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The majority of e-waste is transported from developed to developing countries and there is no appropriate e-waste treatment technology in some developing countries. Ghana is suffering from serious e-waste environmental pollution. Currently, Agbogbloshie (Ghana) treat incoming e-waste in hand, harming the workers’ health. Therefore, we proposed the “e-waste management process for Ghana (EWMP-G).” First, we carried out a literature survey, to identify the current status of the problem and investigate the available technologies. Additionally, we categorized the discarding stage of the life cycle assessment into three steps: 1) sorting, 2) Refuse Derived Fuel (RDF), and 3) incineration. Second, personal computers, refrigerators, and mobile phones, considered high-ranking e-waste entering Ghana, were selected as the samples. We prepared an e-waste dismantling and sorting guidebook, to ensure the workers’ safety. For RDF processing, we applied “shredding” and “pelletizing,” and for incineration, we selected a stoker-type incinerator. RDF and stocker incineration can remove the plastic from e-waste in Ghana in approximately 4.65 years and 0.264 months each. Based on the cost-benefit analysis, the EWMP-G could result in a surplus and manage the e-waste in Ghana within 4.65 years of EWMP-G.

KEYWORDS: Ghana, E-waste, RDF, eco-friendly, Waste assessment

Introduction

As an increasing number of people consume and use electronic devices, the amount of electronic waste (e-waste) is also increasing. Notably, e-waste consists of electronic products that are discarded by their owners but are not broken or unavailable (European Union, 2002; Luther, 2010; United Nations Environment Program, 2007). Waste electric and electronic equipment (WEEE) refers to devices that cannot be used as EEE.

In 2019, 53.6 Mt of e-waste was generated in the world, a significant increase from the 44.75 Mt generated in 2016 (Bald \textit{et al.}, 2020) and 9.2 Mt generated in 2014. On a global scale, as the total weight of EEE consumption increases annually by 2.5 Mt, global e-waste generation is estimated to grow to 74.7 Mt by 2030 (Fortie \textit{et al.}, 2020).

Globally, with an increase in the amount of e-waste, new legislation, policies, and regulations related to e-waste management are also being developed. The Basel Convention is a global agreement that regulates the transboundary movement of hazardous and electronic waste. Notably, the Basel Convention and European Union’s WEEE Directive are representative legislation to prevent an increase in the amount of e-waste and environmental load resulting from improper e-waste treatment.

Although countries have developed and implemented new legislation related to e-waste management, almost 82.6% of e-waste is discarded in a non-environment-friendly manner and illegally traded (Forti \textit{et al.}, 2020; Li \textit{et al.}, 2013).

This study aims to propose an effective e-waste management process for Ghana (EWMP-G) that can allow for eco-friendly e-waste life cycle assessment while suggesting viable processes that can be used to reduce the country’s e-
waste in the short-term. Notably, our study can mitigate and reduce e-waste in other countries and help global economies mitigate and curb environmental issues related to e-waste management.

1. Study area

In this study, we selected Ghana as our study area. Agbogbloshie, located in central Accra, which is the capital city of Ghana; it is the largest informal e-waste recycling scrap market, with an area of 313,000 m$^2$. In fact, in 2013, the Blacksmith Institute of the United States and Swiss Green Cross announced that Agborgloshie in Ghana was one of the world’s top 10 polluted regions (Bernhardt et al., 2013; Earth et al., 2016).

Electronic waste imported to Ghana is collected in Agbogbloshie; generally, this waste is illegally traded through the informal sector and dismantled in an unsafe manner by untrained workers (Kaifie et al., 2020). Developed countries are the ones that generally dump or trade e-waste in Ghana illegally. We chose Ghana as our study area because the illegal e-waste trade with developed countries is the cause of Ghana’s serious environmental problems (Fortie et al., 2020; Rautela et al., 2021). As this is not right from an ethical point of view, Ghana’s environmental problems resulting from e-waste must be resolved as soon as possible.

Moreover, Ghana’s e-waste problem poses serious health risks for the people working in the e-waste processing site. The number of informal and untrained workers in Agbogbloshie is between 4500 and 6000, and more than 90% of them come from poor regions, such as Northern Ghana, Nigeria, and Liberia (Brigden 2005; Höltl et al., 2017; Oteng-Ababio et al., 2020). They work 10-12 hours/day to maintain their livelihood, with their monthly wages being USD 70-140 (Höltl et al., 2017), which is higher than the average income in Ghana; however, they work in poor working conditions that pose serious health risks.

When they break down the e-waste, they use their bare hands to burn or melt the devices, without using any protective mask, gloves, and clothes, even though e-waste contains several hazardous components, including toxic substances, such as heavy metals (Kaya, 2016). (e.g., lead, mercury, chromium, and polychlorinated biphenyls).

Also, the waste sector contributed 14% of Ghana’s total greenhouse gas emissions (Amlalo, 2015). Also, the Environmental Protection Agency Ghana (EPA-Ghana) measured the annual mean PM5 and PM10 levels in residential areas at 78 and 81 lg/m$^3$, respectively, which exceeds the guidance level recommended by the World Health Organization (WHO) (Kanhai et al., 2021).

Thus, illegal e-waste trade with developed countries and continuous informal e-waste incineration are continually deteriorating the environment and the health of e-waste workers in Ghana. To prevent further environmental pollution in Ghana, we need a special system that can collect, transport, dispose of, treat, and recycle e-waste. In other words, there is an urgent need to develop treatment systems that can minimize the hazardous impact of e-waste in Agbogbloshie, Ghana, along with a complete e-waste management system (Wath et al., 2021). Considering the health of workers and the accelerating environmental pollution in Ghana, a proper e-waste management process must be executed in Agbogbloshie.

2. Previous Studies for Ghana and its E-waste

Research on the process of e-waste managements in Ghana has been conducted extensively since 2010, particularly focusing on the challenges and the adoption of sustainable technologies at Agbogbloshie, a complex interplay of socio-economic, technological, and regulatory factors that impacts the e-waste management landscape in Ghana.

It is highlighted that a substantial portion of imported electronics are non-functional and end up exacerbating Ghana’s solid waste management challenges (Oteng-Ababio, 2010; Adanu et al., 2020). Oteng-Ababio (2010) emphasizes the environmental and health hazards posed by informal e-waste recycling practices, which often involve open burning and chemical treatment, releasing toxic substances into the environment.

Adanu et al. (2020) explores the technical and financial constraints faced by e-waste workers at Agbogbloshie, who predominantly rely on primitive methods for e-waste dismantling due to the lack of access to safer and more sustainable technologies.

Despite the evident challenges, the Ghanaian government has made strides towards regulating e-waste management, as seen in the enactment of Act 917 to establish a national e-waste management plant. This legislation marks a critical step towards formalizing e-waste management and integrating sus-
tainable practices.

In conclusion, the previous body of research underscores the urgent need for comprehensive e-waste management strategies in Ghana that incorporate technological innovation, capacity building, and robust regulatory frameworks to mitigate the environmental and health impacts of e-waste. It calls for a collaborative effort among stakeholders, including the government, the informal e-waste sector, and international partners, to foster sustainable e-waste management solutions that not only address the immediate health and environmental concerns but also contribute to the economic empowerment of the local communities involved in e-waste recycling.

3. E-waste management process for Ghana (EWMP-G)

In this study, we proposed an e-waste management process for Ghana (EWMP-G) to mitigate the current e-waste environmental problems in Agbogbloshie, Ghana. The proposed EWMP-G is a life cycle assessment (LCA), which is a proper management system that can be used to examine the complete life of a product, from production to recycling. It is generally used for assessing the performance of e-waste management (Allesch et al., 2014).

Additionally, EWMP-G is an appropriate technology (AT) used for the e-waste processing site in Agbogbloshie; AT expands individual freedom during application and minimizes the damage caused to the environment. The goal of EWMP-G is sustainable consumption and production (SCP), which corresponds to the SDGs (sustainable development goals) number 12. By proposing the EWMP-G, we expect to minimize the hazardous impacts of e-waste and protect the health of workers and nearby residents.

In this study, we developed the different steps of the EWMP-G, while considering its pros and cons systemically. Then, we assessed the impact of the EWMP-G, while focusing on its economic feasibility, environmental impact, and applicability at the global scale.

4. Study Topic

Our study topic is the environmental pollution caused by e-waste in Agbogbloshie, Ghana. In this study, we proposed a viable waste management process to solve the environmental pollution in Ghana resulting from e-waste, while ensuring the safety of the workers responsible for discarding the waste. As most international agreements are not effective, in this study, we considered the Basel Convention, which aims to monitor and regulate the import and export of e-waste in Ghana.

Currently, Ghana residents burn the wire from e-waste and landfill e-waste. The method proposed in this study can optimize the existing method and minimize the risks to human health and the environment in Ghana; notably, our method is more systematic and eco-friendlier, compared to the existing method.

The waste management process proposed in this study is called the e-waste management process for Ghana (EWMP-G). After describing each step of the EWMP-G, we assessed its performance from environmental and economic aspects. Then, we described the limitations of the current regulations and suggested alternative regulations, in line with the aims of the Basel Convention. (i) The international trade of e-waste flow is in contrast to the Basel Convention since the ambiguous definition of e-waste as a trade category (Petridis et al., 2020), and (ii) The Basel Convention is the most comprehensive global environmental agreement on wastes with 175 parties (UNEP, 1995). Therefore, it is necessary to clarify the category of e-waste and establish detailed legislation in Basel Convention.

In this study, only a few electrical devices were selected [personal computers (PCs), mobile phones, and refrigerators], which represent the major devices that contribute to e-waste in Agbogbloshie. Additionally, we considered the main types of e-waste that existed in Ghana for each large and small electronic product.

There are various types of e-waste, such as televisions (TVs), mobile phones, and air conditioners. Thus, to develop the guidelines for the dismantling and sorting processes and evaluate the environmental effects of the EWMP-G, we calculated and searched for the components and amount of e-waste for each device.

To develop effective guidelines for the dismantling and sorting process, PCs, and mobile phones were selected as the study topic, for more specific and realistic data. Notably, mobile phones account for about 60% of the e-waste buried in Agbogbloshie, Ghana (the World Bank, 2015). Also, PCs and mobile phones are representative of electrical equipment (the World Bank, 2015).
Methods

1. Literature analysis for developing an e-waste management process for Ghana (EWMP-G)

To explore the general process for e-waste management in Ghana, we considered the disposal of e-waste and the regulation of existing waste sources, using the existing literature as the foundation. We looked for journals that published studies similar to our topic, using “developing countries,” “e-waste,” and “manufacturing processes” as the keywords, finally, selecting three main journals: “Global Environmental Change,” “Journal of Environmental Management,” and “Waste Management.” We looked through these three main journals between 2017 and 2021 and used “e-waste,” “LCA (life cycle assessment),” “Agbogbloshie,” “Accra,” “waste management,” or “e-waste management,” “WEEE (waste electrical and electronic equipment),” “Ghana” as the keywords.

First, in the “Global Environmental Change” journal, we found two studies that used “e-waste” as the keyword, two that used “LCA (life cycle analysis),” one that used “Agbogbloshie,” seven that used “waste management,” and three that used “Ghana.”

Second, in the “Journal of Environmental Management,” there were 10 studies that used “e-waste” as the keyword, 8 that used “LCA (life cycle assessment),” 1 that used “Accra,” 4 that used “e-waste management,” 3 that used “WEEE (waste electrical and electronic equipment),” and 7 that used “Ghana.”

Finally, in the “Waste Management” journal, we found 35 studies that used “e-waste” as the keyword, 10 that used “LCA (life cycle assessment),” 1 that used “Accra,” 41 that used “waste management,” 28 that used “WEEE (waste electrical and electronic equipment),” and one that used “Ghana.”

The literature analysis was conducted by reading all the study manuscripts found by searching for keywords. In addition, we searched for studies similar to our topic on Google Scholar and other journals.

2. Reverse engineering and sorting process method

For the dismantling and sorting steps of the EWMP-G, we prepared a customized guidebook for the e-waste in Agbogbloshie. To ensure that our guidelines were applicable to workers in Ghana’s electronic waste dumps, we chose PCs and mobile phones as the samples for the decomposition experiment, while considering the amount and representativeness of e-waste devices.

For the decomposition experiment of PCs, we selected the ASUS K52F laptop model. For the mobile phones, we selected the Galaxy S5 model (SM-G900A). We disassembled the ASUS K52F laptop and Galaxy S5 phone and categorized the parts into valuable metals, polychlorinated biphenyls (PCBs), and plastics. After the laptop and mobile phone decomposition experiment, we developed the guidelines for decomposition and sorting, utilizing the results of our experiment.

3. Selection of plastic treatment method

To deal with plastic parts of e-waste in Ghana, we investigated the existing treatment using a literature survey method.

Globally, the representative processes of treating plastic waste are landfill, incineration, and discharge into the environment (Lee et al., 2021; Geyer et al., 2017). Finally, we chose three methods: landfill, incineration, and refuse-derived fuel (RDF), to develop an effective method for plastic waste treatment. In this study, the three methods were compared based on three standards: eco-friendliness, economic feasibility, and practicality. Finally, we chose an effective RDF that could supplement our study’s aims.

After we decided to deal with plastic waste using the RDF process, a literature analysis method was used to find a specific model of RDF that could be customized to remove plastic waste effectively.

Moreover, in ‘Utilization plan and the prospect of waste solid fuel’, RDF technology is used widely in developed countries, such as the United States of America (USA), Japan, and Europe. Among many RDF models, we selected the Japanese model (Kahada Okuise Recycling Plaza in Japan) because considering the country’s history, eco-friendliness, and processing capacity.

In this study, we decided to apply the RDF model that is commonly used in developed countries. Among all the analyzed RDF models, we selected the Japanese model because considering the country’s history, eco-friendliness, and processing capacity. The result and the detailed information are written in Table 1 of the supplementary file.

In contrast to the existing RDF model’s process, we made our distinction as to how the EWMP treats e-waste. A normal RDF process consists of 1) screening, 2) moisture reduction, 3) shredding, and 4) pelletizing. The RDF steps of the EWMP
were selected from the normal RDF process, based on the characteristics of the e-waste.

4. Selection of other components of e-waste and stocker incinerator

The method of treating the other waste was determined while considering the three standards: eco-friendliness, economic feasibility, and practicality. We considered the existing methods of solid waste management, along with the representative methods of incineration, landfills, and upcycling (Mulya et al., 2022) which are more specifically mentioned in the Table 2 of the supplementary file. Finally, we chose the incineration method.

After we decided to manage the other e-waste components using incinerators, we determined the most effective incinerator for the EWMP-G process.

The main types of incinerators are: 1) stoker, 2) rotary kiln, 3) fluidized bed, and 4) plasma pyrolysis incinerators. To select the type of incinerator, we compared the strengths and strengths and limitations of four different incinerator models.

Ireland, Italy, France, Japan, and many other countries use stoker incinerators. The criteria for the countries to select the model were based on the country’s history and the fact that these incinerators are eco-friendly.

In this study, we selected incineration as the method for performing a comparative analysis of the ideas to process the “other components” of e-waste. We set a standard and performed a comparative analysis of several models; the stoker incinerator was the most effective for this study. Among many stoker incinerators through the standards presented in the research method, we selected the Yokohama city resources recycling bureau Asahi factory stoker incinerator. More detailed information about this incinerator model is written in the Table 6 of the supplementary file.

5. E-waste management process for Ghana (EWMP-G): Suitability Assessment Elements application methodology

There are many elements in e-waste devices. In this study, we classified the elements of e-waste, while considering the: 1) efficiency of the EWMP-G, 2) the current method applied in Ghana for e-waste-processing, and 3) the characteristics of e-waste devices.

Also, by conducting a decomposition experiment on mobile phones and laptops, we determined the effective methods to treat each component of the e-waste.

6. Study area selection

To determine the suitability of introducing this process, we identified the local e-waste area using ResearchGate. Then, we set the standards for site selection and selected the most suit-

| Table 1. Results Of Dismantling Mobile Phones and Personal Computers (PCs) |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|
|                                 | Weight of the   | Proportion (%)  | Weight of the   | Proportion (%)  |
|                                 | components (g)  |                  | components (g)  |                  |
| Plastic                         | 45.3349         | 33.97           | 1008.92         | 49.987          |
| Metal                           | 49.0934         | 36.79           | 448.49          | 20.887          |
| PCBs                            | 13.8657         | 10.39           | 325.67          | 15.167          |
| Other components                | 25.1387         | 18.84           | 364.16          | 16.959          |
| Total                           | 133.45          | 100             | 2147.24         | 100             |

*source & reference: [13, 29]

| Table 2. Comparison and analysis of the advantages and disadvantages of two e-waste sites in Agbogbloshie |
|-------------------------------------------------------------|-------------------------------------------------------------|
| North e-waste site                                          | South e-waste site                                           |
| *(5°33'12.40"N, 0°13'39.91"W)*                              | *(5°54'56.57"N, -0°22'41.38"W)*                             |
| – No residential area nearby                                | – Worker’s Residential Area                                 |
| – Near Odaw River and Hansen Road (having good accessibility)| – Near local food market                                     |
| – Undeveloped area                                          | – Insufficient area to install the EWMP                      |
| – Near to existing scrap metal yard                         | – Vulnerable to flooding                                     |

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able area. In this study, the three site selection standards were: 1) electricity supply efficiency, 2) transportation accessibility, and 3) workers’ electronic-waste disposal routines.

We evaluated and selected the regions based on these three standards. Among the selected regions, we analyzed and compared the characteristics of each region. After comparing the regions, we selected the final site to implement the EWMP-G proposed in this study 6.5.

7. Environmental assessment

7.1. Amount of e-waste in Ghana

To identify the environmental expectation effect of the EWMP-G, we considered the amount of reduced e-waste by applying the EWMP-G to Agbogbloshie, Ghana.

Through literature analysis, we could determine the total weight of used-electronic import tonnage volume between 2010 and 2018 (Grant et al., 2021). Refer to Table 7 of the supplementary file, we calculated the annual average tonnage volume of the used electronic devices imported in the past 9 years (2010-2018).

By adding the annual import tonnage volume averages of the used PCs, refrigerators, and mobile phones, we calculated the total amount of e-waste imported into Ghana in 1 year.

In addition to the annual import of e-waste in Ghana, it is also necessary to find the amount of e-waste originally discarded in Ghana, i.e., the current amount of e-waste in Ghana. Through literature analysis, we calculated the amount of e-waste discarded in Ghana in 2020 and determined the number of PCs, refrigerators, and mobile phones present in Ghana in 2020. Additionally, we calculated the average weight of PCs, refrigerators, and mobile phones. By multiplying the number of e-waste (PCs, refrigerators, and mobile phones) currently in Ghana with the average weight of e-waste (PCs, refrigerators, and mobile phones), we calculated the weight (ton) of PCs, refrigerators, and mobile phones in Ghana. Notably, refer to Table 8 of the supplementary file, we assumed the amount of electronic waste in 2020 in Ghana as the current amount.

7.2. Refuse-derived fuel (RDF)

To evaluate the environmental effect of the RDF process, we calculated the amount of plastic to be treated, using the RDF process proposed in the EWMP-G as shown in Table 3 of the supplementary file.

### Table 3. Total profit and cost of e-waste management process for Ghana (EWMP-G)

<table>
<thead>
<tr>
<th>Precious metal</th>
<th>Production electricity</th>
<th>Incinerator</th>
<th>Installation</th>
<th>Workers’ income</th>
<th>Total profit:</th>
<th>Total cost:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe</td>
<td>930,344.25 USD/yr + USD 276,647.9</td>
<td>Incinerator Producing electricity 4,826,095.778 USD/yr</td>
<td>USD 236,510,000</td>
<td>5,374,040.73 USD/yr</td>
<td>USD 255,059,398 (fix) + 6,398,616.185 (yr)</td>
<td>USD 259,901,814.5 (fix) + 5,374,040.73 (yr)</td>
</tr>
<tr>
<td>Al</td>
<td>334728 USD/yr + USD 2,161,008</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cu</td>
<td>185096.34 USD/yr + USD 8,252,227.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ag</td>
<td>4895 USD/yr + USD 13,255,000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Au</td>
<td>53718.467 USD/yr + USD 140,156,363.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pd</td>
<td>4135.95 USD/yr + USD 11,258,973.04</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>International cooperation</td>
<td>Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) USD 10,965,600 (GIZ) + 21,931,200 (EPR)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EU</td>
<td>USD 1,425,528</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GDPC</td>
<td>USD 22,700,600</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Germany</td>
<td>USD 27,676,250</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Note:
Deutsche Gesellschaft für internationale Zusammenarbeit (GIZ)
European Union (EU)
Ghana deposit Protection Corporation (GDPC)
To calculate the amount of plastic to be treated with RDF, we used a method to add the amount of plastic from the current existing Ghana e-waste (PCs, refrigerators, and mobile phones) and the amount of e-waste flowing into Ghana every year with the following formula.

\[
\text{(The amount of plastic to be treated with RDF)} = (\text{Plastic ratio in PCs, mobile phones, refrigerator}) \times \{(\text{the total amount of used PCs, mobile phones, refrigerators imported into Ghana annually}) + (\text{The number of used PCs, mobile phones, refrigerators in Ghana in 2020})\}
\]

In addition, the plastic ratio in PCs, and mobile phones were determined by the decomposition experiment and the ratio of refrigerators was determined by using data from the existing literature. We used the same method for calculating the amount to be treated with incinerators.

Further, we investigated the amount of plastic that could be processed per hour using our RDF model. Through literature analysis, we determined the capacity utilization rate of the proposed RDF model. Then, we calculated the number of years required to treat the total amount of plastic, using the RDF process. Thus, we evaluated and calculated the results of the environmental effects of the RDF process in the EWMP-G.

7.3. Incinerator

In this study, we calculated the amount of waste that could be disposed of in the incinerator to evaluate the environmental effects of the incineration process of the EWMP-G as shown in the Table 4 of the supplementary file.

To calculate the weight of the e-waste that could be disposed of using the stoker incinerator, we used the following formula.

\[
\text{(The amount of e-waste to be treated with Incinerator)} = (\text{etc. ratio in PCs, mobile phones, refrigerator}) \times \{(\text{the total amount of used PCs, mobile phones, refrigerators imported into Ghana annually}) + (\text{The number of used PCs, mobile phones, refrigerators in Ghana in 2020})\}
\]

In addition, the number of other components was calculated after excluding the metal and plastic contents from the e-waste.

8. Economic assessment

To identify the economic effects of the proposed process, we categorized the effects as losses and gains. The losses included: 1) the cost of RDF installation and operation, 2) the cost of installing and operating the stoker incinerator, and 3) the income of the workers at the processing site.

The installation and operation costs were calculated by adopting the cost of our selected RDF and stoker incinerator model. We calculated the workers’ income based on the available relevant literature (Höltl et al., 2017; Oteng-Ababio et al., 2020; Prakash et al., 2010).

The profits included those from selling RDF, electricity from the stoker incinerator, precious metals (Fe, Al, Cu, Ag, Au, and Pd), and subsidies from International Cooperations.

We analyzed the literature to find the precedents and examples of subsidy payments in developing countries. Notably, in this study, we assumed that such international support and subsidies were provided to Ghana.

Table 4. Comprehensive Summary Analysis of Environmental Impact, Economic Feasibility, and Practicality Results

<table>
<thead>
<tr>
<th>Summary of the Results</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Environmental Impact</strong></td>
</tr>
<tr>
<td>Approximately 5 years following the implementation of the EWMP-G, it is anticipated</td>
</tr>
<tr>
<td>that all remaining e-waste in Ghana and annually imported e-waste will be cleared from</td>
</tr>
<tr>
<td>the e-waste site in Agbogbloshie, Ghana.</td>
</tr>
<tr>
<td><strong>Economic Feasibility</strong></td>
</tr>
<tr>
<td>The proposed EWMP-G is projected to transition from a deficit to a surplus in</td>
</tr>
<tr>
<td>approximately 5 years after its implementation.</td>
</tr>
<tr>
<td><strong>Practicality</strong></td>
</tr>
<tr>
<td>The proposed installation of the EWMP-G in Ghana satisfies practicality due to the</td>
</tr>
<tr>
<td>aforementioned characteristics, including the stability of the North e-waste site, its</td>
</tr>
<tr>
<td>proximity to essential resources such as electricity and fuel, convenient transportation</td>
</tr>
<tr>
<td>access near the Odaw River and Hansen Road, and its adjacency to the original scrap</td>
</tr>
<tr>
<td>metal yard, facilitating ease of movement for workers. Additionally, the site meets the</td>
</tr>
<tr>
<td>required area size for our needs which further ensures the practicality.</td>
</tr>
</tbody>
</table>
Result

1. E-waste management process for Ghana (EWMP-G)

The EWMP-G proposed in this study consists of three stages: 1) sorting, 2) RDF, and 3) incineration. For the sorting process, we developed e-waste dismantling and sorting guidelines for the workers who manage the waste in Agbogbloshie, Ghana. Workers can safely dismantle e-waste in Ghana by following the e-waste dismantling guidelines. After dismantling, the disassembled electronic component devices must be classified into four parts (plastic, metal, PCBs, and other components). The classified electronic components were further sorted into plastic, precious metals (e.g., Al, Cu, Fe, Ag, Au, Pd), and other components (e.g., non-precious metal, non-plastic, cable, and rubber), by following the e-waste sorting guidelines.

![Flow chart of the e-waste management process for Ghana (EWMP-G)](image)

**Figure 1.** Description and flow chart of the e-waste management process for Ghana (EWMP-G) proposed in this study; refuse-derived fuel (RDF), polychlorinated biphenyls (PCBs).
First, after sorting e-waste into plastic, precious metal, plastics, and "other components," the waste could be processed using RDF. In the RDF process, the plastic goes through the shredding and pelletizing steps. Second, for precious metals, workers can sell precious metals and earn profits; this has been analyzed in more detail in section 3.9.2. Third, the other components were incinerated in the stoker incinerator while generating electricity. The overall process of the EWMP-G was well organized and has been explained in Figure 1. Notably, in the EWMP-G, we considered Ghana's economic situation, policies, and overall infrastructure, to ensure that the plan is sustainable and can be considered as an AT for Agbogbloshie.

2. Results of dismantling and sorting processes

For the dismantling and sorting processes, we provided our EWMP-G guidelines for manual screening, which the e-waste workers in Ghana can use to ensure their safety and prevent the serious health diseases they are suffering currently.

Through the EWMP-G guidelines, steps are provided to dismantle and sort e-waste as safely as possible. However, to further ensure the safety of workers, an auditing process has been included in our EWMP-G. This auditing process aimed to further ensure compliance and provide accountability, incorporating monitoring procedures.

3. Result of dismantling mobile phones

According to our experiment, the weight of Samsung Galaxy S5 is 133.45 g, varied by ±12 g between the weight 145 g shown in Samsung. After dismantling the mobile phone, we categorized the components into 'plastic,' 'metal,' 'PCBs' and 'other components' and weighed each category, as shown in Table 1.

4. Results of dismantling personal computers (PCs)

In our experiment, the weight of the ASUS K52F laptop was 2147.24 g, varied by ±483 g between the weight shown in ASUS (2630 g). After dismantling the PCs, we categorized the components into “plastic,” “metal,” “PCBs,” and “other components” and weighed each category, as shown in Table 1.

Utilizing the decomposition experiments of PCs and mobile phones and literature analysis, we developed the EWMP-G e-waste dismantling and sorting guidelines. The full guidelines are provided at the end of the manuscript in the Figure 1-3 of the supplementary file.

The guidelines included safety education and the methods used to ensure equipment safety. The biggest difference from the current manual separation work in Ghana is the application of safety education and equipment. At present, the separation process is carried out with bare hands, with the toxic substances of the metal penetrating the human body directly through the skin. In addition, smoke from incineration affects the respiratory health of the workers. Thus, we felt the need for safe methods.

Figure 2. The specific latitude and longitude (5°33’12.40”N, 0°13’39.91”W) of EWMP-G Area.
for the introduction of protective equipment and proper education of workers before the screening.

5. Results of plastic treatment and refuse-derived fuel (RDF) machinery process

Refuse-derived fuel, which is produced from waste by a multi-stage treatment, is a promising feedstock. This process includes sorting, shredding, hygienization, drying, and densification (Longo et al., 2020).

In the case of RDF processing, as the treated waste has the characteristics of e-waste that contains low moisture, it is possible to manufacture RDF quickly and in a simple manner by omitting the ‘drying’ process that lowers the moisture content. Thus, the RDF process in the EWMP-G was simplified into two stages: 1) crushing and 2) molding.

For the EWMP-G RDF model, we selected the Kahada Okuise recycling plaza located in Mie, Japan. Detailed information about this RDF model is specified in the Table 5 of the supplementary file.


Three products can be manufactured through the EWMP-G. These products can be beneficial to Ghana economically and environmentally, through selling or using waste to generate energy.

Precious Metal: After the sorting process, precious metals are sold throughout the worldwide market, resulting in a profit.

Refuse-derived fuel (RDF): RDF is one of the products that uses waste to generate energy. It could substitute fossil fuel; therefore, we propose that RDF can be used for profit.

Electricity produced by the incinerator: The heat generated in the incinerating process can be used to generate power. Thus, the EWMP-G can be used for profit through the sale of generated electricity.

7. Selection of study area

We proposed an EWMP-G for waste management in Agbogbloshie. In this study, we considered the three conditions: 1) the area must be close to the e-waste site, 2) considering the health of the residents, the site should not be near a residential or study area, and 3) the area must be accessible and have transportation resources to export RDF, precious metal, and electricity.

There were two e-waste sites in Agbogbloshie (Oteng-Ababio [28]):
Ababio 2012); we compared the two sites, based on the three abovementioned standards, as shown in Table 2.

To apply the EWMP-G effectively, we needed an area of 73,722 m² (Figure 4), but the South e-waste site was small. Also, the South e-waste site is near Old Fadama, which is an agricultural area that is vulnerable to flooding (Oteng-Ababio, 2021). In the case of the North e-waste site, the region is stable and does not experience flooding and is located near the Odaw River and Hansen Road (Oteng-Ababio, 2020). This makes it easy to supply electricity and fuel and transport the products of EWMP-G. Also, the North e-waste site is near the original scrap metal yard; therefore, the workers find it easier to travel from one site to the other (Oteng-Ababio, 2020). Finally, we decided that the North e-waste site was more appropriate for installing the EWMP-G process which is shown below in the Google map.

Visualizing the e-waste management process for Ghana (EWMP-G) for area selection: We assumed that the stoker incinerator site and RDF site incinerator were installed in a square-shaped model. We developed a map of the EWMP-G site (1:12,000 scale), so we drew the RDF site as 0.852 cm² and the Stoker incinerator site as 22 cm². The drawing process is shown in Figure 4 of the supplementary file.

We drew the RDF site of the EWMP-G as a yellow line and the stoker incinerator site as a red line in Figure 3. These graphs (Figures 4 and 5) show the overall environmental and socioeconomic effect of EMWP-G.

8. Environmental effects [personal computers (PCs), mobile phones, and refrigerators]

8.1. Amount of waste in Ghana

The amount of imported e-waste into Ghana in 2010-2018 was 9152.92 tons (PCs), 79477.8 tons (refrigerators), and 16.12 tons (mobile phones) (Grant et al., 2021). We used the average amount of annual import of e-waste into Ghana, by dividing the amount imported during 2010-2018.

The expected remaining e-waste in Ghana in 2020 was 2.46 million (PCs), 3165 (refrigerators), and 36.4 million (mobile phones) (Manhart et al., 2014). Using the average weights of the PCs and mobile phones considered for the dismantling experiment and assuming that the average weight of a refrigerator was 150 kg (Palermo, 2023), we calculated the amount of remaining e-waste.

![Environmental EWMP-G impact(RDF)](image1)

![Environmental EWMP-G impact(Incinerator)](image2)

**Figure 5.** The environmental effect of EWMP-G.
After we organized the proportions of the components of e-waste as shown in Table 9 of the supplementary file, we calculated the amount of each component (plastic, precious metals, and other components), using the amount of e-waste imported by Ghana annually and the remaining e-waste in Ghana. We considered Fe, Al, Cu, Ag, Au, and Pd as the important precious metals extracted from the e-waste.

In the case of PCs and mobile phones, the average proportions were considered, based on the results of the dismantling experiment and the searched information. For the average proportion of refrigerators, we used information from the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) (GIZ, 2017).

8.2. Refuse-derived fuel (RDF)

To solve the e-waste problem in Agbogbloshie, Ghana, using the RDF process, it is imperative to manage the plastic e-waste imported into Ghana. In our study, among the used electronic devices imported into Ghana, we assumed that PCs, refrigerators, and mobile phones were the most important e-waste devices.

Notably, in addition to regulating the plastic e-waste imported into Ghana, we also need to manage the plastic waste that remains in Ghana. Thus, we considered both the plastic parts of the remaining e-waste and annually imported e-waste. We multiplied the amount of e-waste (annual and remaining) and the proportion of plastic components in each device.

We selected the Kahada Okuise recycling plaza as the ideal site to implement the EWMP-G RDF production system model. The plaza’s capacity utilization rate was 44 tons per 8 h (KONETIC, 2022). We operated the RDF model for 365 days a year and 8 hours a day. Notably, it was more efficient to operate the incinerator 24 h/day, than only a few h/day.

The cost to build the stoker incinerator was USD 236,510,000 (City of Yokohama, 2022), and the capacity utilization rate per year was calculated as 131,400 ton/yr (City of Yokohama, 2022).

Refer to Table 12 of the supplementary file, the selected stoker incinerator could manage to reduce 131,400 tons of e-waste every year. We calculated 2,801.19 ton + 3,834.35 ton/yr - 131,400 ton/yr (Graph 2).

The results indicated that, approximately 0.022 years after the operation of the proposed model, we could remove all the e-waste in Ghana as shown in the right of the Figure 5.

9. Socioeconomic effects of the model

9.1. Refuse-derived fuel (RDF) products

The Kahada Okuise recycling plaza had a processing capacity of 44 ton/8 h and its installation cost was 2.7 billion yen (KONETIC, 2022). The price of RDF per ton was 20.84 USD/ton, we could calculate the profit of selling RDF per year (Jeong et al., 2015), as explained below:

20.84 USD/ton × 2860 ton/yr = 59602.4 USD/yr

9.2. Valuable metals

Refer to the Table 9 to11 of the supplementary file, the prices of the valuable metals were analyzed.

We summed up the weight of the precious metal and the weight of the current remaining e-waste in Ghana, along with the weight of precious metal extracted from the used electronic devices imported into Ghana annually. Notably, we obtained the total precious metal weight and multiplied the price of each precious metal to calculate the profit from precious metals.

Thus, the total profit from selling valuable metals was calculated to be USD 1,512,918.00.

9.3. Electricity produced by the incinerator
The incinerator was able to generate electricity, and the power output of the incinerator model we selected was calculated. Then, we calculated the average amount of electricity that could be produced from the incineration of the e-waste (City of Yokohama, 2022). We considered the unit price of electricity as USD 107.99 (Electric Market Oversight Panel, 2021) and calculated the selling price for the electricity produced by the incinerator.

Thus, the total profit from the electricity generated using the incinerator was:

\[
44,690.210 \text{ MWh/yr} \times (107.99 \text{ USD/MWh}) = \text{USD 4,826,095.778}
\]

Also, the installation cost of the incinerator model was USD 236,510,000 (City of Yokohama, 2022).

9.4. Worker’s income

At present, there are 4500-6000 informal workers that work in Agbogbloshie, Ghana; their monthly wages are USD 380-460 (Höltl et al., 2017; Oteng-Ababio et al., 2020; Prakash et al., 2010). Notably, among all the workers, an average of 5500 make USD 420 per month; considering the GDP, this amount is higher than the average monthly wage in the country.

Thus, the workers’ wages were measured as follows:

\[
420 \text{ USD/month} \times 12 \text{ month/yr} \times 5000 \text{ people} = 25,200,000 \text{ USD}/5,374,040.73 \text{ USD/yr}
\]

10. International cooperation

In the proposed method, we assumed that Ghana was subsidized as a precedent. Examples of the international support and grants found in the literature included the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), European Union (EU), GDPC, Germany (Korea Trade-Investment Promotion Agency, 2020).

The socioeconomic factors considered in this study and the total profit and cost of the EWMP-G calculated in this work are shown in Table 18. We summed the total profit and cost, finally USD -4,842,416.5 (fix) + 1,024,575.453 (yr).

Referring to the Supplementary File for results including calculations about the amount of e-waste (Table 7, Table 8) and the amount of metals in e-waste and its profit (Table 9, Table 10, Table 11) will provide a more detailed understanding of the process. Thus, through these calculations, we can affirm that we have achieved economic feasibility. This is evidenced by the fact that the proposed EWMP-G is projected to transition from deficit to surplus approximately five years after the model’s operation, as depicted in Figure 4. In Figure 4, the break-even point is set at five years, and the presence of surplus (depicted by the green bars) confirms the achievement of economic feasibility.

Conclusion of EWMP–G and Suggestions for Basel Convention

In conclusion, e-waste management process for Ghana (EWMP-G) can be a solution for the massive amount of e-waste, with further visible summary in Table 4 regarding environmental impacts, economic feasibility analysis, and practicality. EWMP-G includes three discarding stages of life cycle assessment which are sequentially sorting, refuse-derived fuel (RDF), and incineration. After 5 years of the application of the EWMP-G, we will be able to remove all the e-waste sites in Agbogbloshie, Ghana and convert the socioeconomic effect from deficit to surplus. In addition, from an international policy point of view, to prevent the movement of e-waste from developed countries to developing countries, we propose an amendment to the Basel Convention.

The Basel Convention which aims to protect the environment of developing countries has not been effective. Therefore, we determined the parts of the convention that were not effective and suggested modifications to optimize the existing policies.

Although according to Article 4, countries not able to manage the waste can export the waste to other countries; however, developed countries, have enough ability to manage the e-waste and export their e-waste to developing countries. In the EU, 10% of e-waste is exported illegally to Africa, with the amount of e-waste recycled properly and documented to be collected being only 0.9% (0.03 Mt) of the total amount (Fortie et al., 2020; Illés et al., 2016). Notably, the indirect danger of illegal e-waste trading is causing environmental problems in developing countries and contravening the Basel Convention (Parakash et al., 2010).

Therefore, the program monitoring the movement of e-
waste imported into Ghana should be supported continuously. Furthermore, the illegal e-waste imports monitored through this program should be punished heavily by preparing detailed bills for the e-waste in Ghana. In this study, we propose modifying Article 10, No. 2 of the Basel Convention which is specified in Table 13 of the supplementary file.

Although there are already many global supporters for Ghana, if these supporters provide sustainable ATs and socio-economic support, we can expect the e-waste management in Agbogbloshie to improve considerably.

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Palermo, A. Average Refrigerator weight (with 58 examples). Pru-


