Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.
Thermochemical treatment of daily COVID-19 single-use facemask waste: Power generation potential and environmental impact analysis

Dan Cudjoe a, Hong Wang b, *, Bangzhu Zhu a, **

a School of Business, Nanjing University of Information Science & Technology, Nanjing, 210044, China
b School of Management and Economics, Beijing Institute of Technology, Beijing, 100081, China

Article history:
Received 17 November 2021
Received in revised form 1 March 2022
Accepted 9 March 2022
Available online 11 March 2022

Keywords:
Single-use facemask waste
Incineration
Environment
Power
COVID-19

1. Introduction

The outbreak of the COVID-19 (SARS-CoV-2) pandemic is affecting physical and mental health worldwide [1]. Regarded as the most critical global health tragedy of all time, the pandemic is the central issue the world has encountered since the Second World war [2]. The Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) is caused by the injection of respiratory samples into the human airway epithelial cells, Vero E6 and Huh7 cell lines, resulting in the segregation of a new respiratory virus whose genome belongs to coronavirus related to SARS-CoV. SARS-CoV-2 is a beta coronavirus originating from the subgenus Sarbecovirus [3]. COVID-19 was declared a global pandemic on March 11, 2020 by the World Health Organization (WHO) [4]. Since then, the virus has kept spreading worldwide, with 205.3 million confirmed cases, including 4.3 million deaths as of August 13, 2021 [5]. The wild spread of the pandemic has subjected over 4.5 billion people, representing about 58% of the world’s population, to restrictions such as travel bans and national lockdowns [6].

The outbreak of the COVID-19 pandemic has not only caused global health crises but has also changed the pattern of global waste generation [7]. The production of personal protective equipment (PPE) waste has dominated waste generation worldwide. Single-use face masks are the common PPE used to avoid spreading the virus [8]. According to the WHO estimate, about 89 million single-use face masks are required monthly for COVID-19 response among health workers in the United States of America [9]. In Africa, it is estimated that about 105 thousand tons of face masks are discarded into the environment monthly [10]. The daily face mask used in Asia alone is estimated at 2.2 billion pieces [14]. It is estimated that about 3.4 billion single-use face masks waste is generated and
Researchers have suggested that thermochemical conversion use facemask waste to minimize its environmental consequences and implement innovative techniques to properly manage single-tons of facemask waste in global oceans annually [12]. This calls for utilization could result in approximately 0.15 million to 0.39 million. Other scholars have also estimated that the increased facemask waste management alternatives. The study concluded that the considerable mask waste, if not controlled, could contribute to micro-plastic pollution. Under the COVID-19 context, Ref. [8] reviewed Peru’s sustainable face-mask waste generation. Valorization of single-use COVID-19 face-mask could contribute 0.34 kg CO2eq to climate change, while the single-use surgical face mask would contribute 3.1 kg CO2eq/year and 60,000 GWh/year. Ref. [20] quantified the potential environmental impact and energy footprint of disposable face masks during the pandemic in Morocco was evaluated by Ref. [19]. The study discovered that the annual greenhouse gas and energy footprints of face masks in the country are about 640 kt CO2eq/year and 60,000 GWh/year. Ref. [20] quantified the environmental impact of embedded filtration layer reusable face masks and single-use surgical face masks using the life cycle assessment technique. The authors found that the embedded filtration layer reusable face mask could contribute 0.34 kg CO2eq to climate change, while the single-use surgical face mask will contribute.

disposed of daily globally [11]. Improper management of such wastes causes a novel form of environmental plastic pollution [8]. Other scholars have also estimated that the increased facemask utilization could result in approximately 0.15 million to 0.39 million tons of facemask waste in global oceans annually [12]. This calls for immediate attention from the international community to invest and implement innovative techniques to properly manage single-use face mask waste to minimize its environmental consequences [13]. Researchers have suggested that thermochemical conversion of disposable face masks could be an economical and ecologically friendly way to minimize COVID-19 plastic waste while producing value-added products [15,16].

Generation and treatment of face mask waste during the COVID-19 pandemic have recently attracted the attention of researchers worldwide (see Table 1). To convince the scientific community to find sustainable means for the disposal and management of face-mask waste, Ref. [14] estimated the facemask waste generated in Asia during the pandemic. Ref. [16] assessed the economic and environmental performance of transforming N95 facemask waste to steam and power through the integration of heat and power plants, ethanol through sugarcane fermentation technology, and energy-dense gasoline-like oil products through syngas fermentation hydrothermal liquefaction technology. The authors concluded that using N95 facemask waste for steam and electricity production has a promising economic and environmental impact. Ref. [17] investigated the co-pyrolysis of single-use facemask waste generated during the COVID-19 pandemic for energy and resource valorization. The authors found that pyrolysis of single-use face-masks yielded 18.4 wt% jet fuel, 14.7 wt% gasoline, 18.1 wt% motor oil-range hydrocarbons, and 34.1 wt% diesel. The environmental consequences of facemask waste during the COVID-19 and ecologically friendly solutions to reduce this waste were studied by Ref. [13]. The authors discovered that the considerable mask waste, if not controlled, could contribute to micro-plastic pollution. Under the COVID-19 context, Ref. [8] reviewed Peru’s sustainable face-mask waste management alternatives. The study concluded that incorporating reusable face masks could essentially reduce face-mask waste generation. Valorization of single-use COVID-19 face-mask via the pyrolysis process to produce syngas has been conducted by Ref. [15]. The authors believed thermochemical conversion of disposable face masks could be an environmentally friendly strategy to reduce COVID-19 plastic waste generation. The potential environmental impact and energy footprint of disposable face masks during the pandemic in Morocco was evaluated by Ref. [19]. The study discovered that the annual greenhouse gas and energy footprints of face masks in the country are about 640 kt CO2eq/year and 60,000 GWh/year. Ref. [20] quantified the environmental impact of embedded filtration layer reusable face masks and single-use surgical face masks using the life cycle assessment technique. The authors found that the embedded filtration layer reusable face mask could contribute 0.34 kg CO2eq to climate change, while the single-use surgical face mask will contribute.
incineration technology. Besides, the study evaluates the global warming potential and acidification potential of electricity generation from single-use facemask waste via incineration technology. This study could provide scientific guidance for environmental sustainability for thermochemical treatment and utilization of single-use facemask waste as a source of power generation. The rest of the study is arranged in the following order: Section 2 gives the background of the chosen thermochemical technology (incineration), the methodological approach used for the estimation of power generation potential and environmental impact analysis are presented in Section 3, the results of the research are presented and discussed in Section 4, and Section 5 lays out the conclusions based on the significant findings of the study.

2. Incineration technology

Incineration of waste is the art of burning waste thoroughly while maintaining or minimizing emission levels below current emission standards [25] and recovering energy [22], as well as final residues combustion. The prominent features of the technology include extensive reduction of volume and weight of waste [21], gaining a compact and sterile residue, treating the voluminous flow of flue gas, and deeply removing a wide array of air pollutants [25].

Gradually, waste incineration has migrated from waste disposal facilities to waste-to-energy plants. The introduction of vast air pollution control devices in today’s incineration facilities has made it valid for solid waste treatment and an attractive renewable energy source. For instance, over 65% of municipal solid waste is incinerated in countries such as Japan, Switzerland, and Denmark, while in the USA and UK, several incineration plants are under construction [23]. In China, about half of the 228 million tons of municipal solid waste generated in 2018 was treated via incineration [28]. Besides, it was estimated that over 220 million tons of solid waste were managed by incineration globally in 2016 [24].

Due to the maturity of incineration technology, it is often used to treat waste worldwide compared to the other methods [27]. The incineration procedure occurs through a grate system, which burns the waste that is not refined and is crude. The boilers are furnished with hydraulic rams that carry the waste into an ignition chamber

3. Methodology

This section details the step-by-step methods utilized to estimate power generation potential and environmental impact of treating daily COVID-19 single-use facemask waste via incineration technique. The environmental impact analysis includes global warming potential and acidification potential. The study used data of day-to-day single-use facemask waste generated (pieces/day) in Africa and Asia during the COVID-19 pandemic from the literature [10,14] for the analysis (see Table A1 in the appendix). The study considered Africa and Asia because they are the two most populous regions globally. Besides, both regions have had their fair share of the consequences of the COVID-19 spread, which has resulted in increased facemask usage and waste generation. Therefore, research into the sustainable treatment of the large amount of facemask waste in these regions will significantly impact the rest of the regions in the world. Based on the available data, 57 countries in Africa and 49 countries in Asia were considered in this study.

3.1. Power generation potential of incineration of single-use facemask

This section presents the model equations employed to calculate the electricity generation potential of the estimated daily single-use facemask waste through incineration technology. When the facemask waste is combusted in the incineration chamber, a large amount of heat is generated. The heat generated during the process could be captured and utilized to produce steam in a boiler for power generation via a steam turbine. In the present study, it is considered that the facemask waste in the regions was combusted in an incineration facility designed with a water wall/mass-burn with a capacity as the quantity of daily single-use facemask waste produced. The amount of applicable heat needed to raise steam in the boiler is based on energy and mass balance [29]. At a temperature of about 850°–950°C, the incineration facility produces steam from the heated flue gas from the furnace, which could be used for heating or electricity generation [29]. Residues such as fly ashes and ashes could contribute to dioxin and furan formation during incineration [30]. Therefore, it has become essential to equip incineration facilities with air pollution control devices to make them environmentally friendly [31].
\[ \text{INC}_{(PC)} = h \times 8760 \times \frac{\mu}{\alpha} \] (1)

\[ F_{M(waste)} = h \times LHV \times \frac{(100 - \gamma_{(sum)})}{100} \] (2)

\[ F_{M(waste)} = W_{(mask)} \times F_{M(pieces)} \] (3)

\[ HHV = 1.1783H + 0.3491C + 0.1005S - 0.1034O - 0.015N - 0.0211A \] (4)

\[ LHV = HHV - [9 \times \%H + \%H_2O] \times 2.44 \] (5)

where \( \mu \) is the steam turbine's power efficiency, taken as 29% [32,34], \( \alpha \) is the conversion factor from Btu to kWh, which is taken as 3412.14 [32]. \( F_{M(waste)} \) is the dry mass of waste feed rate (lb/h) calculated by converting waste flow rate (kg/h) to lb/h, \( F_{M(pieces)} \) is the pieces of single-use facemask waste generated daily (see Table A1), \( W_{(mask)} \) is the average weight of a single-use facemask and is taken as 0.00858 kg [10]. HHV and LHV represent high heating value and lower heating value (MJ/kg) of the incinerated facemask waste, which was calculated from Eqns. (4) and (5), following Ref. [35] and Ref. [36], H, C, S, O, N, and A are the hydrogen, carbon, sulphur, oxygen, nitrogen, and ash content from the ultimate analysis of single-use facemask (see Table A2), \( \%H \) is the weight percentage of atomic hydrogen, \( \%H_2O \) is the weight percentage of atomic water, \( \gamma_{(sum)} \) is the sum of all the efficiency losses, \( h \) is the functional heat, and \( r \) is the region of calculation. The lower heating value or the high heating value is affected by certain efficiency losses \( \gamma_{(sum)} \) [33] and that can be obtained as:

\[ \gamma_{(sum)} = L_{(mut)} + L_{(fg)} + L_{(lh)} + L_{(exf)} + L_{(ms)} \] (6)

\[ L_{(mut)} = PM_{(content)} \left( \frac{\Delta_{(steam)} - \Delta_{(water)}}{LHV} \right) \] (7)

\[ \Delta_{(steam)} = 1062.2 + \rho_{(bef.)} \times \left[ 0.4327 + 39.58 \times 10^{-6} \times \rho_{(bef.)} \right] \] (8)

\[ \Delta_{(water)} = \rho_{(aft.)} - 32 \] (9)

\[ L_{(fg)} = \pi_{(rate)} \times 24 \times \left[ \rho_{(bef.)} - \rho_{(aft.)} \right] \] (10)

\[ \pi_{(rate)} = \frac{1}{LHV} \times \left[ \left( (12.7 \times C + 38.1 \times H) \times \left( 1 + \frac{EX_{(air)}}{100} \right) - 0.5 \times O \right) \right] \] (11)

\[ L_{(lh)} = \left[ \rho_{(bef.)} - \rho_{(aft.)} \right] \times \left[ \frac{100 \times H \times 8.94}{LHV} \right] \] (12)

where \( L_{(mut)} \) is the moisture in fuel loss, which is calculated according to Ref. [33], \( PM_{(content)} \) is the percentage moisture content on a dry basis, \( \Delta_{(steam)} \) is the enthalpy of the steam leaving the stack at the flue gas temperature, \( \Delta_{(water)} \) is the enthalpy of the water, the enthalpies were calculated according to Ref. [32] and Ref. [37], \( \rho_{(aft.)} \) is the temperature of the combustion gas after combustion (°F), \( L_{(lh)} \) is the dry flue gas losses, \( \pi_{(rate)} \) is the mass flow rate of dry gas measured in pounds/Btu flue and was evaluated following Ref. [32] and Ref. [33], \( EX_{(air)} \) is the percentage of excess air utilized, \( L_{(lh)} \) is the latent heat loss, \( L_{(exf)} \) is the unburned fuel loss, and the value depends on the choice of boiler and the amount of excess air fed and is taken as 0.25% for fluidized bed combustion, 3.5% for stoker boiler, and 3% for cyclone combustors [32], \( L_{(ms)} \) is the othermiscellaneous loss, which is taken as the default value of 2.03% [33], and \( \rho_{(bef.)} \) is the temperature of the combustion gas before combustion (°F).

### 3.2. Environmental impact of incineration of single-use facemask waste

The section presents the method used to estimate the environmental impact of treating daily single-use facemask waste through incineration technology. The environmental impact assessment covers the global warming and acidification potential of the incineration of daily single-use facemask waste during the COVID-19 pandemic in Africa and Asia. The incineration of solid waste emits greenhouse gases such as carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), Sulphur hexafluoride (SF6), perfluorocarbons (PFCs), and hydrofluorocarbons (HFCs), which significantly contribute to global warming [38]. Aside from the emissions of greenhouse gases, the incineration process contributes to the emission of air pollutants such as hydrochloric acid, hydrogen fluoride, and Sulphur oxide, which cause acidic rain and forest destruction [36]. Due to the rare nature of the perfluorocarbons and hydrofluorocarbons, carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O) were the greenhouse gases considered for the global warming potential analysis in this study. Besides, the present study considered only hydrogen chloride gas (HCl) and Sulphur oxide gas (SO2) as the air pollutants for the acidification potential evaluation. Estimating greenhouse gas emissions to analyze the global warming potential of the incineration of single-use facemask waste was computed according to the methodology provided in the Intergovernmental Panel on Climate Change (IPCC) guideline for national greenhouse gas inventories [39]. Also, the air pollutant emissions for the calculation of acidification potential were based on the emission factor from US EPA “compilation of air pollutants emission factors” (AP-42) [36,40,41].

The emission of greenhouse gases from the incineration technology into the atmosphere in carbon dioxide equivalent per day (CO2eq/day) can be estimated as:

\[ \text{INC}_{(GWP)} = \sum_{\beta=1}^{n} EM_{\beta} + (EM_{CO2}) \] (13)

\[ EM_{\beta} = F_{(CHG)} \times GWP_{\beta} \times LHV \times F_{M(waste)} \] (14)

\[ EM_{CO2} = CP_{(fossil)} \times F_{M(waste)} \times OX_{(fact)} \times \frac{CO_{2}(\text{mole})}{C_{(\text{mole})}} \] (15)

where is the emission factors of the greenhouse gases, taken as 4 kg/TJ for nitrous oxide (N2O) and 30 kg/TJ for methane (CH4) [36], \( LHV \) is the lower heating value of the incinerated single-use facemask waste as obtained from Eqn. (5), \( GWP_{\beta} \) is the global warming potential of the greenhouse gases, given as 1 kg CO2eq for CO2, 25 kg CO2eq for CH4, and 298 kg CO2eq for N2O [39], \( \beta \) is the type of greenhouse gas, \( CO_{2}(\text{mole}) \) and \( C_{(\text{mole})} \) are the molar mass of carbon
dioxide and carbon, given as 44 kg/mol and 12 kg/mol, respectively [36]. \( OX_{\text{fact}} \) is the oxidation factor, which is given as 1 [39], and \( CP_{\text{fossil}} \) is the fossil carbon component, and 20% was taken as the default value [41] for the calculation in this study.

The emission of potential acid gases from the incineration of single-use facemask waste in Sulphur oxide equivalent per day (SO\(_2\)eq/day) was estimated as:

\[
ACD_{\text{(INC)}} = \sum_{a=1}^{2} s_{(a)} \times EF_{(a)}
\]

where \( s_{(a)} \) is the specific emission factor and is taken as 0.277 kg/mg for SO\(_2\) [41] and 0.106 kg/mg for HCl [39], \( EF_{(a)} \) is the Sulphur oxide (SO\(_2\)) equivalency factor, given as 1.0 kg SO\(_2\)eq for SO\(_2\) and 0.88 kg SO\(_2\)eq for HCl [36], and \( a \) is the type of acid gas considered in this study, which could be HCl or SO\(_2\).

4. Results and discussions

This section presents and discusses the power potential of treating daily single-use facemasks generated in African and Asian countries during the COVID-19 pandemic. The environmental impact of power generation through the incineration of daily single-use facemask waste is also presented and discussed. The ecological analysis conducted was expressed as global warming potential and acidification potential.

4.1. Results

4.1.1. Power generation potential of incineration of single-use facemask waste

The power generation potential of the estimated daily single-use facemask waste in Africa and Asia during the COVID-19 pandemic was evaluated, and the results are depicted in Figs. 1 and 2. The findings show that the treatment of the total daily single-use facemask waste of 2.23 billion pieces/day (equivalent to 19.12 million kg/day) in Asia could produce 32.65 million kWh/day of electricity. Fig. 1 indicates that the power generation potential of the incineration of daily single-use facemask waste in Asian countries ranges from 2171 kWh/day to 14.49 million kWh/day. The highest power generation in Asia was recorded in China (14.49 million kWh/day), India (5.59 million kWh/day), Bangladesh (1.45 million kWh/day), and Japan (1.36 million kWh/day), while the lowest was in Maldives (2171 kWh/day), Brunei (4054 kWh/day), Bhutan (4083 kWh/day), Timor-Leste (5014 kWh/day), and Bahrain (5038 kWh/day). From Fig. 2, it could be seen that the management of a total of 411.82 million pieces/day (equivalent to 3.53 million kg/day) of single-use facemask waste in Africa via incineration technology could generate 6.03 million kWh/day of electricity. Critical observation of Fig. 2 reveals that the power generation potentials of the single-use facemask waste in African countries is from 565 kWh/day to 1.09 million kWh/day. The African countries with the highest power generation from the incineration of single-use facemask are Nigeria (1.09 million kWh/day), Egypt (451.4...
thousand kWh/day), the Democratic Republic of the Congo (422.5 thousand kWh/day), South Africa (407.6 thousand kWh/day), and Algeria (328.4 thousand kWh/day), while the lowest are in Seychelles (565 kWh/day), Mayotte (1288 kWh/day), Sao Tome and Principe (1663 kWh/day), Comoros (2587 kWh/day), and Eswatini (3571 kWh/day).

4.1.2. Environmental impact analysis of incineration of single-use facemask waste

This section analyzed the environmental impact of managing single-use facemask waste during the COVID-19 pandemic in Africa and Asia via incineration technology for power generation. The environmental analysis is expressed as global warming potential and acidification potential. Fig. 3 displays the results of the global warming potential in Asia, while that of Africa is detailed in Fig. 4. Besides, the acidification potentials of incineration of a single-use facemask in Africa and Asia are depicted in Table 2. The findings show that the incineration of daily single-use facemask waste for power generation contributed to a total global warming potential of 787,097.6 kt CO$_2$eq/day in Asia and 145,687.7 kt CO$_2$eq/day in Africa. In Asian countries (see Fig. 3), the global warming potential varied from 52.3 kt CO$_2$eq/day to 349,399.1 kt CO$_2$eq/day. Countries such as China (349,399.1 kt CO$_2$eq/day), India (134,651.1 kt CO$_2$eq/day), and Indonesia (56,242.4 kt CO$_2$eq/day) recorded the highest global warming potential, while the lowest was in countries such as Bhutan (98.4 kt CO$_2$eq/day), Brunei (97.7 kt CO$_2$eq/day), and Maldives (52.3 kt CO$_2$eq/day). Critical observation of Fig. 4 shows that the daily global warming potential from the treatment of single-use facemask via incineration in African countries is from 13.6 kt CO$_2$eq/day to 26,545.1 kt CO$_2$eq/day. In countries such as Nigeria (26,545.1 kt CO$_2$eq/day), Egypt (10,897.7 kt CO$_2$eq/day), and the Democratic Republic of the Congo (10,201.4 kt CO$_2$eq/day), a
The findings demonstrate that managing single-use facemask waste through incineration is beneficial in both regions in power production. The result agrees with Ref. [15] that thermochemical conversion of disposable facemasks could be an economical way to minimize COVID-19 plastic waste and produce value-added products. Besides, this finding is consistent with the findings of Ref. [16], which recommended that the utilization of facemask for steam and electricity generation is a promising approach. This finding is also in line with Ref. [19], who found that the energy footprint of a disposable facemask in Morocco was 60 thousand GWh/year. Compared to Africa, the power generation potential in Asia was the highest, even though the study included more countries in Africa (57 countries) than Asia (49 countries). This could be attributed to the increased daily facemask waste in Asia due to the large population. China and India’s population contributed to Asia’s high facemask waste generation. This is consistent with Ref. [36] findings that population growth played a significant role in high solid waste generation in some areas in Nigeria, which contributed to increased electricity generation via waste-to-energy technologies. Besides, the high facemask waste generation, which led to increased power generation in Asia, could be attributed to the high acceptance rate of the single-use facemask to minimize the spread of the COVID-19 pandemic. This agrees with Ref. [10] and Ref. [14], which concluded that countries with a high acceptance rate of single-use facemask generated the highest daily facemask waste. Compared to Africa, the COVID-19 pandemic was earlier discovered in Asian countries such as China and India. As a result, authorities put measures to minimize the spread as scientists and health experts fought to find vaccines. The mandatory use of facemask was one of the primary measures introduced. That contributed to the increased usage of single-use facemask in these countries, contributing to the overall daily facemask waste generation in the Asian region. Besides, the increased power generation due to the increased amount of incinerated single-use facemask waste in Asia could be attributed to the strict policies that were put in place to make the wearing of facemasks compulsory before one could be allowed access to public areas such as shopping malls, cinema, restaurant, and banks. In African countries, the lower waste collection rates contributed to less single-use facemask waste
treatment by incineration, leading to lower power generation in the region. This is in line with the findings of Ref. [42], who attributed the lower electricity benefits of solid waste recycling in Africa to a lower waste collection rate in the region. The findings demonstrate that the world, especially developing countries, could utilize the increased single-use facemask waste for power generation. Power generation could contribute to a percentage of the energy needs of countries in the developing world. However, to realize the full benefits of the facemask waste during the pandemic, proper waste management practices such as collection and disposal should be intensified.

The study has shown that treating daily single-use facemask waste via incineration technology is beneficial in power generation in both regions. However, the environmental analysis indicates that the treatment process has severe ecological consequences in both regions. Both regions suffer a certain degree of greenhouse gas and acid gas emissions, leading to high daily global warming potential and acidification potential. This conflicts with the finding of Ref. [15], which suggested that thermochemical conversion of disposable facemasks could be an environmentally friendly way to treat COVID-19 plastic waste. However, our findings confirm that of Ref. [20] that the treatment of single-use facemask waste has an essential contribution to climate change. Similarly, our finding agrees with Ref. [19], whose research in Morocco indicated that the annual greenhouse gas emission from the treatment of single-use facemask was 640 kt CO₂eq/year. Management of single-use facemask waste via incineration might reduce its volume and weight but emits a significant amount of greenhouse and acid gases. Compared to Africa, the global warming potential and acidification potential in Asia are higher. The lower and high environmental impact (global warming potential and acidification potential) in Africa and Asia do not signify the incineration process’s good or bad environmental performance. Factors such as high population, early response to the COVID-19 pandemic spread via single-use face-mask, and high single-use facemask acceptance rate in most countries in Asia such as China and India resulted in a large amount of daily single-use facemask waste generation. This resulted in a high amount of incinerated single-use facemask waste in the region, resulting in high power production and emission of greenhouse and acid gases. In the African countries, a lower population coupled with a lower single-use facemask acceptance rate contributed to less waste generation, leading to lower power generation, greenhouse gases, and acid gases emissions. The lesson learned from these findings is that treating single-use facemask waste through incineration for power generation could contribute significantly to climate change. Therefore, countries in both regions should ensure proper incineration practices, such as the mandatory provision of air pollution control devices to the incineration facility and finding a suitable location for the incineration plants to minimize its direct environmental impact on humans’ health. This could enable countries to utilize single-use facemask waste produced during the COVID-19 pandemic as an environmentally friendly energy source through incineration technology.

![Fig. 4. Global warming potential of treatment of single-use facemask waste for power generation in Africa.](image-url)
5. Conclusions

This study evaluated the power generation potential and environmental impact of treatment of estimated daily single-use face mask waste generated during the COVID-19 pandemic in Africa and Asia. The environmental impact of the incineration process was estimated and expressed as global warming potential and acidification potential. It was found that the daily single-use facemask waste produced in Asia was 19.12 million kg/day, and this could generate a total of 32.65 million kWh/day of electricity. In Africa, 3.53 million kg/day of a single-use facemask was generated, generating 6.03 million kWh/day of power. This implies that incineration of single-use facemask waste has promising power generation potential for the countries in both regions. For governments to enjoy high power generation potential, increase facemask waste collection rate and proper disposal should be practiced. It was also found that despite its promising power potentials, incineration of single-use facemask waste has serious environmental

Table 2
Acidification potential of management of single-use facemask waste via incineration in Africa and Asia.

| Africa                  | Country | AP (kg SO₂eq/day) | Asia     | Country | AP (kg SO₂eq/day) |
|------------------------|---------|-------------------|----------|---------|-------------------|
| Algeria                | 71,196  | Afghanistan       | 62,237   |
| Angola                 | 48,967  | Armenia           | 6719     |
| Benin                  | 12,941  | Azerbaijan        | 5441     |
| Botswana               | 3818    | Bahrain           | 1092     |
| Burkina Faso           | 14,411  | Bangladesh        | 315,018  |
| Burundi                | 3702    | Bhutan            | 885      |
| Cabo Verde             | 841     | Brunei            | 879      |
| Cameroon               | 33,060  | Cambodia          | 10,124   |
| Central African Republic | 4619   | China             | 3,142,383|
| Chad                   | 8402    | Cyprus            | 1772     |
| Comoros                | 561     | Georgia           | 6772     |
| Congo                  | 8590    | Hong Kong         | 14,967   |
| Côte d’Ivoire          | 29,919  | India             | 1,211,009|
| Dem. Rep. of the Congo | 91,615  | Indonesia         | 505,826  |
| Djibouti               | 1736    | Iran              | 160,909  |
| Egypt                  | 97,808  | Iraq              | 98,405   |
| Equatorial Guinea      | 2278    | Israel            | 23,377   |
| Eritrea                | 4969    | Japan             | 294,695  |
| Eswatini               | 774     | Jordan            | 23,591   |
| Ethiopia               | 52,691  | Kazakhstan        | 27,562   |
| Gabon                  | 4306    | Kuwait            | 9345     |
| Gambia                 | 3171    | Kyrgyzstan        | 9264     |
| Ghana                  | 39,391  | Laos              | 6498     |
| Guinea                 | 11,390  | Lebanon           | 8757     |
| Guinea-Bissau          | 1970    | Macao             | 1652     |
| Kenya                  | 32,485  | Malaysia          | 22,397   |
| Lesotho                | 1477    | Maldives          | 471      |
| Liberia                | 5962    | Mongolia          | 5615     |
| Libya                  | 11,920  | Myanmar           | 42,892   |
| Madagascar             | 24,017  | Nepal             | 60,510   |
| Malawi                 | 7638    | Oman              | 6124     |
| Mali                   | 19,815  | Pakistan          | 196,221  |
| Mauritania             | 5894    | Palestine         | 10,105   |
| Mauritius              | 1160    | Philippines       | 155,571  |
| Mayotte                | 279     | Qatar             | 4260     |
| Morocco                | 52,539  | Saudi Arabia      | 74,237   |
| Mozambique             | 26,413  | Singapore         | 13,867   |
| Namibia                | 3108    | South Korea       | 46,262   |
| Niger                  | 9150    | Sri Lanka         | 54,443   |
| Nigeria                | 238,391 | Syria             | 34,978   |
| Reunion                | 1991    | Taiwan            | 22,400   |
| Rwanda                 | 5185    | Tajikistan        | 19,328   |
| Sao Tome and Principe  | 361     | Thailand          | 32,472   |
| Senegal                | 18,246  | Timor-Leste       | 1087     |
| Seychelles             | 123     | Turkey            | 82,812   |
| Sierra Leone           | 7629    | United Arab Emirates | 25,161 |
| Somalia                | 16,612  | Uzbekistan        | 42,751   |
| South Africa           | 88,379  | Vietnam           | 147,059  |
| South Sudan            | 6224    | Yemen             | 28,701   |
| Sudan                  | 34,132  |                   |          |
| Togo                   | 7917    |                   |          |
| Tunisia                | 18,400  |                   |          |
| Uganda                 | 26,446  |                   |          |
| United Rep. of Tanzania| 49,150  |                   |          |
| Western Sahara         | 1156    |                   |          |
| Zambia                 | 18,397  |                   |          |
| Zimbabwe               | 12,561  |                   |          |
| TOTAL                  | 1,308,362|                   | 7,078,904|

9
consequences in both regions. The global warming potential in Asia was 787,097.6 kt CO₂eq/day, and 145,687.7 kt CO₂eq/day was recorded in Africa. Besides, the total daily acidification potential of the incineration process in Asia was 7,078,904 kg SO₂eq/day, while that in Africa was 1,308,362 kg SO₂eq/day. This shows that to maintain single-use facemask waste as an ecologically friendly source of energy via incineration technique, the provision of air pollution control devices in every incineration plant should be enforced.

Credit author statement

Dan Cudjoe: Conceptualization, Methodology, Software, Writing – original draft, Validation, Investigation, Data curation, Funding acquisition, Hong Wang: Writing-Reviewing and Editing, Validation, Data curation, Bangzhu Zhu: Writing- Reviewing and Editing, Supervision, Funding acquisition

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The authors gratefully acknowledge the financial support of the National Natural Science Foundation of China (Grant No. 72050410354; 72074120; 71974077) and The Startup Foundation for Introducing Talent of NUIST (Grant No.2021r111).

Appendix

Table A1

| Africa | Country | Face mask (pieces/day) [10] | Asia | Country | Face mask (pieces/day) [14] |
|--------|---------|-----------------------------|------|---------|-----------------------------|
| Algeria | 22,409,695 | | Afghanistan | 19,589,901 |
| Angola | 15,413,069 | | Armenia | 2,114,901 |
| Benin | 4,073,411 | | Azerbaijan | 1,712,729 |
| Botswana | 1,191,263 | | Bahrain | 343,835 |
| Burkina Faso | 4,535,946 | | Bangladesh | 99,155,739 |
| Burundi | 1,857,232 | | Bhutan | 278,639 |
| Cabo Verde | 264,673 | | Brunei | 276,698 |
| Cameroon | 10,406,199 | | Cambodia | 3,186,715 |
| Central African Republic | 1,931,451 | | China | 989,103,299 |
| Chad | 2,844,243 | | Cyprus | 557,645 |
| Comoros | 176,539 | | Georgia | 2,131,462 |
| Congo | 2,730,929 | | Hong Kong | 4,711,180 |
| Côte d’Ivoire | 9,417,259 | | India | 381,179,657 |
| Dem. Rep. of the Congo | 28,836,895 | | Indonesia | 159,214,791 |
| Djibouti | 546,414 | | Iran | 50,648,022 |
| Egypt | 30,805,013 | | Iraq | 30,973,969 |
| Equatorial Guinea | 716,843 | | Israel | 7,358,072 |
| Eritrea | 1,564,116 | | Japan | 92,758,754 |
| Eswatini | 240,656 | | Jordan | 7,425,586 |
| Ethiopia | 16,200,032 | | Kazakhstan | 8,675,482 |
| Gabon | 1,857,232 | | Kuwait | 2,941,510 |
| Gambia | 998,059 | | Kyrgyzstan | 2,916,071 |
| Ghana | 12,398,478 | | Laos | 2,045,271 |
| Guinea | 3,453,219 | | Lebanon | 2,756,412 |
| Guinea Bissau | 619,943 | | Macao | 520,019 |
| Kenya | 5,039,728 | | Malaysia | 7,049,901 |
| Lesotho | 464,904 | | Maldives | 148,090 |
| Liberia | 1,876,470 | | Mongolia | 1,767,209 |
| Libya | 3,752,027 | | Myanmar | 13,500,977 |
| Madagascar | 7,559,728 | | Nepal | 19,046,387 |
| Malawi | 2,310,395 | | Oman | 1,927,692 |
| Mali | 6,237,029 | | Pakistan | 61,762,860 |
| Mauritania | 1,853,219 | | Palestine | 3,180,505 |
| Mauritius | 365,005 | | Philippines | 48,967,769 |
| Mayotte | 87,849 | | Qatar | 1,341,008 |
| Morocco | 16,537,438 | | Saudi Arabia | 23,367,155 |
| Mozambique | 8,311,751 | | Singapore | 4,364,782 |
| Namibia | 978,327 | | South Korea | 14,561,501 |
| Niger | 2,880,031 | | Sri Lanka | 17,136,519 |
| Nigeria | 75,036,504 | | Syria | 11,009,748 |
| Reunion | 626,763 | | Taiwan | 7,050,832 |
| Rwanda | 1,632,016 | | Tajikistan | 6,983,580 |
| Sao Tome and Principe | 113,333 | | Thailand | 10,220,851 |
| Senegal | 5,743,177 | | Timor-Leste | 342,230 |
| Seychelles | 38,554 | | Turkey | 26,066,112 |
| Sierra Leone | 2,401,232 | | United Arab Emirates | 7,919,835 |
| Somalia | 5,228,757 | | Uzbekistan | 13,456,309 |
| South Africa | 27,818,336 | | Vietnam | 46,288,632 |
| South Sudan | 1,931,451 | | Yemen | 9,032,000 |

D. Cudjoe, H. Wang and B. Zhu Energy 249 (2022) 123707
Table A1 (continued)

| Africa | Country | Face mask (pieces/day) [10] |
|--------|---------|-----------------------------|
| Sudan  | 10,743,490 |
| Egypt  | 2,491,991 |
| Tunisia| 5,791,632 |
| Uganda | 8,324,130 |
| United Rep. of Tanzania | 15,470,682 |
| Western Sahara | 363,789 |
| Zambia | 5,790,811 |
| Zimbabwe | 3,953,900 |
| TOTAL  | 4,118,224,984 |

Table A2

Ultimate analysis of single-use face mask waste [17].

| % Carbon | % Hydrogen | % Oxygen | % Nitrogen | % Sulphur | % Ash | % Moisture |
|----------|------------|----------|------------|-----------|-------|------------|
| 75.9     | 14.9       | 8.4      | 0.8        | N/A       | 9.5   | 0          |

References

[1] Torales J, O’Higgins M, Castaldelli-Maia JM, Ventriglio A. The outbreak of COVID-19 coronavirus and its impact on global mental health. Int J Soc Psychiatr 2020;66(4):317–20. https://doi.org/10.1007/s10276-020-01522-2.

[2] Chakraborty I, Maity P. COVID-19 outbreak: migration, effects on society, global environment and prevention. Sci Total Environ 2020;728:138882. https://doi.org/10.1016/j.scitotenv.2020.138882.

[3] Ciotti M, Ciccuzi M, Terrinoni A, Jiang W-C, Wang C-B, Bernardini S. The COVID-19 pandemic. Crit Rev Clin Lab Sci 2020;57:365–88. https://doi.org/10.1080/01469580.2020.1781398.

[4] Tison GH, Avram R, Kuhar P, Abreau S, Marcus GM, Pletcher MJ, Olgin JE. Liﬁcation layer - characterization of heavy metals and dioxins in COVID-19 waste. J Environ Chem Eng 2021;9:105222. https://doi.org/10.1016/j.jece.2021.105222.

[5] Benson UN, Fred-Ahmud HO, Bassey ED, Arayero AA. COVID-19 pandemic and emerging plastic-based personal protective equipment waste pollution and management in Africa. J Environ Chem Eng 2021;9:105222. https://doi.org/10.1016/j.jece.2021.105222.

[6] Benson UN, Bassey ED, Palanisami T. COVID pollution: impact of COVID-19 pandemic on global plastic waste footprint. Helyon 2021;7(2):e06343. https://doi.org/10.1016/j.helyon.2021.e06343.

[7] Chowdhury H, Chowdhury T, Sait MS. Estimating marine plastic pollution generation during the COVID-19 pandemic in Iran: challenges and problems. Int J Health Life Sci 2021;7(3):e115046. https://doi.org/10.5812/ijhls.115046.

[8] Mejnad N, Cherif EK, Rodero A, Krawczyk DA, El Kharrar J, Mounen A, Lqaibagi M, Feki A. Disposal behavior of used masks during the COVID-19 pandemic in the Moroccan community: potential environmental impact. Int J Environ Res Publ Health 2021;18(8):4382. https://doi.org/10.3390/ijerph18084382.

[9] Lee AWL, Neo ERK, Khoo Z-Y, Yeo Z, Tan SY, Chng S, Yan W, Lok BK, Low C, S J. Life cycle assessment of single-use surgical and embedded ﬁlter layer (EFL) reusable face mask. Resour Conserv Recycl 2021;170:105580. https://doi.org/10.1016/j.resconrec.2021.105580.

[10] Brunner HP, Rechberger H. Waste to energy – key element for sustainable waste management. Waste Manag 2015;37:3–12. https://doi.org/10.1016/j.wasman.2014.02.003.

[11] Escamilla-García FP, Camarillo-López HR, Carrasco-Hernández R, Fernández-Rodríguez E, Legal-Hernández MJ. Technical and economic analysis of energy generation from waste incineration in Mexico. Energy Strategy Reviews 2020;31:1000542. https://doi.org/10.1016/j.esr.2020.100542.

[12] Damgaard A, Riber C, Fruegraedt T, Hugløa T, Christensen HT. Life-cycle assessment of the historical development of air pollution control and energy recovery in waste incineration. Waste Manag 2010;30(7):1244–50. https://doi.org/10.1016/j.wasman.2010.03.025.

[13] Kaza S, Yao L, Bhada-Tata P, Woerden VF. What waste a 2.0 A global snapshot of solid waste management to 2050. Washington, DC 20433, US: World Bank Publications, The World Bank Group, 1818 H Street NW; 2018. https://doi.org/10.1596/978-1-464-1329-9. ISBN (paper): 978-1-464-1329-9 (ISBN electronic): 978-1-464-1347-4.

[14] Buekens A. Incineration technologies. Springer New York Heidelberg Dor- drecht London; 2013. https://doi.org/10.1007/978-1-4614-5752-7. ISBN (electronic) 978-1-4614-5752-7 (Ebook).

[15] Damgaard A, Riber C, Fruegraedt T, Hugløa T, Christensen HT. Life-cycle assessment of the historical development of air pollution control and energy recovery in waste incineration. Waste Manag 2010;30(7):1244–50. https://doi.org/10.1016/j.wasman.2010.03.025.

[16] Silva ERBV, Cardozo J. Chapter 1 – introduction and overview of using computational fluid dynamics tools. Computational Fluid Dynamic Applied to Waste-to-energy Process 2020:3–28. https://doi.org/10.1007/978-90-8-817540-8-00001-7.

[17] Kumar S, Ankaram S. Chapter 12 - waste-to-energy model/tool presentation. Current Development in Biotechnology and Bioengineering. 2019:239–58. https://doi.org/10.1007/978-0-444-64083-3.00012-9.

[18] OBE DKR, Ghaatara SG, Lynn JC. 3 - sewage sludge ash production. Sustainable Construction Materials 2017:25–67. https://doi.org/10.1051/procconf/20171200120017.

[19] Youcai Z, Chapter five - characterization of heavy metals and dioxins in ﬂy ash. Pollution Control and Resource Recovery: Municipal Solid Wastes Incineration 2017:161–90. https://doi.org/10.1007/978-0-812-811265-8-00005-5

[20] Barros MR. 16 - MSW ash. Waste and supplementary cementitious materials in concrete. 2018. p. 513–57. https://doi.org/10.1051/procconf/201808-0121356-600003-2.

[21] Ogunjuyigbe ASO, Ayodele TR, Alao MA. Electricity generation from municipal solid waste in some selected cities of Nigeria: an assessment of feasibility, potential and technologies. Renew Sustain Energy Rev 2017;80:149–88. https://doi.org/10.1016/j.rser.2017.05.177.

[22] Jorgenson J, Gilman P, Dobos A. Technical manual for the SAM biomass power generation model. Golden, CO (United States): National Renewable Energy Publications, The World Bank Group, 1818 H Street NW; 2018. https://doi.org/10.2172/1026561.
[34] Gómez A, Zubizarreta J, Rodrigues M, Dopazo C, Fuego N. Potential and cost of electricity generation from human and animal waste in Spain. Renew Energy 2010;35(2):498–505. https://doi.org/10.1016/j.renene.2009.07.027.
[35] Parikh J, Channiwala AS, Ghosal KG. A correlation for calculating HHV from proximate analysis of solid fuels. Fuel 2005;84(5):487–94. https://doi.org/10.1016/j.fuel.2004.10.010.
[36] Ayodele TR, Ogunjuyigbe ASO, Aalao MA. Life cycle assessment of waste-to-energy (WtE) technologies for electricity generation using municipal solid waste in Nigeria. Appl Energy 2017;201:200–18. https://doi.org/10.1016/j.apenergy.2017.05.059.
[37] Igosi HA, Ayotamuno MJ, Eze CL, Ogaji SOT, Probert DS. Designs of anaerobic digesters for producing biogas from municipal solid waste. Appl Energy 2008;86(6):430–8. https://doi.org/10.1016/j.apenergy.2007.07.013.
[38] Cudjoe D, Acquah MP. Environmental impact analysis of municipal solid waste incineration in African countries. Chemosphere 2021;265:129186. https://doi.org/10.1016/j.chemosphere.2020.129186.
[39] IPCC. IPCC guidelines for national greenhouse gas inventories. Geneva, Switzerland: IPCC fourth assessment report; 2006.
[40] Environmental Protection Agency (EPA). Solid waste disposal. Refuse combustion. AP 42, fifth ed. 1996. USA.
[41] Assamo B, Lawryshyn Y. The environmental comparison of landfilling vs. incineration of MSW accounting for waste diversion. Waste Manag 2012;32(5):1019–30. https://doi.org/10.1016/j.wasman.2011.10.023.
[42] Cudjoe D, Zhu B, Nketiah E, Wang H, Chen W, Qianqian Y. The potential energy and environmental benefits of global recyclable resources. Sci Total Environ 2021;798:149258. https://doi.org/10.1016/j.scitotenv.2021.149258.