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CONSIDERATIONS ON WASTE CHARACTERIZATION AND THE PRODUCTION OF ENERGY: HOW USEFUL CAN WASTE BE?

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ABSTRACT

The proposed work reports a compilation of municipal solid waste composition in several geographies, discussing the impacts and repercussions of different waste classification nomenclature and related definitions. In addition, different scenarios are evaluated using the average waste composition in each location to further describe the possibility of covering the energy demand in those places, with energy produced from waste. For that, the thermal conversion efficiency of each Waste-to-Energy (WtE) procedure (combustion, incineration, hydrothermal liquefaction, pyrolysis, gasification, and plasma gasification) was used, so that a comparison of performances is put forward, to potentially aid in policy- and/or decision-making processes. Hydrothermal liquefaction presented higher efficiencies, followed by gasification-based techniques. Incineration, combustion and pyrolysis show a declining performance. In terms of waste production, OECD countries exceeded the average waste production values as well as the energy demand per capita, while Europe and Central Asia depicted the lowest contribution of energy produced from the waste generated.

1. INTRODUCTION

New policy packages and government plans and targets such as the RePowerEU plan and the Fit for 55 package (European Union), the Inflation Reduction Act (United States), the Climate Change Bill (Australia), and the GX Green Transformation (Japan), are setting the tone to an accelerated clean energy development this decade, especially in advanced economies. A decreasing demand for all fossil fuels by 2030 is expected and already on the march in advanced economies, however these measures take time to roll out (Agency, 2022; Bois von Kursk et al., 2022). To reduce the dependency on fossil fuel imports, especially in Europe, short-term actions are required, giving consumers a key role in terms of behaviour change; nevertheless technological advances namely in energy production systems are also a major driver for this transition. While in emerging markets and developing economies the demand for fossil fuel upsurges more slowly, the slowdown in fossil fuel demand progress is led by China, where the combination of decelerating the economic growth and the policy efforts lead to a peak in emissions (Agency, 2022).

The importance of waste management is emphasized in the 2030 agenda for Sustainable Development Goals (SDG) (Nations, 2016). Waste may be seen as a multidimensional subject with technical, environmental, economic, social, and ethical dimensions, highlighting major disadvantages and differences of marginalized communities over less difficult contexts (Nations, 2021). Nevertheless, by means of the concept of Waste-to-Energy (WtE), waste is regarded as a raw material for alternative energy production, ideally replacing the use of fossil-based options (Ramos & Rouboa, 2020). This enforces the perspective of waste as a valuable resource, namely contributing to the clean energy transition, diminishing the negative impacts usually related to it. Indeed, the values of sustainable production and consumption, as well as circular economy principles are also being met by this approach, as a strategy to close the loop on residues and comply with the SDGs (E. Commission, 2020).

Figure 1 shows the progress of two key energy system indicators for the global energy transition envisioned by the International Renewable Energy Agency (Gielen et al., 2019) (on the left), as well as the average global share of waste treatment as reported by the World Bank Group (Kaza, Yao, Bhada-Tata, & Woerden, 2018) (on the right).

From Figure 1 it is observed that although the energy consumption per capita is expected to decrease roughly 25% until 2050, the required levels will still be high while more environment-friendly production procedures are deemed to be used (lowering CO_2 emissions). Meanwhile, in what regards waste treatment techniques, these are somehow misadjusted, open dumps and landfill combining a great

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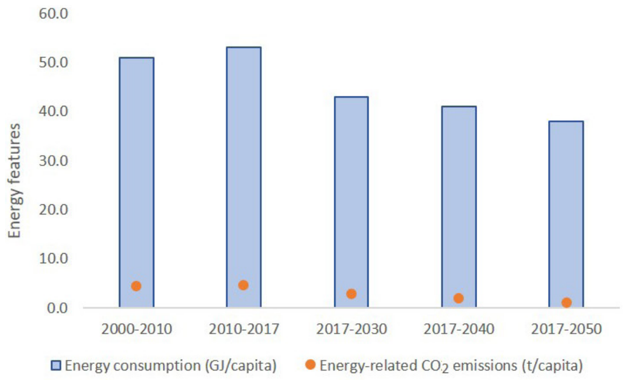

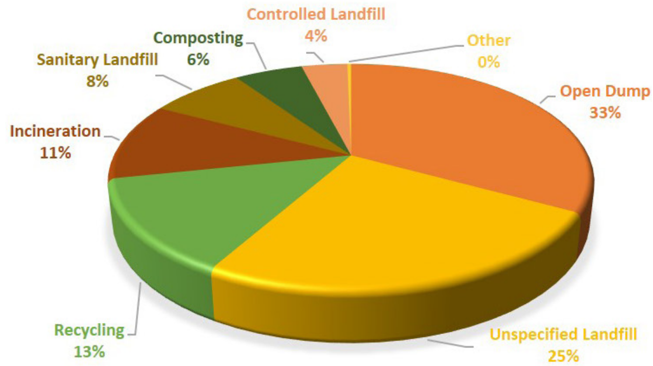

FIGURE 1: Energy consumption and emissions data (on the left); global shares of treatment and disposal of waste (on the right).

share of disposal options, while the thermal procedures depict a low portion of the share. This means that there is space for the thermal treatments' segment to grow, once their efficiency and environmental character is proved (Sun et al., 2020). This will add value to most residues at their end-of-life stage, widening the spectrum of available WtE techniques, which enhances the sustainable energy production to potentially meet the population's energy demand.

This work proposes a screening through waste composition across distinct world regions, discussing aspects related to waste production and classification. Also, the possibility of producing energy through several WtE to fulfill part of the energy demand in those places is put forward, as a novel feature in this type of literature reviews, especially because this is done for distinct waste-to-energy techniques, enhancing the body of knowledge in the field.

2. MATERIALS AND METHODS

2.1 Bibliographic review

Recent literature in the topic was searched with significant keywords in relevant scientific databases (Web of Science, Scopus, Science Direct, Google Scholar). The keywords applied were "municipal solid waste composition", "MSW composition", "municipal solid waste characterization", "MSW characterization", "urban waste composition", "urban waste characterization", "urban residues composition", and "urbanc residues characterization" (MSW stands for Municipal Solid Waste).

The entries retrieved were reviewed for duplicates, and individually inspected for effective content, a shortlist of pertinent works being compiled in Table 1 (*please see the supplementary material*).

2.2 WtE conversion efficiency

The energy efficiency used to perform the conversion calculations in this work was previously achieved in other works (shown in Table 2), namely conducted for the evaluation of the environmental assessment of the WtE techniques such as incineration, gasification and plasma gasification (Lombardi, Carnevale, & Corti, 2012; Ramos & Rouboa, 2020; Ramos, Teixeira, & Rouboa, 2019), or retrieved from dedicated literature for pyrolysis (D'Alessandro, D'Amico, Desideri, & Fantozzi, 2013), combustion (D'Alessandro et al., 2013; Viganò, Consonni, Grosso, & Rigamonti, 2010) and hydrothermal liquefaction (University, 2013; B. Zhang et al., 2017). Gasification involves the partial combustion of biomass to generate flammable gases like CH_4, H_2, and CO, which are often mixed with other substances like benzene, toluene, aliphatic hydrocarbons, and tars, resulting in a mixture known as syngas. This gas fuel is created by subjecting biomass to high temperatures exceeding 800°C within an environment of oxygen, air, or steam (Ramos, Monteiro, & Rouboa, 2019). Plasma consists of ionized gases at elevated temperatures, enabling rapid and effective heat transfer through electrical discharge. This method significantly enhances the conversion process due to the exceptionally elevated temperatures, causing even the most resistant inorganic compounds that typically resist gasification to "melt" and undergo transformation (Boulos, Fauchais, & Pfender, 2013). In the process of pyrolysis, thermal energy is utilized to break down the chemical bonds within materials (Elgarahy et al., 2021). This technique finds applications across a range of domains, including the chemical industry, as well as in the study of natural and biological substances, forensic resources, and trace-level analysis (Wampler, 2006). Combustion employs air as the oxidizing agent to generate heat energy. In this method, the feedstock is subject to oxidation, resulting in the creation of high-temperature gases ranging from 800°C to 1000°C. These gases are then utilized to generate steam or heat (Elgarahy et al., 2021). Hydrothermal techniques break down the solid biopolymeric components of the feedstock, yielding valuable high-energy products and chemicals. These processes occur within a temperature range of 250°C to 375°C and under pressures ranging from 4 MPa to 22 MPa. As the temperature rises, the viscosity of water decreases, enhancing the efficiency of mass transfer and diffusion coefficients (M. Kumar, Oyedun, & Kumar, 2018).

As main assumptions, zero losses in waste conversion and a constant average waste composition were adopted, in order to extrapolate the electricity produced from the MSW generated in several parts of the world. This is a feasible approach as seen in literature (Hoornweg & Bhada-Tata, 2012).

2.3 Contribution to the electricity consumed

An estimation of the share of energy hypothetically produced from the waste generated per capita was conducted, considering the average yield and composition of waste, as well as the average electric consumption in each area (Bank, 2018; Hoornweg & Bhada-Tata, 2012). The proportion of the electrical demand per capita served by the energy achieved from the thermal conversion of the MSW generated by each person (which is then used as electricity) was calculated through Equation 1, assuming no losses in conversion efficiency.

$$\%\,MSW\ contribution = \frac{average\ waste\ yield \times WtE\ conversion\ efficiency}{\text{average electric power consumption}} \quad (1)$$

This calculation enables the proposal of a parameter relating the electricity consumed and the waste generated in each part of the world, as a potential measure of economic development. This is mainly related to the fact that most of the nowadays' commodities depend on electric power, implying the social welfare of the population. In a previous report, this indicator has been suggested as a basis for the strategic development regarding waste management options or electrical grid planning (Ramos & Rouboa, 2020).

3. RESULTS AND DISCUSSION

3.1 Literature review on waste characterization

Table 1 (*please see the supplementary material*) presents the key composition features for the MSW described in selected literature.

3.1.1 Prevalence of MSW composition

From Table 1 (*please see the supplementary material*) it is possible to observe a prevalence of the organic fraction in the vast majority of the assessed MSW samples, depicting around 75.6% of the total share of literature assessed. It is also possible to notice that this is a dominant trend within the same country, except in occasional cases as for instance Tekirdag in Turkey (Bolukbas & Akinci, 2018), Kanpur and Hyderabad in India (Dixit et al., 2022; Singh & Uchimura, 2022), and Xi'an in China (Xiao et al., 2009), where Others has a higher fraction when compared to the remaining cities in the same countries. This is also the case for Mexico (Tsydenova et al., 2018) and Norway (Sorum et al., 2001). Actually, the Others fraction represents 11.2% of the total distribution within the assessed literature, in ex aequo with Paper. A fact possibly concurring to higher shares of the Others components is the source of energy used in those places, as for instance coal-based activities generate ashes which account for this category, whilst activities fuelled by natural gas or electricity are cleaner regarding this aspect (Grammelis, 2010; Hoornweg & Bhada-Tata, 2012).

Paper is the dominant fraction in countries such as Taiwan (Chen, 2018), Japan (Du et al., 2021), and Israel (Q. L. Zhang et al., 2012). Nottingham is an outlier to the dominance of the organic fraction seen in other UK locations, Paper being the prevailing component in this city (D. Wang et al., 2018). Other representations of this phenomn are Mavallipura (India), where Plastic is the higher fraction seen in the reported MSW sample (Naveen, 2018), and Ilorin (Nigeria), where the plastic fraction prevails over the paper fraction seen in Lagos (Ibikunle et al., 2020).

Metal, glass, textiles and wood are not considered the main components in any of the literature reported. Oppositely, these are most of the times the less significant fractions as seen for the case of Taiwan (Chen, 2018), Thailand (Outapa & Roi-et, 2018), Indonesia (Indrawati & Purwaningrum, 2018), Saudi Arabia (Osra et al., 2021), Romania (Ciuta et al., 2015), China (Ding et al., 2021; Du et al., 2021; Xiao et al., 2009), and Singapore (Bolukbas & Akinci, 2018; Du et al., 2021).

This might sometimes be explained by the different sampling and characterization methods, which may attribute different categories for the same type of residues (for instance classifying some residues as Others instead of a defined category), or even by the fact that there is no detailed information available in literature (Hoornweg & Bhada-Tata, 2012; Parfitt & Bridgwater, 2008; Ramachandra et al., 2018; Singh & Uchimura, 2022). The rapid urbanization of some developing countries may also contribute to the outliers in the waste composition and management systems, as seen in Santa Cruz (Bolivia), parameters such as household size, education level, and number of children in the family being considered (Lozano Lazo et al., 2023). Section 3.1.2 discusses the contribute of waste terminology and categorization in more detail.

Overall, high-income regions produce relatively less organic waste than middle- and low-income areas, dry waste (in general recyclable - plastic, paper, cardboard, metal, and glass), accounting for higher shares of waste. Middle-income countries generate more levelled proportions of organic and recyclable waste increasing as economic development levels decrease, while low-income countries report only around 20% of recyclable materials. Averagely speaking, all regions seem to generate around or more than 50% of organic waste, exceptions being made for Europe and Central Asia and North America, where higher shares of dry waste are reported. This is in line with The World Bank projections (Kaza et al., 2018).

3.1.2 Discrepancies in definitions and standards

The differences in terminology, concept meaning and law enforcement in what relates to waste management may lead to situations where the same component may be understood as recyclable in one country, energetically valorizable in another region and general waste in a different location (Kawai & Tasaki, 2016; Park & Lah, 2018). For instance, under the EU legislation, less than 27% of the MSW produced in 2015 was recycled, whereas under a more conservative system as the one in South Korea, a recycling rate of 59% was reported for the same year, and roughly 30% in the USA (Development, 2016). Nonetheless, if the EU standards were applied for the South Korean and American systems, recycling rates as high as 70% and 40% would be respectively achieved (Park & Lah, 2018). Another example of incongruence is the fact that 17% of plastic waste worldwide is collected for recycling, although there are large differences between regions: for example, in Europe 25% is collected for recycling while less than 10% is collected in the United States. Also, recycling rates are completely different depending on the waste fraction considered and the interest it brings: plastics are much less likely to be recycled than steel, aluminium and paper (Agency, 2022). Indeed, the effect of variables such as incentives to source reduction, collection and recycling rates, and the existance of composting and incinerating facilities are totally distinct depending on the income level of the world region (Hoornweg & Bhada-Tata, 2012). All these factors account for inconsistencies and hamper an archetype pathway towards revalorizing waste streams and avoiding landfilling and open dumping.

Apart from the perceived different standards and waste management legislation pieces in distinct world locations/ socioeconomic organizations, waste availability also promotes dissimilar composition for the same kind of waste streams, if a specific composition has to be met depending on the purpose (Bergeron, 2017). Waste composition and production rate may be considered two of the central contributions for the enhancement of waste management systems, helping to shape policies to meet the stated regulations (Engineering, 2011). It should also be noticed that waste yields might be incorrectly estimated when inadequate population data is considered (Hujare & Telsang, 2020). Besides, by overlooking the closed characteristics of compositional waste fraction data, the statistical analyses can lead to illegitimate or misleading results (Edjabou et al., 2017). Bottom-up and topdown methods for analyzing the physical composition of MSW have been discussed by Zhou et al (Zhou et al., 2022) in Wuhan, China.

Depending on the characteristics of the area where the waste is generated, it may show completely distinct profiles, which will furthermore define its potential revalorization (Adeniran, Adelopo, Aina, Nubi, & Apena, 2019; Baran, 2018; Ciuta et al., 2015). Events related to tourism, geophysical constrains or socioeconomic and cultural activities also promote discrepancies in waste composition in defined locations (Bolukbas & Akinci, 2018; Diaz-Farina, Díaz-Hernández, & Padrón-Fumero, 2020; Ibikunle et al., 2020; Park & Lah, 2018). This may sometimes trigger mismanagement practices if the system reveals itself insufficient to deal with amounts of waste larger than usual, unbalancing the conventional or expected residues' streams, due to operational and governance weaknesses (Abdulredha et al., 2020; Diaz-Farina et al., 2020). Climate conditions may further endorse changes in waste composition interfering with parameters as moisture content, type and amount of biodegradable and recyclable components (Hoornweg & Bhada-Tata, 2012). The existence of dedicated and suitable containers according to the separation legislations in place is also a major conditioning factor in what regards waste collection, categorization and management (Hogg & Consulting, 2016; Hoornweg & Bhada-Tata, 2012).

3.2 Electrical needs vs waste produced

3.2.1 World regions classification

According to the World Bank, countries may be classified upon their income level, the world's economies being allocated to one of four income groups — low, lower-middle, upper-middle, and high income (Rompaey, Metreau, & Eapen, 2022). In terms of geographical areas, the classification is based on the regions used for administrative purposes by the World Bank (Group, 2017). Figure 2 depicts the geographical classification, and Figure 3 presents the relation between the income level and the regional classification.

This classification was utilized in this work as a guidance to better discuss the results presented in the following sections. For the sake of simplicity, acronyms for the world regions were used, as follows: MENA – Middle East and North Africa; AFR – Sub-saharan Africa region; EAP – East Asia and Pacific; ECA – Europe and Central Asia; OECD – Organization for Economic Co-operation and Development; SAR – South Asia region; LCR – Latin America & the Caribbean region.

High-income countries generate circa 34% (683 million tonnes) of the world's waste, although they represent only 16% of the world's population (Kaza et al., 2018). Overall,

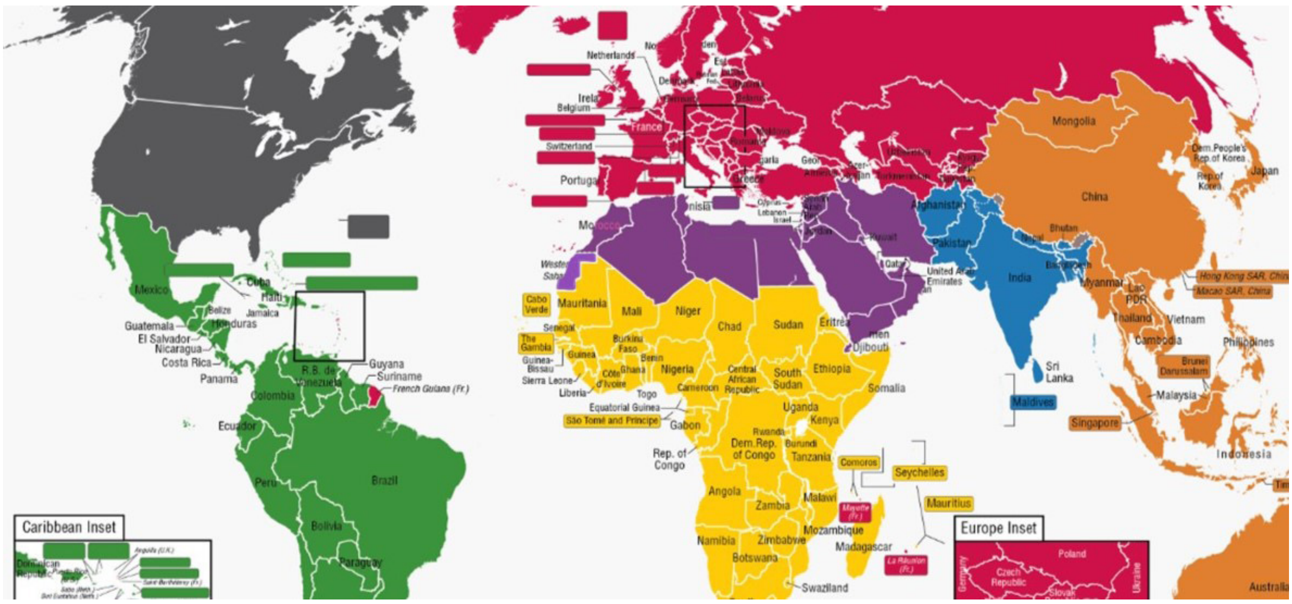

FIGURE 2: World Bank grouping of countries by regions, including economies of all income levels (adapted from Group, 2017).

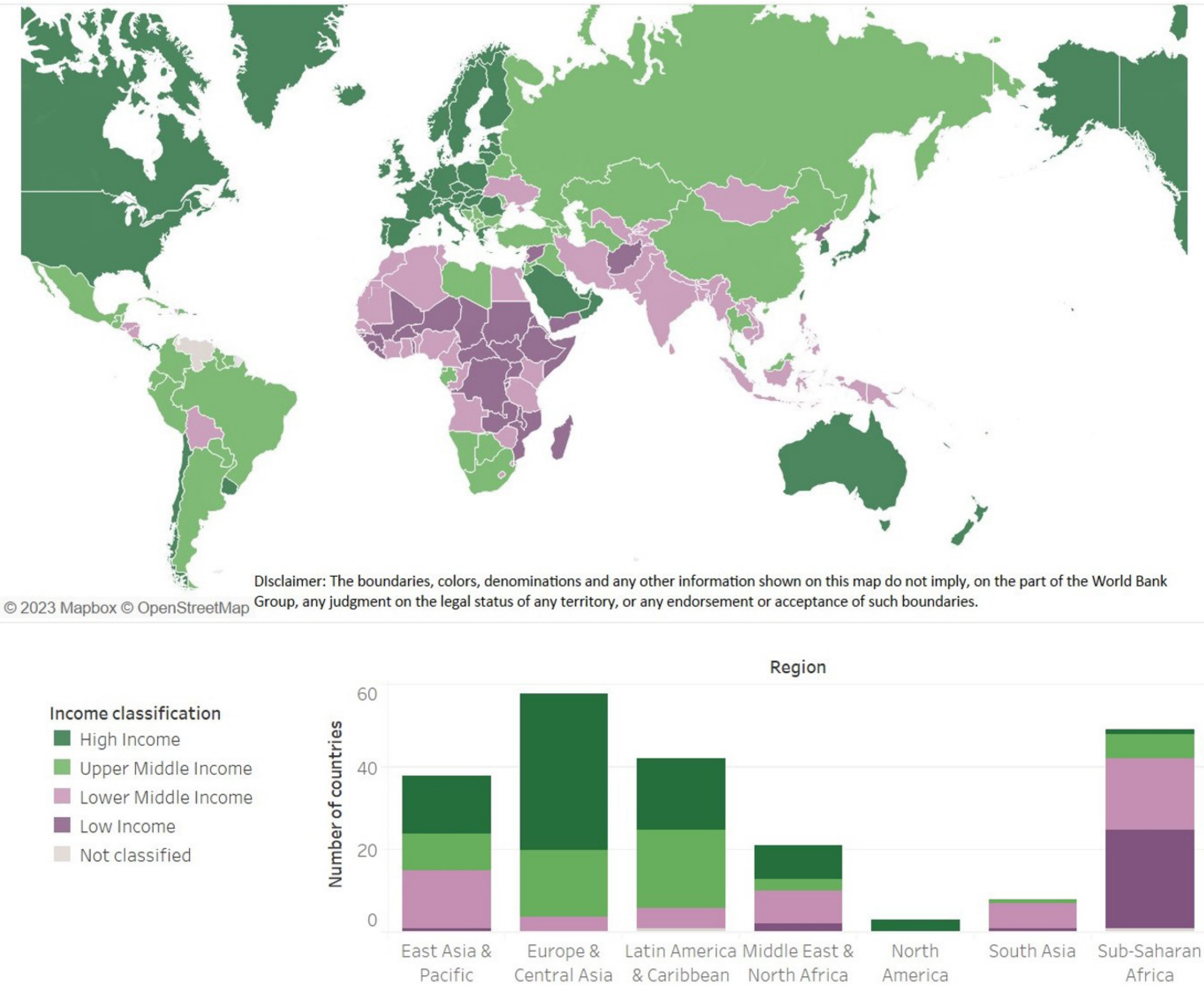

FIGURE 3: World Bank country classification by: top) income level; bottom) share of income levels by world region (adapted from Rompaey et al., 2022).

low-income countries collect around 48% of waste in urban areas, this proportion significantly dropping to 26% in rural areas. SAR collects about 44% of waste, whereas ECA and North America collect more than 90% of waste (Kaza et al., 2018). Generally speaking, the higher the income level and rate of urbanization, the greater the amount of solid waste produced (Hoornweg & Bhada-Tata, 2012).

3.2.2 Relation between energy consumption and waste production

Computing the waste production against the electricity demand for all the world regions, a major trend can be seen, as shown in Figure 4. Developed countries reveal higher shares of electricity demand and waste production, whilst developing regions present inferior values.

Based on the results presented in Figure 4, OECD is the part of the world where more waste is produced (almost half of the world waste according to (Hoornweg & Bhada-Tata, 2012)), followed by regions such as ECA, LCR, and MENA. EAP and AFR show lower waste production yields, while SAR is the region where less waste is produced per capita. In terms of income, high income countries are responsible for 46% of the total waste generated worldwide, while upper-middle income countries generate 19% of this share, lower-middle income regions contribute with 29%, and low income countries are responsible for a 6% share (Hoornweg & Bhada-Tata, 2012). Likewise, the collection rates show a similar profile by geographical area, higher collection rates being seen in higher income regions.

On the same trend, OECD is the major power consumer, followed by ECA and EAP; MENA and LCR show lower energetic needs, whereas SAR and AFR exhibit energetic demands one order of magnitude lower the rest of the world. This is in accordance to the fact that over 620 million people living in Africa do not have access to electricity (Bois von Kursk et al., 2022). Nevertheless, as stated by Kaza et al (Kaza et al., 2018), the fastest growing regions in terms of waste production are AFR, SAR and MENA where, by 2050, total waste generation is expected to be three-, two-, and two-fold respectively. The energetic demand has been raising and will continue to grow, mainly due to the ever-increasing will of developing countries to thrive and meet

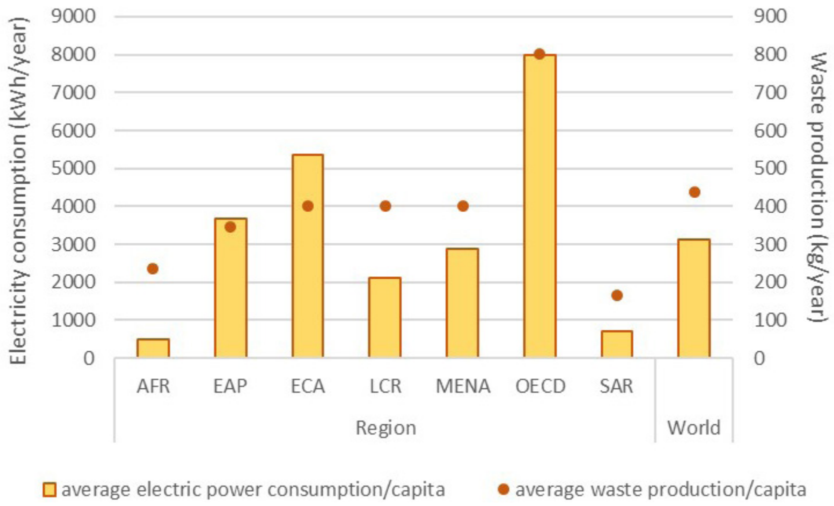

FIGURE 4: World data for electricity consumption vs waste generation.

their socio-economic needs (Bois von Kursk et al., 2022). In these regions, more than 50% of waste is currently sent to open dumps, with the associated environmental, health and socioeconomic implications (Hoornweg & Bhada-Tata, 2012). Therefore, this requires urgent action, one of the suitable options being to convert this concern into an opportunity in the energy sector (Agency, 2022; Chand Malav et al., 2020; U. N. B. Commission, 1987; Grammelis, 2010).

This energy transformation fosters socio-economic benefits as enhanced economic growth, new jobs and overall prosperity, while reduces net costs and environmental impacts (Gielen et al., 2019; Ramos & Rouboa, 2020).

3.2.3 MSW contribution to the energy demand

Depending on the waste composition, its production rate, and the power needs of the population per area, different contributions from the conversion of the residues into energy are expected. Table 2 presents the hypothetical share of electricity produced by the thermal conversion of MSW in several regions, for each WtE.

It should be noted that the values seen in Table 2 must be faced cautiously and within the defined boundaries for each scenario. Indeed, it shows that, according to the location and socioeconomic context, the thermal treatment of the waste produced per capita may provide between 2% and 53% of the electricity consumed by each person. WtE techniques such as hydrothermal liquefaction show potential to cover a higher share of the energy needs (up to 53% input), especially in AFR and SAR, followed by the gasification-based technologies (6%-41% contribution). Incineration depicts a lower performance, granting 4% to 23% of electricity coverage, followed by combustion (2% to 15% share) and pyrolysis with 2% to 12% contribution. This is supported by literature referring to the production of energy from biosolids and other residues (Elgarahy et al., 2021; Grammelis, 2010; Jung et al., 2021; Rezaei, Ghobadian, Samadi, & Karimi, 2018; Vallejoa, Díaz-Roblesa, Cubillosa, & Perez, 2020). Elgahary et al (Elgarahy et al., 2021) refer the economic aspects of the thermochemical conversion as a promosing integrated approach, while Jung et al (Jung et al., 2021) discuss the suitability of livestock manures to be used as different biofuels instead of using edible crops as biomass feedstock for the same purpose. Rezaei et al (Rezaei et al., 2018) review the sensitivity analysis of different scenarios for choosing an effective and efficient technology for the conversion, comparing incineration and gasification; whereas Vallejoa et al (Vallejoa et al., 2020) compare gasification to hydrothermal carbonization. Complementarily, current practices, challenges, and future opportunities of using MSW as a renewable source of energy were reviewed in topical works (Agency, 2013; Chand Malav et al., 2020; Foster et al., 2021; Nunes, Matias, & Catalão, 2017; Ofori-Boateng, Lee, & Mensah, 2013). Chand Malav et al (Chand Malav et al., 2020) put forward a number of recommendations for improving the currently implemented solid waste management in the Indian context, Foster et al (Foster et al., 2021) examining the processes and barriers related to the conversion of solid residues in the UK; moreover, Nunes et al (Nunes et al., 2017) review the main parameters that influence the quality of biomass for application in WtE in Portugal, while Ofori-Boateng et al

TABLE 2: Average values for waste production and electric power consumption per capita, and the potential contribution of thermally converted MSW worldwide.

Location	MSW contribution to the energy consumed (%)					
	C	HTL	P	I	G	PG
AFR	14.62	52.63	11.70	23.28	40.93	41.23
EAP	2.81	10.10	2.25	4.47	7.86	7.92
ECA	2.22	8.01	1.78	3.54	6.23	6.27
LCR	5.61	20.21	4.49	8.94	15.72	15.83
MENA	4.16	14.96	3.33	6.62	11.64	11.72
OECD	2.99	10.77	2.39	4.77	8.38	8.44
SAR	6.91	24.89	5.53	11.01	19.36	19.50
World	4.17	15.01	3.34	6.64	11.67	11.76

C: Combustion; HTL: Hydrothermal Liquefaction; P: Pyrolysis; I: Incineration; G: Gasification; PG: Plasma Gasification

(Ofori-Boateng et al., 2013) refer the perspective of waste management on Ghana.

Taking into consideration the geographies evaluated in this work, OECD countries depict one of the lowest coverages of electrical demand provided by the produced MSW fraction (2% to 11%), despite being the ones with higher MSW yields. This is also seen for ECA, where the coverage is even lower (2% to 8%), and for EAP (2% to 10%). The MENA region follows, MSW contributing with 4% to 15% to the electrical demand, while LCR shows contributions ranging between 5% and 20%.

From this, socioeconomic correlations related to the population habits and access to energy may be implied, higher income countries producing more waste and requiring more energy than lower income countries, where the energetic needs are met more effortlessly, while waste is produced in a significantly lower amount. This is in accordance with expected trends seen for other indicators (Ramachandra et al., 2018; Ulgiati et al., 2011).

4. CONCLUSIONS

After a review of the most recent literature concerning MSW composition, major trends could be seen especially in what relates to the income level and geographic positioning of the regions assessed. Then, an estimation of the electricity share potentially produced from the waste generated per capita in the world was put forward. Comparing the performance of six different Waste-to-Energy techniques in what regards producing energy for the assessed regions, hydrothermal liquefaction depicted higher efficiencies, followed by gasification-based techniques. Incineration, combustion and pyrolysis displayed a decreasing performance.

Major contributions were observed for Sub-Saharan Africa and South Asia due to the lower electrical demand in these areas, though OECD countries clearly surpassed the average waste production values as well as the energy demand per capita. Latin America & the Caribbean and Middle East and North Africa regions followed; East Asia and Pacific, and Europe and Central Asia depicting the lowest contribution of energy produced from the waste generated.

The main general take-away message from this work is that waste cannot be “thrown away”. Whatever the disposal option is, it remains in our planet affecting our lives in one or another way. It depends on us to take advantage of the situation already in place and take it as an opportunity to evolve in a more environment-friendly direction. Hence, behavioural changes from the end-users would contribute both to diminish the amount of waste created as well as the energetic needs associated to a comfortable and wealthy way of living; while on a macroeconomic level, overall rethinking the current production and supply chains would also foster a more sustainable life on Earth.

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