**Supplementary material**

**Manuscript title:** Suggestion of e-waste management process for Ghana(EWMP-G) for eco-friendly e-waste life cycle assessment: A study on Agbogbloshie, Ghana

## 1. E-waste

Moreover, the amount of e-waste increased during the recent COVID-19. During the lockdown, most companies promoted online working, which increased the use of EEE and, consequently, e-waste production [1-3].

## 2. Health impact of e-waste in the study area (Agbogbloshie, Ghana)

Burning e-waste may expose the workers to high concentrations of toxins, greenhouse gasses, and fine dust, which may have adverse effects on the health of not just the workers, but also the residents that live near the site.

According to the literature on health impacts in the Accra region, the waste sector contributed 14% of Ghana's total greenhouse gas emissions [4]. Also, the Environmental Protection Agency Ghana (EPA-Ghana) measured the annual mean $PM_5$ and $PM_{10}$ levels in residential areas at 78 and 81 lg/$m^3$, respectively, which exceeds the guidance level recommended by the World Health Organization (WHO) [5]. Regarding toxicity, previous studies confirmed a high level of polycyclic aromatic hydrocarbons (PAHs) in the breast milk of mothers who resided in e-waste processing and residential areas [6]. In another study, scholars tested the urine of individuals exposed to e-waste recycling in Ghana and confirmed high PAH metabolite concentrations [7].

Additionally, the smoke from the incineration of e-waste contains toxic substances. Notably, the chemical components from e-waste contaminate dust, soil, and water near the e-waste processing sites [8-9], along with the lack of governmental regulation and informal e-waste dismantling, have resulted in Ghana being one of the most polluted regions in the world [10].

The ultimate purpose of the guidelines is to ensure that the residents actively understand and safely participate in the screening process. This can maximize the efficiency of the screening process.

### 3.1 Selection Method (Table 1, Table 2)

We selected a treatment process for how to dispose of e-waste by its components.

Eco-Friendliness, Economic feasibility, and Practicality was used as a tool to select the Plastic Treatment method between Incineration, Landfills, and RDF. We applied '5-point' rating scale expressed as 'Excellent, very good, good, fair, and poor, as shown in Table 1.

**Table 1**. Selection criteria for plastic treatment method

| Standards/methods | Incineration. | Landfills | RDF |
|---|---|---|---|

| | | | |
|---|---|---|---|
| Eco-friendliness | Fair (Incineration needs the exhaust gas purification process (DDN Process [De - Dioxin&De-NOx Process])) | Fair (it should be careful not to cause soil pollution during the decay process.) | Excellent (it is a case of recycling plastic and converting the plastic waste to energy products.) |
| Economic feasibility | Good | Good | Very good |
| Practicality | Excellent (there are a lot of previous incinerators in the world.) | Poor (it needs the land space for landfills, but it is not appropriate because the Ghana e-waste site was polluted.) | Good (this method has precedent in developed countries such as Japan, USA.) |

We select criteria for other components of e-waste by using '5-point' scale tool expressed as 'Excellent, very good, good, fair, and poor'. Eco-friendliness, Economic feasibility, and Practicality was used as standard to select criteria for other components of E-waste between Incineration, Landfills and Upcycling, as shown in Table 2.

**Table 2**. Selection criteria for other components of e-waste

| Standards/methods | Incineration | Landfills | Upcycling |
|---|---|---|---|
| Eco-friendliness | Fair (Incineration needs the exhaust gas purification process (DDN Process [De - Dioxin&De-NOx Process])) | Fair (it should be careful not to cause soil pollution during the decay process.) | Excellent (it is a case of recycling plastic and converting the plastic waste to energy products.) |
| Economic feasibility | Good | Good | Good (There is a possibility that the profits of upcycling products are unstable.) |
| Practicality | Excellent (there are a lot of previous incinerators in the world.) | Poor (it needs the land space for landfills, but it is not appropriate because the site of Ghana e-waste site was polluted.) | Poor (it is difficult to make the upcycling product as large-manufacturing products.) |

**3.2 Calculation Method (Table 3, Table 4)**

We calculated the weight of plastic, metals, and other components of e-waste for the RDF, Incineration environmental assessment.

To calculate the amount of plastic e-waste in Ghana, we multiplied the ratio of plastic in the PC, refrigerators, and mobile phones by the amount of used PC, refrigerators, and mobile phone in the same year. We also classified weight of plastic e-waste which were remained in Ghana(Remaining e-waste) and weight of plastic e-waste which flows into Ghana annually(Annual e-waste). To see the values at a glance, we calculated for the RDF environmental assessment. (Table 3).

**Table 3.** Total Weight of Plastic E-waste in Ghana (unit: tonne)

| | Unit (tonne) | | PC | Refrigerator | Mobile phone | Total |
|---|---|---|---|---|---|---|
| Remaining e-waste | RDF plastic | Plastic | | | | |
| | Unit (tonne/yr) | | PC | Refrigerator | Mobile phone | Total |
| Annual e-waste | RDF plastic | Plastic | | | | |

We also calculated the total weight of the e-waste in Ghana to be processed using the incinerator. We also classified the weight of plastic e-waste which were remained in Ghana (Remaining e-waste) and the weight of plastic e-waste which flows into Ghana annually (Annual e-waste). To see the values at a glance, we calculated the Incineration environmental assessment. (Table 4).

**Table 4.** Total weight of the e-waste in Ghana to be processed using the incinerator (unit: tonne)

| | Unit (tonne) | | PC | Refrigerator | Mobile phone | Total |
|---|---|---|---|---|---|---|
| Remaining E-waste | Incineration | Etc. | | | | |
| | Unit: tonne/yr | | PC | Refrigerator | Mobile phone | Total |
| Annual E-waste | incineration | Etc. | | | | |

**4.1 Result of dismantling process (Figure1, Figure 2, Figure 3)**

Based on the decomposition experiment of PCs and mobile phones, we created the guideline for the dismantling and sorting process. If it will be applied to Ghana Agbogbloshie, it will be offered to workers of the dismantling and sorting process.


**Figure 1.** E-waste management process for Ghana **(**EWMP-G) guidelines for dismantling mobile phones

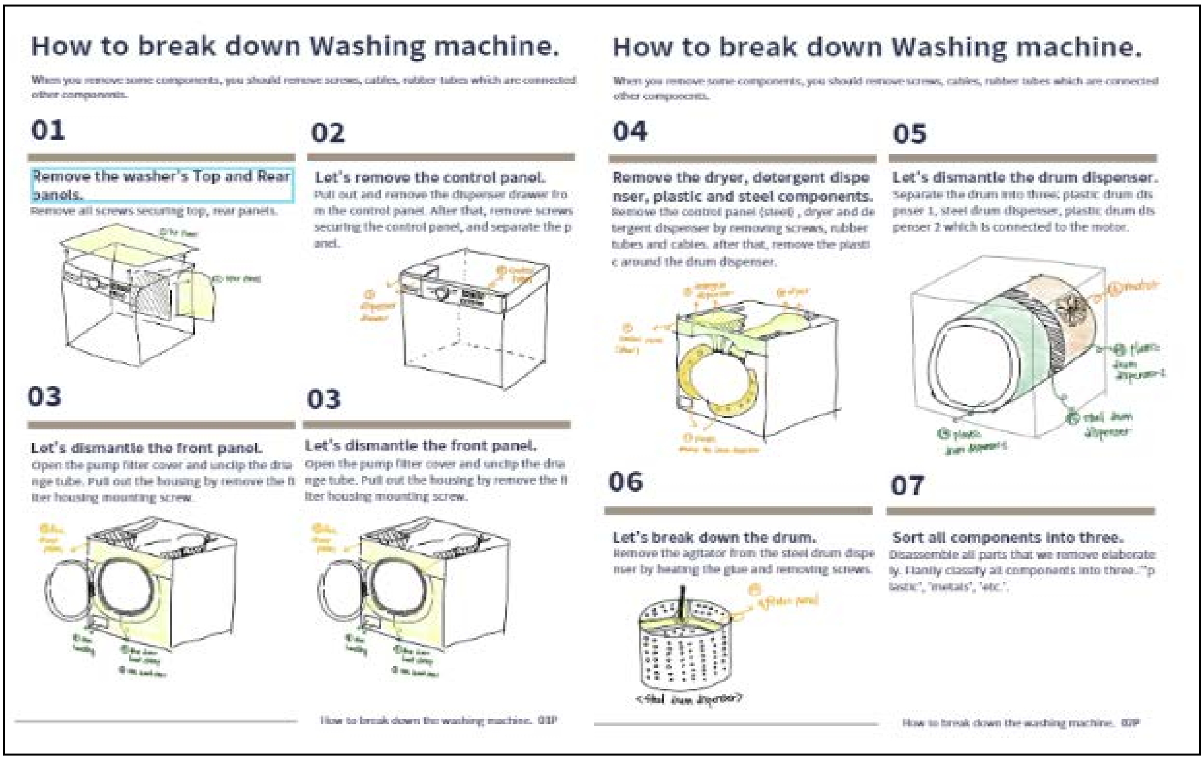



**Figure 2.** E-waste management process for Ghana **(**EWMP-G) guidelines for dismantling washing machines

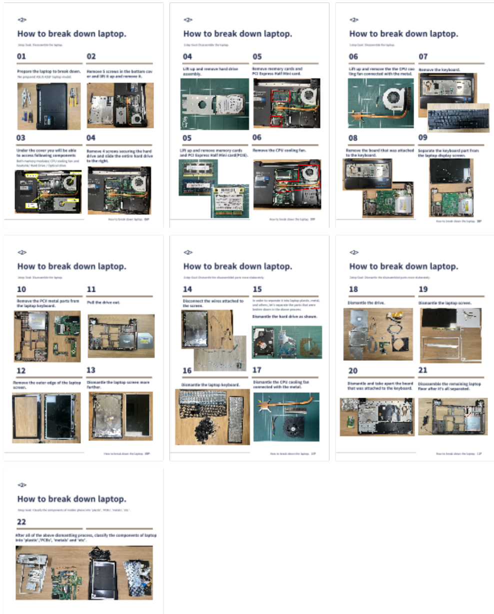


Figure 3. E-Waste Management Process for Ghana (EWMP-G) Guidelines for Dismantling Personal Computers (PCs)

### 4.1.1 The reason for the EWMP-G's manual dismantling guideline

The reason why this step must be performed manually, rather than via a mechanized process, is that each electronic device has a different and complicated structure that requires delicate separation. Currently, the local people handle and treat the e-waste dump in Agbogbloshie. There are two advantages of using the residents' skills. First, without separate technical training, EWMP-G e-waste dismantling and sorting guidelines were sufficient to enable the workers to carry out the sorting process safely. Second, the local economy can be revitalized by allowing residents to participate in this process. Notably, by selling precious metals from the e-waste, local workers can earn more money, thus boosting the local economy. Notably, the guidelines have been prepared to facilitate the workers' understanding of the above steps, especially regarding the use of safety equipment and the correct methods to dismantle the products.

### 4.2 Result: Selection and Application of EWMP-G E-waste site

we compared the north e-waste site(5º33'12.40"N, 0º13'39.91"W) and the south e-waste site(5º54'56.57"N, -0º22'41.38"W) as shown in the Figure 4.

**Figure 4.** Two e-waste sites in Agbogbloshie; excerpt from Oteng-Ababio [11].

We calculated its scale to draw the EWMP-G E-waste site on the map.

RDF site:

$$18{,}000\ m^2 = 134.164^2\ m^2$$

$$1\ cm = 120\ m\ in\ this\ map,$$

$$134.164\ mvo\ 1cm/120cm = 0.8497\ cm, so\ approximately\ 0.85^2\ cm^2\ in\ this\ map.$$

Stoker incinerator site:

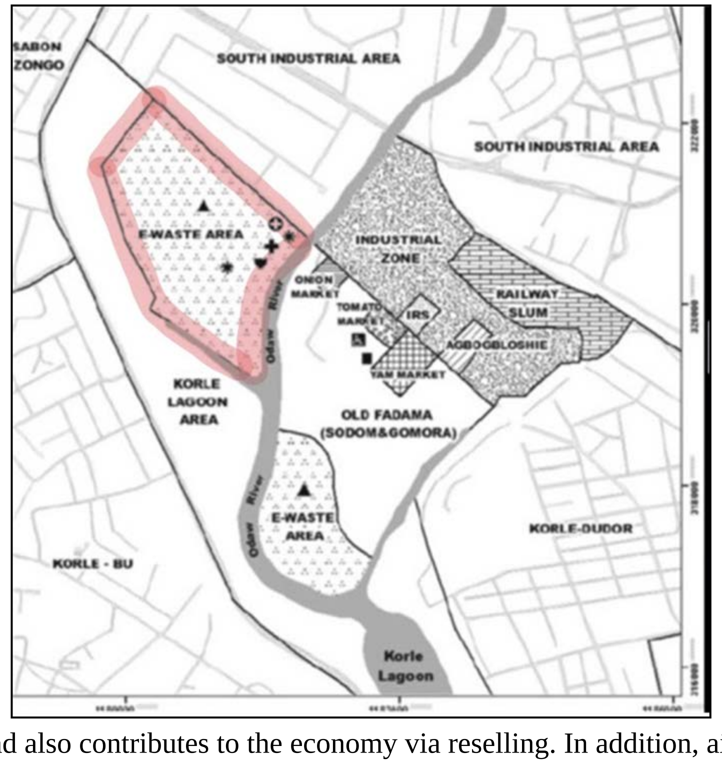
$55{,}722\ m^2 = 236.055^2\ m^2$

$$1\ cm = 120\ m\ in\ this\ map,$$

$236.055\ mvo\ 1cm/120cm = 1.9671\ cm, so\ approximately\ 2^2\ cm^2\ in\ this\ map.$

**4.3 Result of selected RDF, Incineration model (Table 5, Table 6)**

We selected Japanese RDF, Incineration model. To add, RDF can be shaped into different forms of




standard products and also contributes to the economy via reselling. In addition, air pollution can be reduced due to the low concentration of hydrogen chloride and dioxin by screening out large products and via calcination. Generally, the existing RDF devices need to go through the drying process first, but we simplified the process steps by omitting the drying process.

The detailed information about their locations, costs, and ability of power generation is in Tables 5 and 6.

**Table 5.** Information of Kahada Okuise Recycling Plaza in Japan

| | |
|---|---|
| Facility name | Kahada Okuise Recycling Plaza |
| Location | 4290 Niu, Taki-cho, Taki-gun, Mie Prefecture, Japan |
| Construction period | 1999.6~2001.3 |
| Site area | 18,000 $m^2$ |
| Building outline | Waste solid fuel conversion facility: building area 2,175 $m^2$ (site area 2,998 $m^2$)<br>Recycle Plaza: building area 1,334 $m^2$ (site area 1,922 $m^2$)<br>Process Ability: 13 tonne/ 5 h (Incombustible, coarser treatment, and recycling facilities) |
| Total Facility Cost | JPY 4400000000 (about USD 34,079,203.12) |
| RDF Manufacturing facilities | |
| - Process Ability | - 44 tonne/8 h (22 tonne* 2 months), 22 tonne/8 h RDF manufacture |
| - Process method | - drying + crushing and molding process |
| - RDF facility construction cost | - JPY 2700000000 (about USD 20,915,668.06) |
| - RDF place of use | - Fuel utilization of RDF power plants and hot water pools in Mie Prefecture |
| Business Operator | KahadaOkui Tax Resources Development Union (Taki-gun County 8 Township Union) |
| Facility Management Body | Japan steel pipe industry |

*source and reference: Korea Environmental Industry and Technology Institute (KEITI)[12]

**Table 6.** Information of Yokohama City Resources Recycling Bureau Asahi Factory Stoker Incinerator

| | |
|---|---|
| Site Area | Approximately 55,722 $m^2$ |
| Construction Period | September 1944 to March 1999 |
| Total Budget | Approximately 27.3 billion yen |

| Fiscal year | H19 | H20 | H21 | H22 | H23 | H24 | H25 |
|---|---|---|---|---|---|---|---|
| Total power generation | 43,237,879 | 43,594,852 | 45,405,620 | 41,974,780 | 45,352,950 | 46,614,160 | 45,445,29 |

| FiscalYear | H26 | H27 | H28 | H29 | H30 | H31 | Avg. |
|---|---|---|---|---|---|---|---|
| Total power generation | 43,201,590 | 47,791,730 | 47,916,070 | 45,841,280 | 42,105,220 | 42,491,310 | 44,690,210 |

*source and reference: city of Yokohama website [13-15]

**4.4 Result: Calculation about the amount of e-waste (Table 7, Table 8)**

We calculated the annual e-waste and remaining e-waste separately.

First, we calculated the amount of annual e-waste imported into Ghana during 2010-2018. We used the average amount of annual import of e-waste into Ghana to the environmental assessment, by dividing the amount imported during 2010–2018 [16], as shown in Table 7.

**Table 7.** Amount of Annual E-Waste Imported in Ghana During 2010–2018 (unit: tonne)

| Unit: tonne | 2010–2018 | Annual average |
|---|---|---|
| PCs | 9152.92 | 1016.9911 |
| Refrigerators | 79477.8 | 8830.8667 |
| Mobile Phones | 16.12 | 1.7911 |
| **Total** | 88646.84 | 9849.65 |

Second, we calculated the amount of remaining e-waste in Ghana. 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, we calculated the amount of remaining e-waste in Ghana (Table 8).

**Table 8.** Amount of Remaining E-Waste in Ghana (personal computers, refrigerators, mobile phones)

| | Number of devices | Average weight (kg) | The remaining amount (tonne) |
|---|---|---|---|
| PCs | 2.46 million | 2.14724 | 5282.210400 |
| Refrigerators | 3,165 | 150 | 474.750 |
| Mobile phones | 36.4 million | 0.13345 | 4857.58 |
| Total | 38,863,165 | 302.28069 | 11089.2904 |

**4.5 Result: Calculation about the amount of metals in e-waste and its profit. (Table 9, Table 10, Table 11)**

To calculate the profit of metals in e-waste, we had to calculate the amount of metals in e-waste of Ghana. we calculated the number of metals in the e-waste of Ghana by using the proportion of different components of the e-waste in Ghana, shown in Table 9.

**Table 9.** Proportions of Different Components of E-Waste in Ghana

| Unit: % | | PCs | Refrigerators | Mobile phones |
|---|---|---|---|---|
| Plastic | | 49.9868 | 16 | 33.97 |
| Precious Metal | Fe | 2.83 | 43 | 11.03 |
| | Al | 18.28 | - | 4.84 |
| | Cu | 2.93 | - | 24.61 |
| | Ag | - | - | 0.0496 |
| | Au | - | - | 0.059 |
| | Pd | - | - | 0.020 |
| Other components (not precious, rubber, or glass) | | 25.968 | 41 | 25.4214 |
| **Total** | | 100 | 100 | 100 |

*sources and references:
The proportion of precious metals in metal of PC: [17]
The proportion of precious metals in metal of mobile phones: [18]
The proportion of precious metals in PCBs of PC: [19]
The proportion of precious metals in PCBs of mobile phones: [20]
Abbreviations: personal computers (PCs), polychlorinated biphenyls (PCBs)

To calculate the profit of metals in e-waste, we searched the price of each precious metal per tonne shown in Table 10.

**Table 10.** Price of Each Precious Metal per tonne

| Precious Metal | The price of precious metal per tonne (unit: USD/tonne) |
|---|---|
| Iron (Fe) & steel scrap | 253 USD /tonne[1)] |
| Aluminum (Al) | 1,800 USD /tonne[2)] |
| Copper (Cu) | 6,110 USD /tonne[2)] |
| Silver (Ag) | 550,000 USD /tonne[1)] |
| Gold (Au) | 48,834,970 USD /tonne[2)] |
| Palladium (Pd) | 11,488,748 USD /tonne[1)] |

* Sources and references: [1)]Prakash et al [21] and [2)]Oteng-Ababio [11]

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. The calculations are shown below in Table 11:

Fe = 3677.25 tonne/yr*253 USD/tonne = USD 930344.25

Al = 185.96 tonne/yr*1800 USD/tonne = USD 334728

Cu = 30.294 tonne/yr*6110 USD /tonne = USD 185096.34

Ag = 0.0089 tonne/yr*550000 USD /tonne = USD 4895

Au = 0.0011tonne/yr*48834970 USD /tonne = USD 53718.467

Pd = 0.00036 tonne/yr*11,488,748 USD /tonne = USD 4135.95

**Table 11.** The calculated annual profit from selling valuable metals extracted from the E-Waste in Agbogbloshie, Ghana

| | |
|---|---|
| Fe | USD 930344.25 |
| Al | USD 334728 |
| Cu | USD 185096.34 |
| Ag | USD 4895 |
| Au | USD 53718.467 |
| Pd | USD 4135.95 |
| Total | USD 1,512,918.007 |

**4.6 Environmental Effect of the Stoker Incinerator (Table 12)**

To manage the e-waste in Agbogbloshie using a stoker incinerator, we considered the weight of the e-waste, excluding the metal and plastic components, that needed to be disposed of in the imported incinerator. We multiplied the amounts of e-waste in Ghana (annual import and remaining) and the proportions of other components in each device (Table 12)

**Table 12.** Total weight of other components of e-waste in Ghana

| | Unit: tonne | | PCs | Refrigerators | Mobile phones | Total |
|---|---|---|---|---|---|---|
| Remaining e-waste | Incineration | Other components | 1371.68 | 194.65 | 1234.86 | 2801.19 |
| | Unit: tonne/yr | | PCs | Refrigerators | Mobile phones | Total |
| Annual e-waste | Incineration | Other components | 213.24 | 3620.65 | 0.46 | 3834.35 |

### 4.7 The proposal for correcting the Basel convention (Table 13)

Table13 portrays the proposed amendments in the Basel Convention.

**Table 13.** Original and proposal of the Basel convention

| Original Basel Convention | Proposal of Basel Convention Amendment |
|---|---|
| "1. The Parties shall cooperate with each other in order to improve and achieve environmentally sound management of hazardous wastes and other wastes.<br><br>2. To this end, the Parties shall:<br><br>(a) Upon request, make available information, whether on a bilateral or multilateral basis, with a view to promoting the environmentally sound management of hazardous wastes and other wastes, including harmonization of technical standards and practices for the adequate management of hazardous wastes and other wastes;<br><br>(b) Co-operate in monitoring the effects of the | 2. To this end, the Parties shall:<br><br>(a) Upon request, make available information, whether on a bilateral or multilateral basis, with a view to promoting the environmentally sound management of hazardous wastes and other wastes, including harmonization of technical standards and practices for the adequate management of hazardous wastes and other wastes; It aims to ensure that information is understood by party officials and workers.<br><br>(b) Co-operate in monitoring the effects of the management of hazardous wastes on human health and the environment; It is mandatory that waste exports be made possible only by countries that have implemented technical and financial support to the importer. |

| | | |
|---|---|---|
| | management of hazardous wastes on human health and the environment. “ | |
| | "(c) Co-operate, subject to their national laws, regulations and policies, in the development and implementation of new environmentally sound low-waste technologies and the improvement of existing technologies with a view to eliminating, as far as practicable, the generation of hazardous wastes and other wastes and achieving more effective and efficient methods of ensuring their management in an environmentally sound manner, including the study of the economic, social and environmental effects of the adoption of such new or improved technologies;" | (c) Co-operate, subject to their national laws, regulations and policies, in the development and implementation of new environmentally sound low-waste technologies and the improvement of existing technologies with a view to eliminating, as far as practicable, the generation of hazardous wastes and other wastes and achieving more effective and efficient methods of ensuring their management in an environmentally sound manner, including the study of the economic, social and environmental effects of the adoption of such new or improved technologies; If it is proved that the health of the residents of the importing country has deteriorated due to the export of waste from the exporting country, the exporting country will be obliged to compensate for the damage. |
| | "(d) Co-operate actively, subject to their national laws, regulations and policies, in the transfer of technology and management systems related to the environmentally sound management of hazardous wastes and other wastes. They shall also co-operate in developing the technical capacity among Parties, | (d) Co-operate actively, subject to their national laws, regulations, and policies, in the transfer of technology and management systems related to the environmentally sound management of hazardous wastes and other wastes. They shall also co-operate in developing the technical capacity among Parties, especially those which may need and request technical assistance in this field; The technology supported by the exporter must be sustainable for the importer and be able to improve the health and economic conditions of its residents. The initial cost and installation of |

| | | |
|---|---|---|
| | especially those which may need and request technical assistance in this field;<br><br>(e) Co-operate in developing appropriate technical guidelines and/or codes of practice<br><br>3. The Parties shall employ appropriate means to co-operate in order to assist developing countries in the implementation of subparagraphs a, b, c and d of paragraph 2 of Article 4.<br><br>4. Considering the needs of developing countries, co-operation between Parties and the competent international organizations is encouraged to promote, inter alia, public awareness, the development of sound management of hazardous wastes and other wastes and the adoption of new low-waste technologies. " | the technology shall be taken by the exporting country, but subsequent profits shall be managed by the importer or the importer. Financial support shall be provided in the form of an environmental levy, and the amount shall be calculated in consideration of the amount of waste exported so far and the amount of export in the future.<br><br>(e) Co-operate in developing appropriate technical guidelines and/ or codes of practice.<br><br>3. The Parties shall employ appropriate means to co-operate in order to assist developing countries in the implementation of subparagraphs a, b, c and d of paragraph 2 of Article 4.<br><br>4. Considering the needs of developing countries, co-operation between Parties and the competent international organizations is encouraged to promote, inter alia, public awareness, the development of sound management of hazardous wastes and other wastes and the adoption of new low-waste technologies. |

*sources and references: original Basel Convention referred from UNEP [22]

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