waste amounts to 2-10% of global CO_{2eq} emissions[37].

However, very few studies comprehensively assess and model MSW at the global scale. A recent study estimates the global trends and environmental impacts of MSW up to 2100[3] in terms of MSW generation, composition, and treatment, as well as environmental impacts. Other studies look at MSW as a potential source of secondary materials and energy. It is estimated that the relative contribution of energy from waste and wastewater to the global primary energy demand could increase from 2% to 9% by 2040 and deliver 64

[1] https://unfccc.int/ghg-inventories-annex-i-parties/2020

EJ of energy per year (1 EJ = 10^{18} Joules) at the end of this period, if circular management systems are installed[38]. Current estimates are that only around 13% of the global MSW generated is recycled and 5.5% composted[4]. In a trend scenario perpetuating current conditions, this share is expected to increase to 39% in 2050 (includes composting and incineration)[3]. Recycling of waste, including composting and anaerobic digestion, can potentially be boosted in a sustainability-oriented scenario, but so far the extent to which that could be achieved has not been quantified.

Clearly, these assessments provide some insights on the contribution of MSW to GHG and air pollutants emissions as well as a source of energy and secondary materials. However, most of them focus on a single aspect of MSW (i.e., emissions from landfills and open burning) rather than on the MSW management system as such. Studies providing evidence of the potential environmental co-benefits resulting from the implementation of circular MSW management systems are still scare. Furthermore, to our knowledge, no global analysis exists that considers differences between urban and rural settings and assesses how MSW generation, composition, management and associated environmental burdens might change under alternative, plausible future scenarios. We here fill that gap. Our main motivation is to contribute to improved understanding how different societal choices could transform MSW management practices in order to address global climate, pollution, and sustainability issues. To our knowledge, this is the first global study to show how the Shared Socioeconomic Pathways (SSPs) can be translated into emission baselines (CLE) and mitigation scenarios (MFR) for the MSW sector.

We present a new method to globally assess the current and future MSW generation in urban and rural areas and associated emissions as well as their implications for ambient $PM_{2.5}$ concentrations for a range of future population and macroeconomic developments to 2050 using the GAINS model as framework. These are represented by the five SSPs and a scenario consistent with the future macroeconomic and population pathways of the IEA's World Economic Outlook 2018[39]. Two variant scenarios are developed for each of the six future socioeconomic pathways; a 'Baseline - CLE' and a 'Maximum Technically Feasible Reduction – MFR', in which circular municipal waste management systems are implemented globally. This means that landfilling of MSW is restrained, material recycling rates are increased, technological improvements and behavioral measures such as reduction of food and plastic waste generation are assumed to be implemented. Emissions of CH_4, CO_2 (fossil fraction), PM2.5, BC, OC, CO, SO_2, NOx, and NMVOCs are calculated for 184 countries/regions (differentiating urban and rural areas) for the period 2010 – 2050. Results are presented at the level of thirteen world regions and the global aggregate. Based on this comprehensive analysis, we quantify the potential reduction of GHG emissions as well as particulate matter and air pollution through circular MSW systems. We also assess which SDGs can be reached or will be failed under the different scenario assumptions. Our detailed representation of the MSW sector and associated emissions and mitigation potentials can be used as input to Integrated Assessments Models (IAMs) applied to develop emission scenarios for the IPCC, support regional and local scale air pollution studies, and inform local and national governments about the likely developments, environmental consequences, and mitigation opportunities in the MSW sector.

Results

Scenarios of MSW generation until 2050

Different socioeconomic assumptions underlying each of the SSPs lead to significant differences in future MSW flows (Fig. 1). The lowest quantities of MSW generation in 2050 are expected in SSP3 and SSP4 due to slow economic growth and inequalities between regions which is reflected in different consumption patterns. By contrast, in the SSP5 both income and urbanization rates increase strongly, resulting in a growth of the MSW generation quantities estimated at to 4296 Tg/yr. Interestingly, in a sustainability-oriented scenario (SSP1) MSW generation is expected to be just 10% lower than that in the SSP5 by 2050. However, when boosting the SSP1 with the adoption of measures targeted at reducing food and plastic waste (SSP1_MFR), it will be possible to reduce MSW generation by an additional 20% compared to SSP5 quantities by 2050.

The amount of MSW generated, its composition as well as prevalent management systems and policies strongly depend on the dynamics of population and economic activity. We parameterized the drivers of MSW as follows: the most important driver of future MSW generation is GDP. Separate elasticities that relate MSW/cap/yr to GDP/cap/yr are estimated for groups of countries representing four different average income levels under the assumption that MSW generation and its composition are highly dependent on average national income levels. The future composition of MSW is recalculated based on the estimated income elasticity of per-capita food waste generation to GDP/cap/yr. MSW composition fractions estimated separately include food, paper, plastic, glass, metal, wood, textile, and other mixed waste.

Quantities and composition of MSW generated differ between rural and urban populations. Data on rural waste generation are available for a limited number of countries. For countries where data on rural MSW generation are unavailable, rural waste generation is estimated by applying ratios of urban:rural MSW generation per capita for each region that were deriving from the available information for limited number of countries (see Methods). While the uncertainty of the estimate might be high, the split into urban and rural MSW quantities highlights where actions are needed to improve MSW management systems at local levels, allowing for better quantification of impacts and consequently serves better for policy design. Our estimates suggest that urban areas are currently responsible for 70% of the global MSW generated. In 2050 urban areas are expected to generated 80% of the total MSW while rural areas are expected generated the remaining 20%, i.e., MSW per capita in rural areas is expected to be 50% lower than in urban areas. In general, rural per capita MSW generation is much lower than those in urban areas due to their smaller purchasing power. However, in high-income countries these differences between urban and rural areas shrink over time.

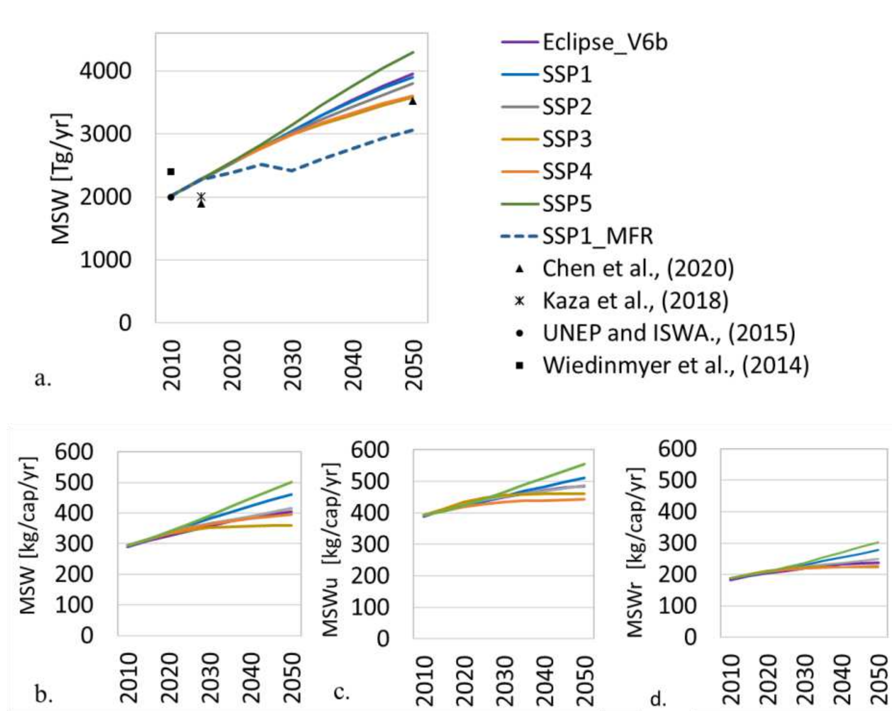

Fig. 1: a. Global total MSW generation. b. Global MSW generation per capita. c. Global urban MSW generation per capita. d. Global rural MSW generation per capita

North America (NAM) is likely to continue having the highest average per capita MSW generation in both urban and rural areas by 2050, followed by Oceania and Europe. China is expected to have the highest growth in MSW generation per capita for urban and rural areas increasing by about 45% compared to 2015. The reason is the stronger economic growth expected in China over the next decade [41]. India is expected to generate about 13% less MSW than China in 2050 across all scenarios. Even though South Asia (SASIA) and Latin America and Caribbean (LCAM) had similar average per capita MSW generation for both urban and rural areas in 2015, per capita MSW generation in Asia is expected to overtake LCAM in 2050 by about 15%. Even though Africa will experience the highest increase on MSW generation compared to 2015, it is likely to continue having the lowest MSW generation per capita in the future (Fig. 2). Supplementary Results. S1 displays total, urban, and rural waste generation by region and scenario.

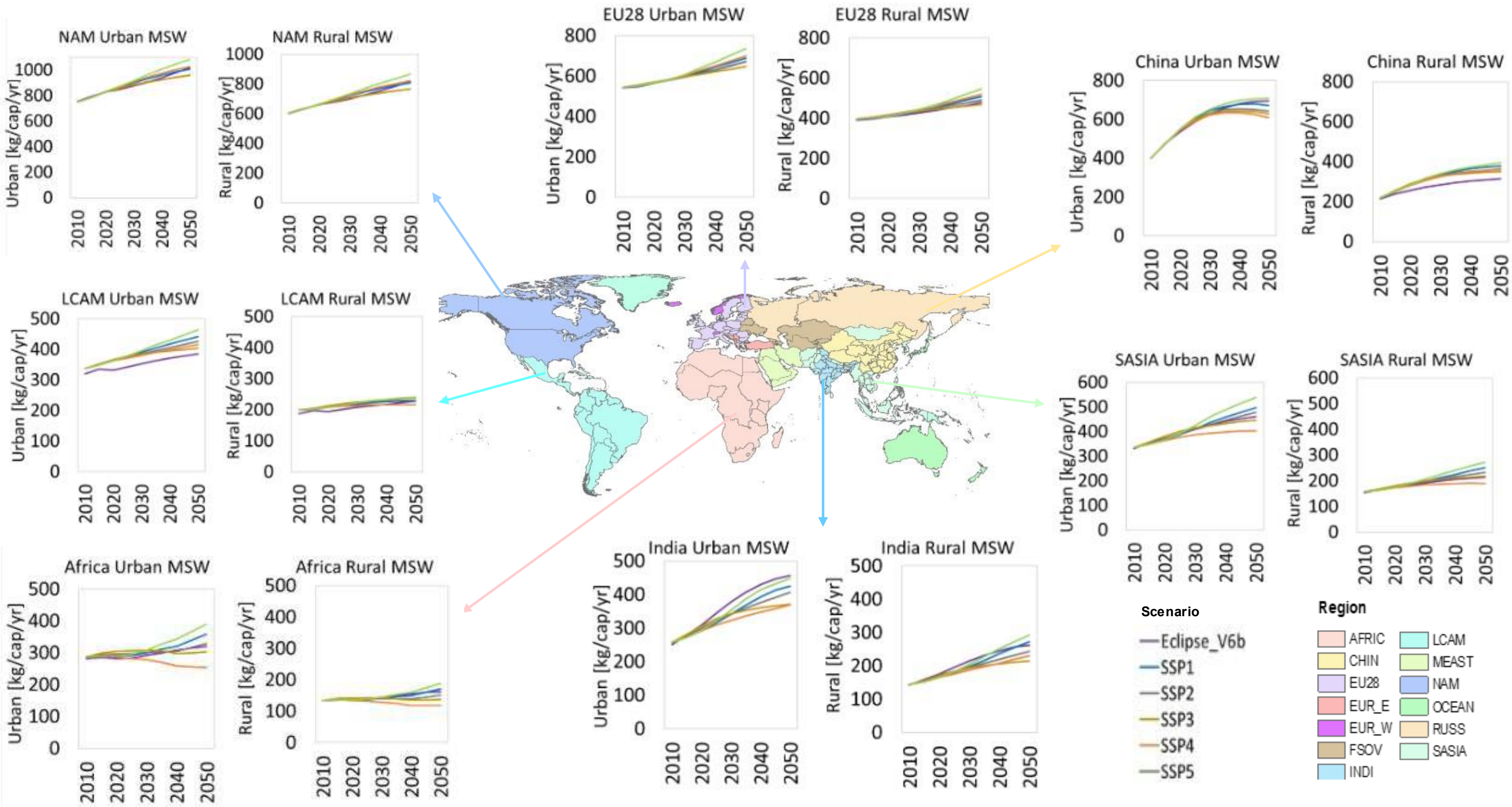

Fig. 2: Municipal solid waste (MSW) generation rates in urban and rural areas by scenario. For high-income regions as NAM and EU28, MSW per capita will remain pretty the same independent of the underlying socio-economic pathway. However, the different pathway trajectories have a strong influence on MSW per capita generation in low, and middle-income regions.

Unfortunately, regions generating the highest amounts of MSW quantities per year have the lowest collection rates and the poorest MSW management systems. Average MSW collection rates in Africa, India, SASIA, and China are estimated to be in average of about 50% - 60%, having urban areas collection rates of ~70% and rural areas ~40%. Moreover, the unsuitable management (i.e., disposed in dumpsites or burned without air pollution controls), of the collected fraction exacerbates the already precarious situation. Based on the detailed MSW activity and management strategies matrix of the GAINS model which comprises eight MSW streams and fourteen treatment technologies [38], our estimates suggest that in 2015, 43% of the global MSW collected ended up either in landfills (13%) that are compacted and/or covered but not meeting environmental standards to prevent leakage[42], in unmanaged landfills without any type of management (hereafter referred as dumpsites) (21%), or was openly burned (9%) either directly at the dumpsites (including unintended fires) or in transfer stations. The remaining 29% of the collected waste was either disposed in sanitary landfills (10%), incinerated (high quality with air pollution controls and energy recovery) (7%), recycled (7%), or composted or anaerobically digested (4%), which is mostly happening in high-income countries. From the uncollected fraction, around 20% is estimated to be scattered MSW with a high probability of eventually reaching water courses and 10% openly burned (Fig. 3). The latter estimates are based on global assessments and detailed country-level studies presented in Table 1 in the methods section.

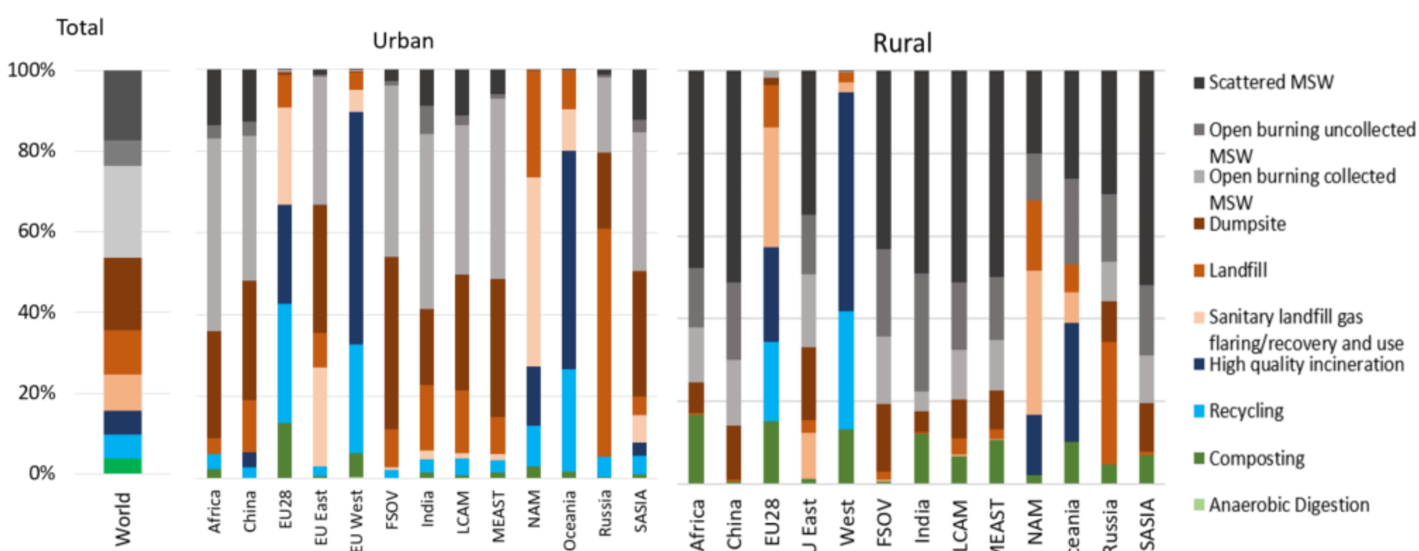

Fig. 3: Municipal solid waste (MSW) management in 2015. Urban areas in low-middle income regions have increased MSW collection rates in last years. However, MSW treatment has not improved at the same pace, hence most of the waste is dumped, scattered or is subject to open burning. Rural areas face an even more challenging situation as in low-middle income regions collection rates are just about 35% - 45%. In general, high-income regions have established suitable MSW treatment systems in both urban and rural areas.

Despite legislation banning open burning of MSW in most of the countries, our calculations indicate that around 16 % of global MSW generated (whereof 55% collected and 45% uncollected), was openly burned, which is equivalent to 380 Tg/yr and 394 Tg/yr in 2010 and 2015, respectively. While in urban areas about 60% occurs either on transfer stations or dumpsites i.e., in the collected fraction, in rural areas is estimated that about 80% of the burning occurs in the uncollected fraction. Rural areas often lack appropriate MSW management systems and therefore the uncollected waste is usually subject to be dumped, scattered or openly burned[43].

If current MSW management strategies are maintained into the future, the expected quantities of MSW disposed of in dumpsites and openly burned would rise proportionally to the increase of MSW quantities. In contrast, in an ideal situation where a circular MSW management system (MFR), is implemented globally, it would be probable to avoid almost all dumping and open burning of MSW in 2050, thereby eliminating the environmental and health burdens associated with current management practices. Circular MSW management systems include restrained landfilling of MSW, increase material recycling rates, technological improvement, and implementation of behavioral measures such as reduction of food and plastic waste generation.

Emissions to air

Our estimates indicate that current CH_4 emissions from MSW handling account for 8 % (28 Tg/yr) of the global CH_4 anthropogenic emissions estimated at 344 Tg/yr in 2015[31]. Under the current management strategies, baseline CH_4 emissions in 2050 are projected to rise by a factor between 1.7 (SSP3_CLE) and 2 (SSP5_CLE) over the amount observed in 2015, increasing the contribution of MSW to 13% of the projected global CH_4 anthropogenic emissions estimated at 450 Tg/yr in 2050[31]. At the regional level, China, NAM, LCAM, and SASIA emitted the higher CH_4 from MSW in 2015. If current conditions are maintained until 2050, then India, Middle East, Africa and SASIA will face the highest growth in CH_4 emissions from MSW, with an increase of about 60% compared to 2015 levels. The expected rise of the CH_4 emissions on those regions is due to the increase of MSW generated, couple with the MSW (mis)management as scattered MSW, dumpsites and precarious landfills (cover or compacted without leakage controls or gas recovery) are the main options to deal with the MSW generated thereby increasing CH_4 emissions.

CH_4 emissions from waste deposited of in landfills today will be generated in future years as it depends on the degradability of the organic matter[18]. MSW generation quantities, composition and policy adoption at early stages makes a significant difference in the trends of CH_4 emissions through the years. In a world implementing circular MSW management systems, the maximum diversion of MSW from dumpsites by 2030 is reached in SSP1_MFR with 91% less compared to the baseline. This is the result of the adoption of MSW reduction measures, speedy implementation of anaerobic digestion to treat organic waste and the establishment of source separated MSW collection systems to increase the recycling of materials. Total elimination of this practice is expected to happen around 2035 in this sustainability-oriented scenario. The adoption of measures is comparatively slower in scenarios depicting high inequalities between and within countries. Therefore, the diversion of MSW from dumpsites takes more time resulting in higher future CH_4 emissions. With the exception of SSP1_MFR in which CH_4 emissions are projected to decrease by 4% in 2030, an increase of about 1%-2% is expected to happen in all other MFR scenarios compared to the corresponding CLE. The maximum CH_4 emission reduction potential by 2050 will be reached in the SSP1_MFR in which CH_4 emissions are expected to decrease by 87% compared to the baseline, thus leaving still 182 CO2eq of CH_4 to be released in 2050. Other scenarios are expected to release more CH_4, namely, SSP3_MFR will leave 646 CO2eq of CH_4 and SSP5_MFR 292 CO2eq of CH_4 to be emitted by 2050 which is 50% and 80% lower compared to the respective CLE counterparts (Fig. 4).

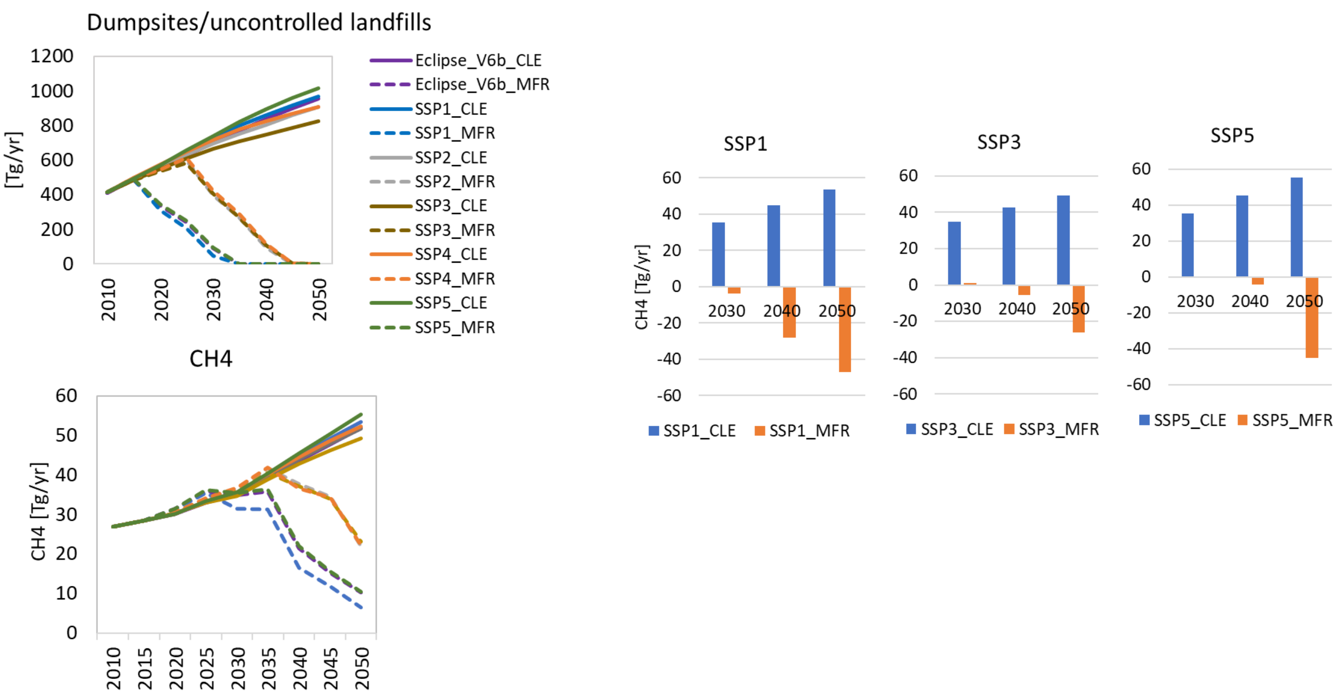

Fig. 4: Global CH_4 emissions under CLE and MFR scenarios. Faster adoption of measures improving MSW systems will result in an early decrease of MSW ending up in dumpsites/uncontrolled landfills and therefore brings quicker reductions of future CH_4 emissions from this source. Supplementary Results S2 presents a detailed analysis of the MFR scenarios.

Emissions of particulate matter and air pollutants depend on the quantities of MSW subject to open burning. Our results suggest that open burning of MSW is responsible for 3.5 Tg/yr of $PM_{2.5}$ in 2015. BC emissions are estimated to be 7% and OC 60% of the $PM_{2.5}$ emissions. Overall, $PM_{2.5}$ emissions from MSW account for 8% of the total global anthropogenic $PM_{2.5}$ emissions. Global anthropogenic BC emissions are estimated at 6.0 Tg/yr (GAINS) of which , following our results, 6% are from MSW burning (see supplement Table S3 for estimates for all pollutants). At the regional level, our calculations indicate that SASIA plus India, China, Africa, and LCAM emitted 89% of the particulate matter and air pollutants from MSW. India and China contributed about 50% and Africa 21% and LCAM the remaining 18% to those aggregate flows in 2015. Although open burning of MSW occurs in the collected and uncollected fraction in both urban and rural areas, most of emissions come from the collected MSW in urban areas. For example, in Indian cities waste handlers burn waste, despite being aware of the ban, mainly due to lack of infrastructure and to prevent accumulation[44]. Furthermore, with the projected growth of MSW generation and if the current conditions prevail into the future then the anticipated global emissions of particulate matter and air pollutants from MSW are expected to nearly double in 2050 for all SSPs. SASIA, India, Africa, China and LCAM are expected to be responsible for 93% of the emissions. Future emissions in the CLE scenarios will increase proportionally to the quantities of MSW open burned. Consequently, the reduction of the fraction of MSW being openly burned translates directly into the same particulate matter and air pollutants emission reduction levels (Fig. 5). In that sense, in the SSP1_MFR, SSP5_MFR and ECLIPSE_V6b_MFR scenarios will be feasible to virtually eliminate open burning and therefore this source of air pollution already in 2030 while in the other scenarios this could potentially happen 10 to 15 years later.

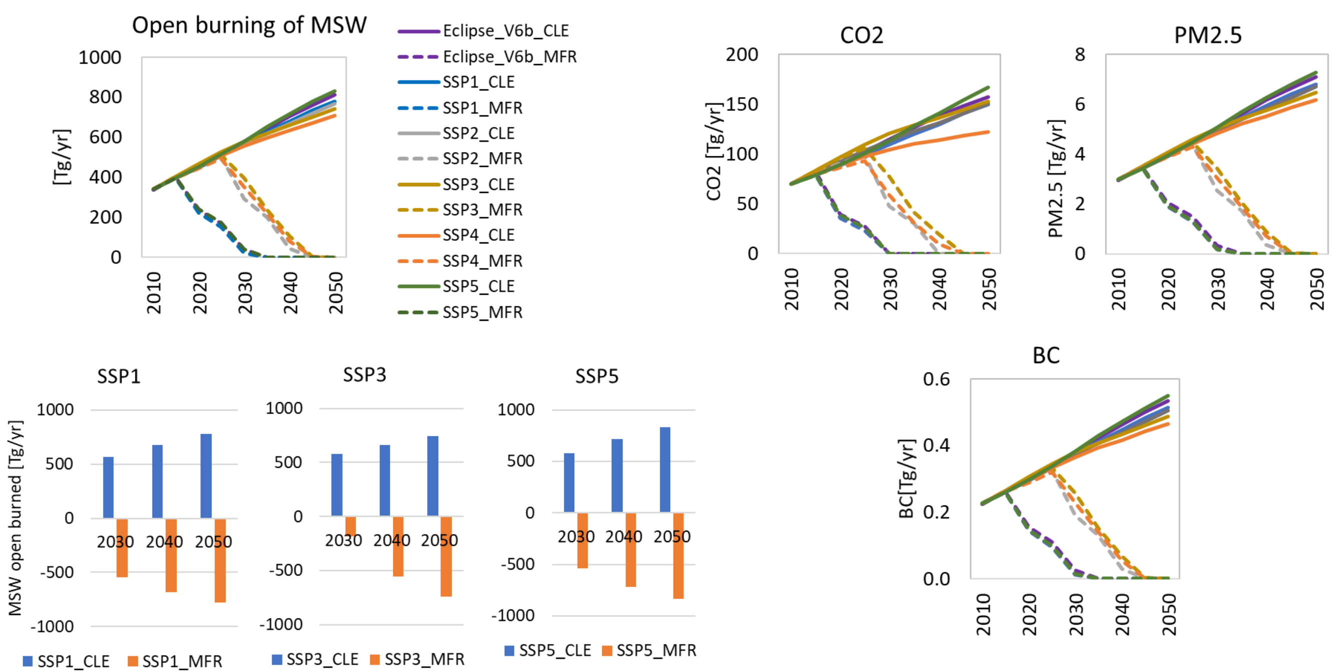

Fig. 5: Global amounts of MSW open burned and related emissions under CLE and MFR scenarios. Reduction fractions of MSW open burned result in the same reduction percentage of particulate matter and air pollutants. Supplementary Results S2 presents a detailed analysis of the MFR scenarios.

At a regional level (Fig. 6), the pre-conditions of the MSW management systems in Europe, Oceania and to certain extent NAM show that the level of effort required to reduce emissions is similar across scenarios. This is the result of the historical evolution on MSW management systems together with the already high-income level and appropriate political arrangements in most of these regions. By contrast, all other regions show high variation across scenarios due to the different dynamics. When comparing the scenarios for regions such as China, India, SASIA, and LCAM, we see that in a sustainability-oriented scenario (SSP1_MFR) a speedier decrease in emissions is observed in urban and rural areas compared to the other scenarios. Moreover, the adoption of circular MSW management systems is slower in scenarios representing a world in which inequalities persist resulting in big differences between urban and rural areas. Consequently, higher emissions are expected across the years.

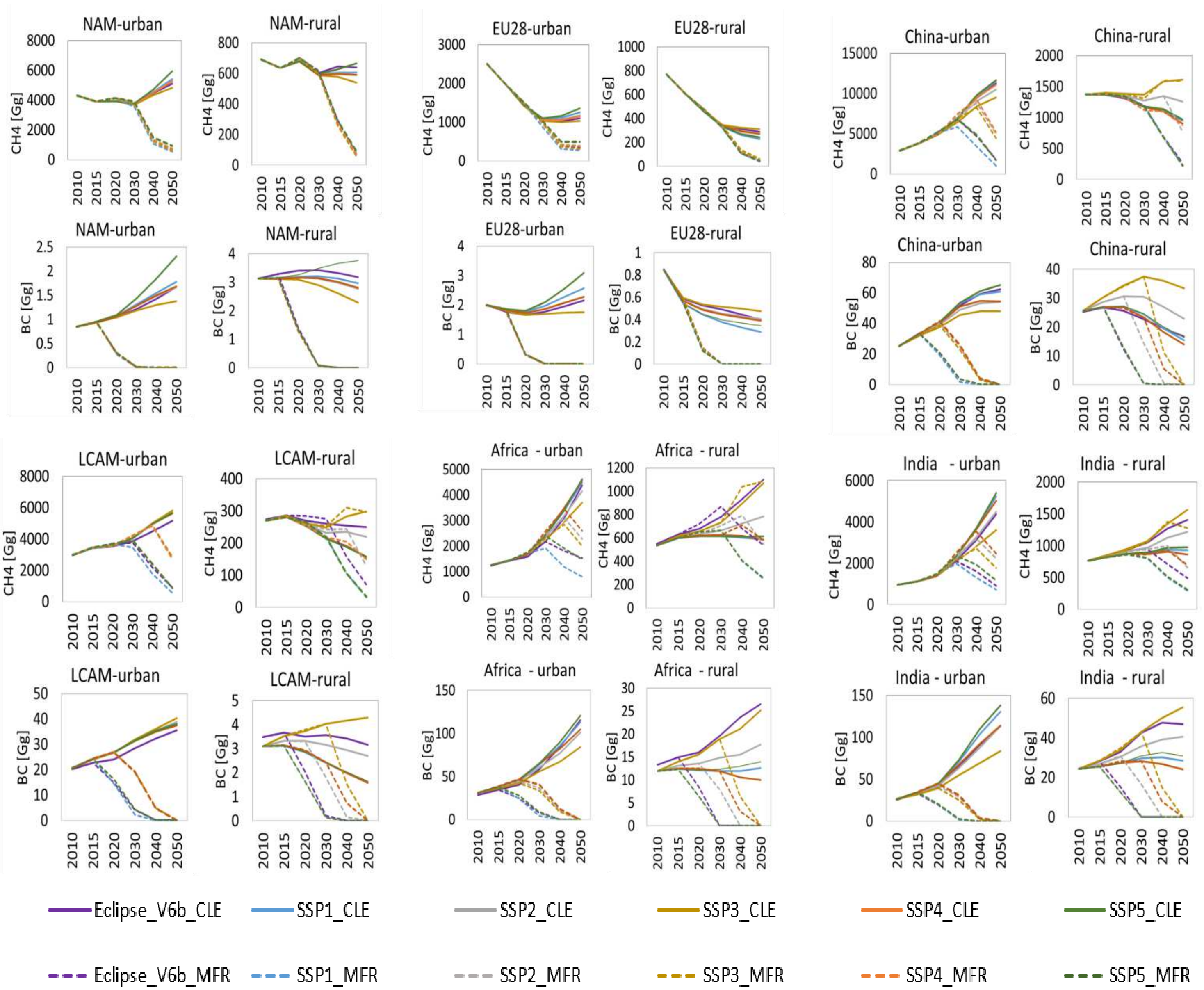

Fig. 6: Regional emissions of CH_4 and BC from MSW. The target of all modelled scenarios is set to reach ~100 % of MSW collection and management by 2050. The environmental co-benefits will be obtained at different levels upon the level of socio-economic development and political and institutional arrangements. The different assumptions on policy interventions are then translated into a wide range of future emissions.

As emissions from MSW burning contribute significantly to ambient $PM_{2.5}$, particularly since the sources are often low-level and spatially located close to population, the improvement of MSW management will also have benefits in ambient $PM_{2.5}$. To illustrate the possible contributions and mitigation potential from this sector, we here quantify the contribution of MSW to $PM_{2.5}$ levels in different world regions. Calculations follow the approach applied in ref[45] and are briefly described in the Methods section below. Differences between the scenarios are driven both by emission changes as well as urbanization trends. Concentrations are highest in India and other South Asia and are expected to grow further under CLE following the emission trends. Other developing regions show similar growth trends but lower absolute concentrations. In China, initial increases level off, peaking around 2035 (SSP1,2,3,4) or 2050 (SSP5). In Europe, North America and Oceania, contributions from MSW burning are much lower since the combustion happens in well-controlled installations and not as open burning. Gradual implementation of better practices and emission controls eventually decreases concentrations to ~zero before 2050 in all MFR cases, although this is achievable at different points in time depending on the SSP storyline.

Discussion

Here we present for the first time a systemic assessment of reduction potentials of GHGs and air pollutants emissions from implementing circular MSW management systems under six future socio-economic development pathways. The assessment includes the development of two scenarios, namely baseline (CLE) and maximum feasible mitigation potential (MFR) for each of the pathways. The explicit representation of urban and rural MSW generation, composition and management allows for a deeper analysis of future plausible management and emission trends. This study can assist national, regional, and local governments in developing strategies to limit the release of emissions into the environment as well as support assessments of feasibility and progress in achieving the UN Sustainable Development Goals (SDGs).

Our results show that future MSW generation quantities are expected to be between 1.7 to 2 times higher in 2050 compared to current levels in all scenarios. Our results also highlight that urban areas are responsible for about 80% and will continue being responsible for the higher share of MSW generated in the future. The generally high collection rates of MSW in urban areas does not necessarily imply appropriate management. In SASIA, India, China, LCAM and Africa about 80% of the collected MSW is either dumped or openly burned. Furthermore, most of the MSW generated in rural areas is uncollected and thus ends up being illegally dumped, scattered, or openly burned resulting in several environmental impacts related to air pollution and greenhouse gas emissions and other health and environmental impacts out of the scope of this study. Our findings also indicate that in urban areas about 60% of the open burning occurs either on transfer stations or dumpsites i.e., in the collected fraction, while in rural areas is estimated that about 80% of the burning occurs in the uncollected fraction.

In the baseline (CLE), in which current MSW management practices persist without further policy implementation, emissions to air would increase proportionately to the growth in MSW generation. We then developed a set of mitigation scenarios (MFR) to assess the impacts of abatement measures compared to the corresponding baseline (CLE). The common target of our MFR scenarios is to achieve ~100% of MSW collection and treatment by 2050 through the implementation of circular MSW management systems to simultaneously tackle emissions of CH_4, CO_2, particulate matter, and air pollutants. Co-benefits are obtained at different stages upon the level of socio-economic development and political and institutional arrangements. Evidently, all countries would benefit from reduced MSW generation and improved management in the sustainability-oriented scenario (SSP1_MFR), however, the additional benefit of respective measures are especially relevant for regions generating large MSW quantities and lacking suitable management systems. We show that the environmental co-benefits of avoided MSW generation combined with the speedy implementation of anaerobic digestion to treat organic waste and the establishment of source separated MSW collection to increase the recycling of materials (SSP1_MFR) yields major and earlier co-benefits in terms of reducing CH_4, particulate matter, and air pollutants. However, more ambitious sustainability-oriented scenarios are crucial to meet the waste related SDGs, specially the 6.3 target which aims at "*By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally*"[46]. We demonstrate that under the current SSP1_MFR, it will not be possible to totally eliminate scattered and open burning of MSW by 2030. Under this scenario the realization of the objective will be obtained five years later i.e., in the year 2035.

Our analysis also suggest that in 2030, 881 Gg CO_2eq of CH_4 (GWP_{100} of 28 CO_2eq[19]) will still be released in the SSP1_CLE. Nonetheless, this is 13% lower compared to the CH_4 emissions expected in the SSP2_CLE, SSP3_CLE and SSP4_CLE and 11% lower in comparison to the SSP5_CLE and Eclipse_V6b_CLE. Considering that in 2030 high emissions of CO_2 from open burning of MSW would still be released in SSP2_MFR, SSP3_MFR, SSP4_MFR, the total average GHG emissions (CH_4, and CO_2) in these scenarios will sum up to an average of about 1079 CO_2eq, that is 18% higher than the emissions expected in the SSP1_MFR. In 2050, SSP1_MFR leaves 182 Gg CO_2eq of CH_4, to be released. That is 37% lower than the SSP5_MFR and Eclipse_V6b_MFR and 3.5 times lower than the expected emissions in the SSP3_MFR. These variation in emissions can make a substantial difference when considering that the world should stay below 1.5 degrees global warming i.e., the world can emit as maximum as 10 Pg CO_{2eq}/yr of all GHGs in 2050[47].

The reduction of MSW being openly burned translates into the same reduction level of emissions of particulate matter and air pollutants. Under the development of SSP1_MFR, SSP5_MFR and ECLIPSE_V6b_MFR, the maximum emission reduction potential will be realized in 2030 whereas in the SSP2_MFR will take 5 years more i.e., in 2040 and for the SSP3_MFR and SSP4_MFR 10 years more i.e., in 2045. At the same time, MSW combustion contributes to ambient $PM_{2.5}$ – in some world regions, this contribution is substantial. Most low-income countries, and particularly those with already high concentrations, show an increasing trend from this source under all SSPs, highlighting the importance of counteracting. The positive message is that mitigation is possible and the MSW contribution to ambient $PM_{2.5}$ can be virtually eliminated by 2050. However, this will not happen by itself.

Comparison to other studies: Our calculations suggest that the world generated 2289 Tg/yr of MSW in 2015. Estimates from other studies vary from 1999[3] to 2010[4] Tg/yr for the same year. Past assessments estimated global MSW generation between 2000[48] to 2400 Tg/yr [14] in 2010. Looking at MSW generation projections, our estimate for the SSP3 and SSP4 in 2050 are similar to the 3539 Tg/yr projected by Chen et al., 2020 (ref [4]). Our calculations suggest that although the SSP1 represents a sustainability-oriented pathway, MSW quantities in the baseline are foreseen to reach 3901 Tg/yr in 2050, which is only 10% lower than the expected MSW amounts in the SSP5. Our projection for MSW generation in the SSP2 is 3801 Tg/yr while ref[3] estimated a MSW generation of about 3500 Tg/yr in 2050 for the same scenario. However, this estimate is more comparable with our SSP3 and SSP4 projection. The ECLIPSE_V6b_CLE (3948 Tg/yr) is comparable to the SSP1. At the regional level, we find that India is expected to generate about 13% less MSW than China in 2050 across all scenarios. This contrasts findings ref [4], in which projected MSW generation in India was about 40% higher than the projection for China in 2050. However, our finding for India is in line with the projection carried out by ref [49]. Furthermore, the average per capita MSW generation in China is projected to be between 30% - 40% higher than those in India. The fact that estimates for 2010 are lower than those in 2015 and the variability of the results reflect on the one hand, the uncertainty of the data and on the other hand the differences of the methodologies used to derive these numbers. Furthermore, Our estimate of MSW openly burned is 61% lower than the estimate of ref[14], who estimated that 40% or an equivalent of 970 Tg/yr of total MSW generated in 2010 was openly burned (whereof 64% at residential sites and 36% at unmanaged dumpsites) and 57% higher than the estimate of ref[36], who estimated that about 115 Tg/yr– 160 Tg/yr of MSW was openly burned in 2010. Differences in estimated quantities can be attributed to variations in the per capita MSW generation rates adopted referring partly to different data sources, but also to differences in the methodology used to estimate the fraction of waste openly burned. While the assumption in ref[14] refers to a fraction recommended in the IPCC (2006) guidelines, we develop our own method which we believe better represents the complexity of the MSW sector e.g., in terms of the urban-rural split and the country/region-specific MSW composition and MSW management pathways (see Methods). The differences of the estimates puts a magnifying glass on the urgency to develop national standardized MSW reporting systems, which in addition of being key to governments for the implementation and evaluation of MSW treatment, can serve as part of the monitoring system of GHGs, air pollution and SDGs.

Our estimations indicate that current CH_4 emissions from MSW handling account for 8 % (28 Tg) of the global CH_4 anthropogenic emissions estimated at 344 Tg in 2015[31]. Our estimate is 17% lower than the one estimated by ref[35] and which has been adopted within the CMIP6 project [50]. It is difficult to assess the level of agreement between both studies as estimates from ref[35] include MSW and industrial waste while the focus of this study is on MSW and the importance to properly represent the sector for climate and air pollution assessments. However, comparing CH_4 emissions from MSW in the Eclipse_V5a [36] to this study, we can see that the estimate in the latter is 30 Tg /yr or 6% higher.

Recent global CO_2 emissions area assessed at of 39153 Tg/yr in 2015, whereof 130 Tg/yr or 0.33% are generated from waste combustion (including industrial and municipal sources) [35,51]. Ref[14] calculates CO_2 emissions from open burning of MSW of 1413 Tg/yr in 2010, estimate that is around 10 to 15 times higher than that from ref[35,51] and the one from this study.

In 2010, emissions of $PM_{2.5}$, BC, and OC have been assessed at 6.1, 0.6 and 5.1 Tg, respectively[14]. Our estimates are comparatively lower to those results. In contrast, our results for particulate matter are 60% higher than those from ref [36]. In both cases the differences are related to the assumed quantities of MSW openly burned. Other studies[35,51] have estimated BC and OC emissions from waste of 0.7 Tg and 4.2 Tg [35], respectively (Supplementary Results S3 show a comparison of different studies for different pollutants).

Conclusions

Significant potentials exist to reduce GHG, and air pollution provided the implementation of circular MSW management systems. The 6.3 target of the SDG 6 can only be achieved through more ambitious sustainability-oriented scenarios that limit MSW generation and improve management. Similarly, these kinds of scenarios can directly contribute to the achievement of other SDGs, especially SDG 7, 9, 12, 14 and

15. Our results highlight the importance of acting at various fronts, namely, consumers behavior, technological development, technology transfer and institutional coordination. For instance, the benefits from reduction of MSW generation can be jeopardized by social and economic inequalities between and within regions which could restrain the adoption and implementation of measures to improve MSW management systems. Furthermore, for a world focused solely on end-of-pipe solutions will be also beneficial the implementation of policies targeted at reducing MSW generation. The finding is that the development of measures at the consumer side will not bring the expected benefits in terms of emissions reduction if quicker and responsible actions are not taken to bring MSW management systems as an important point in governmental agendas. Finally, we see that the majority of countries have developed some kind of legislation regarding the improvement of municipal solid waste management systems, however, the compliance is highly uncertain. A solid system for the reporting of MSW couple with a transparent systematic follow-up of policy enforcement will help to reduce the uncertainty of the estimates as well as will provide clearer insights into the efforts needed by countries to meet their climate, air pollution and SDGs commitments.

Methods

The methodology for developing MSW generation scenarios and associated greenhouse gas and air pollutant emissions involves the following five elements: 1. Socioeconomic drivers are taken from the Shared Socioeconomic Pathway (SSP) Scenarios for the five SSPs[52] and from the World Energy Outlook and UNDESA[53] for the Eclipse_V6b_CLE (Supplementary Methods S4 presents a short description of the SSPs storylines). 2. The country-specific generation in per capita MSW is driven by expected growth in average per capita income as described in the Supplement of ref [38] and further developed in this study (Supplementary Methods Fig. S2 and Fig.S3 show GDP per capita and urbanization rates) . 3. Estimation of emissions draw on the methodologies presented in ref [33,36,54], but are extended to improve source-sector resolution and accommodate for new, MSW sector-specific, information. 4. Implementation of the current legislation for waste management adopted before 2018. 5. Implementation of circular waste management systems are developed in accordance with the EU's waste management hierarchy - Directive 2008/98/EC[6]. The IIASA-GAINS model is used as a framework to carry out this assessment.

Municipal waste generation (MSW) activity and its characteristics.

Current MSW generation quantities, composition, collection rates, and waste management practices are retrieved from several sources, including national official statistics, peer-reviewed literature, and technical reports (see supplement of Gómez-Sanabria et al., 2018). The driver used to project future per capita MSW generation is GDP per capita. This is linked to MSW generation using elasticities estimated following the methodology first developed in ref[33] and further developed in ref [55]. This methodology is further developed in this study (Supplementary Methods S6). Separate elasticities are estimated for groups of countries representing four different average income levels under the assumption that MSW generation and its composition are highly dependent on average national income levels. Furthermore, MSW composition is recalculated based on the estimated income elasticity to per capita food waste generation. MSW composition fractions estimated separately include food, paper, plastic, glass, metal, wood, textile, and other waste. This last fraction includes ordinary mixed waste and may in some cases also include bulk waste.

Quantities and composition of MSW generated by rural and urban population are different. Data on rural waste generation is available for a limited number of countries, when underlying data on rural MSW generation is unavailable, rural waste generation is estimated by applying different shares related to the specific urban MSW generation rate per capita within specific region and using Eq. (1). This approach is likely to be an improved version of the one-half rural-urban waste generation ratio used by some studies [4,56] because it captures the differences between regions (Supplementary Methods S7 presents the adopted rural urban rates for different regions).

$$MSW_u = MSW_t * \left(\frac{P_u}{P_u + \left(R_{(r/u)} * P_r \right)} \right) \quad (1)$$

$$MSW_r = MSW_t - MSW_u$$

where MSW_t is total MSW generated in a country/region, MSW_u and MSW_r are MSW generated in urban and rural areas, respectively, $R_{(r/u)}$ represents rural per capita MSW generation as a fraction of the per capita urban MSW generation, and P_u and d P_r is rural are urban and rural population, respectively.

Open burning of MSW.

In countries without proper implementation of waste legislation, waste mismanagement is aggravated by poor waste separation at the source, low collection rates and low budget allocated to the waste sector [40]. In the absence of reliable waste management systems, dumping and open burning of MSW, either at residential or dumpsites, become the only alternatives to reduce waste- volumes [13,14]. Total MSW openly burned is estimated here as the sum of the fractions of uncollected MSW openly burned and collected MSW openly burned at dumpsites and transfer stations in urban and rural areas. The starting point to derive the quantities of MSW openly burned is the total MSW generated in urban and rural areas. Waste amounts are then split into collected and uncollected waste for urban and rural areas, respectively. Collected waste includes MSW collected by official authorities but also (recyclable) waste collected by the informal sector. Information on collection rates is gathered from sources presented in [55] and complemented from information available in [4,56]. The fraction of uncollected waste is then split into scattered waste or waste openly burned. The fraction of uncollected waste openly burned is assigned based on the information presented in Table 1, considering the current implementation of waste related legislation, income level, collection rates, and urbanization rate of each region. The fraction of collected MSW openly burned is estimated at 10% - 20% of the waste ending up in dumpsites, partly due to self-ignition resulting from poor management and partly due to deliberate burning to reduce waste volumes. In addition, a fraction of the collected waste is assumed to be burned at the transfer station or before reaching the disposal site, which is the case in several developing countries [57]. Fractions of MSW openly burned, either on the streets or at dumpsites and transfer stations, are dependent on the improvement of the MSW management systems and enforcement of the waste and air pollution legislation. Improvement of waste treatment systems results in reduction of the frequency of MSW openly burned [58]. The quantification of these fractions is however highly uncertain. Literature provides a few different methodologies to estimate the amounts of waste openly burned (Table 1). The IPCC (2006)[18] suggests 0.6 as a representative value for the fraction of total available waste to be burned that is actually openly burned. This assumption is used by Wiedinmyer et al., 2014 to estimate GHGs and air pollutants from open burning of waste. Bond et al., (2004)[59] assumed lower rates of open burning of waste in rural areas in developing countries based on the statement that most of the waste in rural areas is biodegradable. Table 1 also shows that in many cases the default representative value of the IPCC maybe inadequate for several regions.

In general, the quantification of MSW openly burned in region i and year y - $MSW_{(ob)iy}$ is calculated as the sum of MSW openly burned in urban areas $MSW_{(obu)}$ and MSW openly burned in rural areas $MSW_{(obr)}$ applying Eq (2).

$$MSW_{(ob)iy} = MSW_{(obu)iy} + MSW_{(obr)iy} \tag{2}$$

Where,

$$MSW_{(obu)iy} = [(MSW_{(u)iy} * C_{(u)iy} * (ß_{0u} + ß_{1u})) + (MSW_{(u)iy} * (1 - C_{(u)iy}) * ß_{2u})]$$

$$MSW_{(obr)iy} = [(MSW_{(r)iy} * C_{(r)iy} * (ß_{0r} + ß_{1r})) + (MSW_{(r)iy} * (1 - C_{(r)iy}) * ß_{2r})]$$

Where, $MSW_{(u)iy}$ and $MSW_{(r)iy}$ are the total amounts of MSW generated in urban and rural areas, respectively. $C_{(u)iy}$ and $Coll_{(r)iy}$ are the MSW collection rates in urban and rural areas, respectively. $ß_{0u}$ and $ß_{0r}$ represent the fractions of collected MSW openly burned on transfer stations and $ß_{1u}$ and $ß_{1r}$ represent the fractions of collected MSW openly burned at dumpsites in urban and rural areas, respectively. $ß_{2u}$ and $ß_{2r}$ are the fractions of uncollected waste openly burned in urban and rural areas, respectively.

Emission estimations.

Emissions of non-CO_2 greenhouse gases and air pollutants (*E)* by source *(s)* and region (*i)* are calculated in GAINS using Eq (3) [54]:

$$E_{it} = \sum_{sit} A_{is} * ef_{sm} * Appl_{itsm}$$

where A_{is} is the activity data, i.e., the amount of MSW generated before management, ef_{sm} is the emission factor subject to technology *m,* and $Appl_{itsm}$ is the application rate of the technology *m* to the activity A_{is}. The GAINS model matrix comprises fourteen different MSW waste management technologies including different types of source separation, recycling and treatment, different types of solid waste disposal sites and different types of incineration technologies and open burning of waste (Supplementary Methods 8). This extensive characterization of alternative treatment flows allows for a detailed representation of the solid waste management system and its emissions at the national/regional level. Emission factors for CH_4 and CO_2 are developed according to the 2006 IPCC Guidelines, Volume 5, Chapter 3 and Chapter 5[18]. PM emission factors are adopted from ref [36]. These are 8.75 for $PM_{2.5}$, 5.27 for OC and 0.65 g/kg for BC. Emission factors for SO_2, NOx and NMVOC are adopted from ref[60] and are consistent with ref [14]. These are 0.5 for SO_2, 3.74 for NOx, and 7.5 g/kg for NMVOC. The $PM_{2.5}$ concentrations are obtained using the annual $PM_{2.5}$ emissions applying a simplified version of the atmospheric calculation in the GAINS model [45]. Those estimates build on a linearized representation of full atmospheric chemistry model simulations. Here, an atmospheric transfer coefficient is developed to related $PM_{2.5}$ emissions to ambient $PM_{2.5}$ concentrations from MSW burning.

Description of the scenarios.

The baseline scenarios associated with the six socio-economic pathways describe the expected developments of municipal solid waste generation and management systems under current legislation ‘CLE’, hereafter baseline , i.e., assuming no further policies affecting the MSW sector are adopted until 2050. In addition, for each baseline an alternative scenario is constructed, which considers full implementation of circular MSW management systems globally and is referred to as the maximum technically feasible reduction 'MFR' scenario, hereafter mitigation scenario. Note that the technical frontier is explored here without taking account of the cost to implement various waste management strategies.

The MFR scenario is developed according to the SSP narratives and assumes a maximum technically feasible phase-in of a waste management system that is fully consistent with the EU's waste management hierarchy (Directive 2008/98/EC)[6]. This means that a first priority is given to technologies that circulate materials, thereafter to technologies that recover energy, and only as a last resort to well managed landfills. The following maximum recycling potentials of waste streams are applied: 90% of municipal paper and textile waste and 80% of municipal plastic and wood waste can be recycled. It is further assumed that 100% of food waste can be source separated and treated in anaerobic digesters with biogas recovery. These MFR potentials are adopted in consonance with the socioeconomic development for each scenario. Supplementary Methods S9 presents a description of the MFR management narratives specified for each scenario along with the regional aggregation.

Uncertainty

Regarding uncertainty, several data inputs (activity data, emission factors, type of management) go into the estimations and therefore is difficult to do a quantitative uncertainty estimation[3,14]. Historical estimates of MSW generation, collection, management, and related emissions have associated uncertainties resulting from the different definitions of MSW coupled with contradictory reported values for generation and composition. The quality of the data suffers from inconsistencies in the definition of MSW generation across countries [56]. In some cases, amounts reported for MSW generation correspond to the gross quantities of waste collected and in other cases to the MSW quantities left for landfill after quantities separated for treatment have been deducted [61]. In developed countries, in particular in Europe, MSW covers household waste and waste that is similar in nature and composition . In developing countries, data on waste suffers from incomplete characterizations and clear definitions of the fractions and source sectors included in the

MSW are often lacking. These uncertainties are relatively high in developing countries compared to developed countries as in various cases data availability is quite limited in the former case[3]. Additionally, some data reported for generation and collection refers to urban areas rather than national totals [4,40], which makes necessary to adopt assumptions based on dedicate studies for particular regions and expert knowledge to arrive at reasonable national MSW generation rates and attributions to urban and rural waste amounts. These uncertainties become bigger when estimating fractions of MSW openly burned as this information is in most of the cases not attainable. Moving to emission factors, CH_4 emission factors are based on the IPCC Guidelines 2006[18], thereby carry out the uncertainties there described. Emissions factors for air pollutants and particulate matter depend on the composition of waste and burning conditions. Although we adopted the most recognized emission factors in the scientific arena, we acknowledge that large uncertainties are related to the values (uncertainties can be seen in ref[14]). Concerning uncertainty in projections, this is by some means assessed by adopting alternative activity scenarios which allows the comparison of the different estimates and reflect the sensitivities of the proposed measures to input assumptions[63]. In general, there is a global need to improve information on MSW generation rates, treatment and level of policy implementation[3]. Regardless of the uncertainties, we demonstrate the importance of improving global estimates of GHGs and air pollutant emissions from MSW and highlight the considerable role of this sector when assessing the respective mitigation potentials.

Data Availability

The data used for this analysis is available in the Supplementary Information and excel spreadsheet.

References

1. Krausmann, F. *et al.* Long-term trends in global material and energy use. in *Social Ecology* 199–216 (Springer, 2016).

2. Tisserant, A. *et al.* Solid waste and the circular economy: A global analysis of waste treatment and waste footprints. *Journal of Industrial Ecology* **21**, 628–640 (2017).

3. Chen, D. M.-C., Bodirsky, B. L., Krueger, T., Mishra, A. & Popp, A. The world's growing municipal solid waste: Trends and impacts. *Environmental Research Letters* (2020).

4. Kaza, S., Bhada-Tata, P. & Van Woerden, F. *What a waste 2.0. A global snapshot of solid waste management to 2050*. (2018).

5. Yadav, P. & Samadder, S. R. A global prospective of income distribution and its effect on life cycle assessment of municipal solid waste management: a review. *Environmental Science and Pollution Research* **24**, 9123–9141 (2017).

6. Directive 2008/98/EC of the European parlament of the Council of European Union. (2008).

7. Ministry of the Environment. History and current state of waste management in Japan. (2012).

8. Resource Conservation and Recovery Act of 1976 in the United States. (1976).

9. Van Ewijk, S. & Stegemann, J. A. Limitations of the waste hierarchy for achieving absolute reductions in material throughput. *Journal of Cleaner Production* **132**, 122–128 (2016).

10. Manaf, L. A., Samah, M. A. A. & Zukki, N. I. M. Municipal solid waste management in Malaysia: Practices and challenges. *Waste Management* **29**, 2902–2906 (2009).

11. Ghanimeh, S. *et al.* Two-Level Comparison of Waste Management Systems in Low-, Middle-, and High-Income Cities. *Environmental Engineering Science* **36**, 1281–1295 (2019).

12. Parajuly, K. & Fitzpatrick, C. Understanding the Impacts of Transboundary Waste Shipment Policies: The Case of Plastic and Electronic Waste. *Sustainability* **12**, 2412 (2020).

13. Sharma, G. *et al.* Gridded Emissions of CO, NOx, SO2, CO2, NH3, HCl, CH4, PM2.5, PM10, BC, and NMVOC from Open Municipal Waste Burning in India. *Environ. Sci. Technol.* **53**, 4765–4774 (2019).

14. Wiedinmyer, C., Yokelson, R. J. & Gullett, B. K. Global Emissions of Trace Gases, Particulate Matter, and Hazardous Air Pollutants from Open Burning of Domestic Waste. *Environ. Sci. Technol.* **48**, 9523–9530 (2014).

15. Young Koo, Y. K. and K., Wooram and Jo, Young Min. Release of Harmful Air Pollutants from Open Burning of Domestic Municipal Solid Wastes in a Metropolitan Area of Korea. *Aerosol and Air Quality Research* **13**, 1365–1372 (2013).

16. Walker, T. & Xanthos, D. A call for Canada to move toward zero plastic waste by reducing and recycling single-use plastics. *Resources, Conservation and Recycling* **133**, 99--100 (2018).

17. Jambeck, J. R. *et al.* Marine pollution. Plastic waste inputs from land into the ocean. *Science* **347**, 768–771 (2015).

18. IPCC. IPCC Guidelines for National Greenhouse Gas Inventories 2006. (2006).

19. IPCC. The Fifth Assessment Report of the Intergovernmental Panel on Climate Change. *Geneva, Switzerland* (2014).

20. Melamed, M. L., Schmale, J. & von Schneidemesser, E. Sustainable policy—key considerations for air quality and climate change. *Current Opinion in Environmental Sustainability* **23**, 85–91 (2016).

21. Zhang, Y. *et al.* Tropospheric ozone change from 1980 to 2010 dominated by equatorward redistribution of emissions. *Nature Geoscience* **9**, 875–879 (2016).

22. Anenberg, S. *et al.* Global air quality and health benefits of mitigating short-lived climate forcers. (2011).

23. Andersson, K. *et al. Sanitation, Wastewater Management and Sustainability: from Waste Disposal to Resource Recover*. (2016).

24. Anenberg, S. C. *et al.* Global Air Quality and Health Co-benefits of Mitigating Near-Term Climate Change through Methane and Black Carbon Emission Controls. *Environ Health Perspect* **120**, 831–839 (2012).

25. Das, B., Bhave, P. V., Sapkota, A. & Byanju, R. M. Estimating emissions from open burning of municipal solid waste in municipalities of Nepal. *Waste Management* **79**, 481–490 (2018).

26. Arnold, C. Disease burdens associated with PM2.5 exposure: how a new model provided global estimates. *Environmental health perspectives* **122**, A111–A111 (2014).

27. Beelen, R. *et al.* Effects of long-term exposure to air pollution on natural-cause mortality: an analysis of 22 European cohorts within the multicentre ESCAPE project. *The Lancet* **383**, 785–795 (2014).

28. Brauer, M., Amann, M. & Burnet, R. T. Global Burden of Disease Assessment (draft). (2012).

29. Janssen, N. A. H. *et al.* Black carbon as an additional indicator of the adverse health effects of airborne particles compared with PM10 and PM2.5. *Environ Health Perspect* **119**, 1691–1699 (2011).

30. Harmsen, M. J. H. M. *et al.* Co-benefits of black carbon mitigation for climate and air quality. *Climatic Change* (2020) doi:10.1007/s10584-020-02800-8.

31. Höglund-Isaksson, L., Gómez-Sanabria, A., Klimont, Z., Rafaj, P. & Schöpp, W. Technical potentials and costs for reducing global anthropogenic methane emissions in the 2050 timeframe –results from the GAINS model. *Environmental Research Communications* **2**, 025004 (2020).

32. Yusuf, R. O., Noor, Z. Z., Abba, A. H., Hassan, M. A. A. & Din, M. F. M. Methane emission by sectors: A comprehensive review of emission sources and mitigation methods. *Renewable and Sustainable Energy Reviews* **16**, 5059–5070 (2012).

33. Höglund-Isaksson, L. *Global anthropogenic methane emissions 2005–2030: technical mitigation potentials and costs*. (2012) doi:10.5194/acpd-12-11275-2012.

34. Saunois, M., Jackson, R. B., Bousquet, P., Poulter, B. & Canadell, J. G. The growing role of methane in anthropogenic climate change. *Environ. Res. Lett* **11**, 12 (2016).

35. Hoesly, R. M. *et al.* Historical (1750–2014) anthropogenic emissions of reactive gases and aerosols from the Community Emissions Data System (CEDS). *Geoscientific Model Development* **11**, 369–408 (2018).

36. Klimont, Z. *et al.* Global anthropogenic emissions of particulate matter including black carbon. *Atmospheric Chemistry and Physics* **17**, 8681–8723 (2017).

37. Reyna-Bensusan, N. *et al.* Experimental measurements of black carbon emission factors to estimate the global impact of uncontrolled burning of waste. *Atmospheric Environment* **213**, 629–639 (2019).

38. Gómez Sanabria, A., Höglund Isaksson, L., Rafaj, P. & Schöpp, W. Carbon in global waste and wastewater flows–its potential as energy source under alternative future waste management regimes. *Advances in Geosciences* **45**, 105–113 (2018).

39. IEA. *World Energy Outlook 2018*. (2018).

40. Hoornweg, D. & Bhada-Tata, P. *What a waste. A global review of solid waste management*. (2012).

41. OECD. *OECD Economic Surveys. China*. (2019).

42. Calvo, F., Moreno, B., Zamorano, M. & Szanto, M. Environmental diagnosis methodology for municipal waste landfills. *Waste Management* **25**, 768–779 (2005).

43. Mihai, F.-C. & Grozavu, A. Role of waste collection efficiency in providing a cleaner rural environment. *Sustainability* **11**, 6855 (2019).

44. Ramaswami, A., Baidwan, N. K. & Nagpure, A. S. Exploring social and infrastructural factors affecting open burning of municipal solid waste (MSW) in Indian cities: A comparative case study of three neighborhoods of Delhi. *Waste Management & Research* **34**, 1164–1172 (2016).

45. Amann, M. *et al.* Reducing global air pollution: the scope for further policy interventions. *Philosophical Transactions of the Royal Society A* **378**, 20190331 (2020).

46. United Nations. Resolution adopted by the General Assembly on 25 September 2015. (2015).

47. IPCC. Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. (2018).

48. UNEP & ISWA. *Global Waste Management Outlook*. (2015).

49. Joshi, R. & Ahmed, S. Status and challenges of municipal solid waste management in India: A review. *Cogent Environmental Science* **2**, 1139434 (2016).

50. Gidden, M. *et al.* Global emissions pathways under different socioeconomic scenarios for use in CMIP6: A dataset of harmonized emissions trajectories through the end of the century. *Geoscientific Model Development* **12**, 1443–1475 (2019).

51. van Marle, M. J. E. *et al.* Historic global biomass burning emissions for CMIP6 (BB4CMIP) based on merging satellite observations with proxies and fire models (1750–2015). *Geosci. Model Dev.* **10**, 3329–3357 (2017).

52. Riahi, K. *et al.* The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change* **42**, 153–168 (2017).

53. UNDESA. *World Urbanization Prospects: The 2018 Revision*. https://population.un.org/wup/ (2018).

54. Amann, M. *et al.* Cost-effective control of air quality and greenhouse gases in Europe: Modeling and policy applications. *Environmental Modelling & Software* **26**, 1489–1501 (2011).

55. Gómez-Sanabria, A., Höglund-Isaksson, L., Rafaj, P. & Schöpp, W. Carbon in global waste and wastewater flows-its potential as energy source under alternative future waste management regimes. *Advances in Geosciences* **45**, 105–113 (2018).

56. Karak, T., Bhagat, R. M. & Bhattacharyya, P. Municipal Solid Waste Generation, Composition, and Management: The World Scenario. *Critical Reviews in Environmental Science and Technology* **43**, 215–215 (2013).

57. Permadi, D. A. & Kim Oanh, N. T. Assessment of biomass open burning emissions in Indonesia and potential climate forcing impact. *Atmospheric Environment* **78**, 250–258 (2013).

58. Hodzic, A., Wiedinmyer, C., Salcedo, D. & Jimenez, J. L. Impact of Trash Burning on Air Quality in Mexico City. *Environ. Sci. Technol.* **46**, 4950–4957 (2012).

59. Bond, T. C. *et al.* A technology-based global inventory of black and organic carbon emissions from combustion. *Journal of Geophysical Research: Atmospheres* **109**, (2004).

60. Akagi, S. K. *et al.* Emission factors for open and domestic biomass burning for use in atmospheric models. *Atmospheric Chemistry and Physics* **11**, 4039–4072 (2011).

61. EEA. *Managing municipal solid waste. A review of achievements in 32 European countries.* (2013).

62. EUROSTAT. *Guidance on municipal waste data collection*. (2016).

63. Schöpp, W., Klimont, Z., Suutari, R. & Cofala, J. Uncertainty analysis of emission estimates in the RAINS integrated assessment model. *Environmental Science & Policy* **8**, 601–613 (2005).

Acknowledgements (optional)

The development of the ECLIPSE_V6b scenarios was supported by the European Union funded Action on Black Carbon in the Arctic.

Ethics declarations

The authors declare that they have not conflict of interest.

Supplementary Information

The supplement related to this article is available at

Tables

Table 1. Collection of studies quantifying municipal solid waste (MSW) openly burned.

Source	Scale	Assumption	Results
Sharma et al., 2019	India	Calculation of waste burned at landfills was based on a study in a landfill in Mumbai using average FRP. Fraction open burning of waste 7% - 12%	68 Tg a^{-1} was open burned in India in 2015
Wang et al., 2017	China	In reference to the limited literature, China's averaged proportion of open MSW burning is set to 18.0% at residential and dumpsites and 38.0% at landfills.	The proportion of open burning is estimated from 79.8% in 2000 to 57.0% in 2013
Klimont et al., 2017	Global	IPCC guidelines 2006; CEPMEIP, 2002; EAWAG, 2008; Neurath, 2003. Fraction of open burning of waste is 0.5% - 5% for developed world and 10% -20% for developing world.	Global estimation of MSW openly burned is estimated 115 Tg a^{-1} to 160 Tg a^{-1} in 2010
Wiedinmyer at al., 2014	Global	Follows IPCC guidelines 2006 in which 60% of the total waste available to be burned that is actually burned	970 Tg a^{-1} of waste are globally openly burned. 620 Tg a^{-1} at residential level and 350 Tg a^{-1} at dumpsites.
Hodzic et al., 2012	Mexico City	Assigned percentage of MSW burned according to socioeconomic status. Low and middle-low 60%, mid 30%, mid-high and high 20%. Based on anecdotal evidence with Mexican researchers.	The burned fraction exceeds 4 Gg day^{-1}
Bond et al., 2004	Global	Fraction of burned waste in urban areas base on United Nations Human Settlement Programme, 2000	Worldwide 33 Tg a^{-1}, including 14 Tg a^{-1} in Asia and 5 Tg a^{-1} in Africa

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- MunicipalwasteGHGreductionpotentialsSupplement.pdf
- GraphssupplementGOMEZetal.xlsx