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Article

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Extended exergy sustainability analysis comparing environmental impacts of disposal methods for waste plastic roof tiles in Uganda

Paige Balcom [*], Juliana Mora Cabrera, Van P. Carey

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ABSTRACT

The world is facing an increasingly dire plastic waste crisis that affects people in developing countries disproportionately more than those in industrialized nations. To compare the environmental effects of end of life disposal and recycling options for plastic/sand roof tiles in Uganda, we use an extended exergy analysis (EEA) to quantify the resources used in the disposal process, the resources saved from replaced virgin materials by recycling, and any additional resources needed to bring the tiles, byproducts, and pollutants to an environmentally acceptable end state. We evaluated disposing of waste plastic/sand roof tiles through open burning, burying, landfilling, pyrolyzing, incinerating in cement kilns, mixing into asphalt to pave roads, and recycling into plastic pavers. With a net exergy avoided of 16,462 MJ/tonne of tiles, mixing the waste plastic/sand tiles into asphalt roads proved to be the best option followed by pyrolysis with 11,303 MJ/tonne of net exergy avoided (including remediation). Recycling the tiles into pavers also saved net exergy while burying, landfilling, and incinerating all had negative net exergy values showing that inputting some thermal energy to recycle waste can add value and save net resources. We determined it is not practically feasible to bring all of the pollutants from open burning to an environmentally acceptable end state with the limited technology available in Uganda. However, the method we recommend for remediating CO_2 by planting trees requires only 0.7% of the exergy used in CO_2 scrubbers currently used in developed countries. Such an empirical study focusing specifically on plastic products and disposal options feasible in developing countries has not been done before, so our paper can be useful to policy makers, multilateral organizations, and NGOs making decisions about solid waste management practices in less-industrialized nations. The results from this paper are valid for HDPE, LDPE, and PP plastics but not for PET or PVC.

1. Introduction

In the last six decades, 8.3 billion metric tons of plastic were produced worldwide, equivalent in weight to 55 million jumbo jets (Geyer et al., 2017). Only 9% was recycled (Parker, 2018). When China banned the importation of most plastic waste in 2018 (Katz, 2019; Mcnaughton and Nowakowski, 2019) and India followed suit in 2019 (Cockburn, 2019), the plastic waste crisis became more dire and more visible to Western nations since they could no longer export their trash. The plastic waste issue is even more severe in developing countries because waste is generally not collected and recycling options are extremely limited (Nkwachukwu et al., 2013; Weber et al., 2011). Fig. 1 describes the current disposal situation of plastic waste in Uganda.

Sub-Saharan Africa is thought to have the worst solid waste management (SWM) of any region in the world (R20 and "Open Burning of Was, 2019). For example, Kampala, the capital city of Uganda, generates approximately 180 tons of plastic waste daily (Kinobe et al., 2015) and only 40–50% of the city's waste is collected and brought to Kiteezi landfill (Reporter, 2013; WaterAid, 2011). Gulu, the second largest population center after Kampala, only has a 20% waste collection rate (Fitchner and Infra, 2018). Open burning in homes and landfills is the primary method of waste disposal, but burning plastic releases lethal carcinogens, other toxins, and greenhouse gases not accounted for in global inventories (Wiedinmyer et al., 2014). 74.1% of Uganda's uncollected waste is burned in open fires (R20 and "Open Burning of Was, 2019). Additionally, plastic is often littered, so it clogs drains leading to flooding and breeding grounds for malaria-bearing mosquitoes or gets embedded in the soil and disrupts crops (Oehlmann et al., 2009). Over 75% of Ugandans live in rural areas and rely on subsistence agriculture (gov, 2020), so this is a significant issue. One study found that 60% of stray cattle in Uganda die from consuming polyethylene bags (Nampijja). Plastic waste is causing a host of environmental and public health

* Corresponding author.
E-mail address: pbalcom@berkeley.edu (P. Balcom).

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issues in Uganda, so environmentally friendly disposal options that are feasible in a developing country context are needed.

This paper seeks to answer the research question: What is the most environmentally friendly approach that is feasible and appropriate in the developing country context of Uganda to dispose of recycled plastic/sand roof tiles? We use a quantitative, empirical approach through an extended exergy analysis (EEA) to compare the natural resources and energy required to reach an environmentally-acceptable end state through different disposal methods. This paper builds on the author's previous thermodynamic exergy analysis of the manufacturing process of roof tiles made from plastic waste and sand by the Kampala company, Resintile LLC (Balcom and Carey, 2020). Samples of the Resintile roof tiles are shown in Fig. 2. The previous paper also expanded on the plastic waste situation and informal picker economy in Kampala. This paper focuses on practical end of life disposal options for the Resintile roof tiles which will eventually crack and break from UV degradation and weathering. We propose seven different end of life options that are either already practiced in Uganda or are feasible in the limited

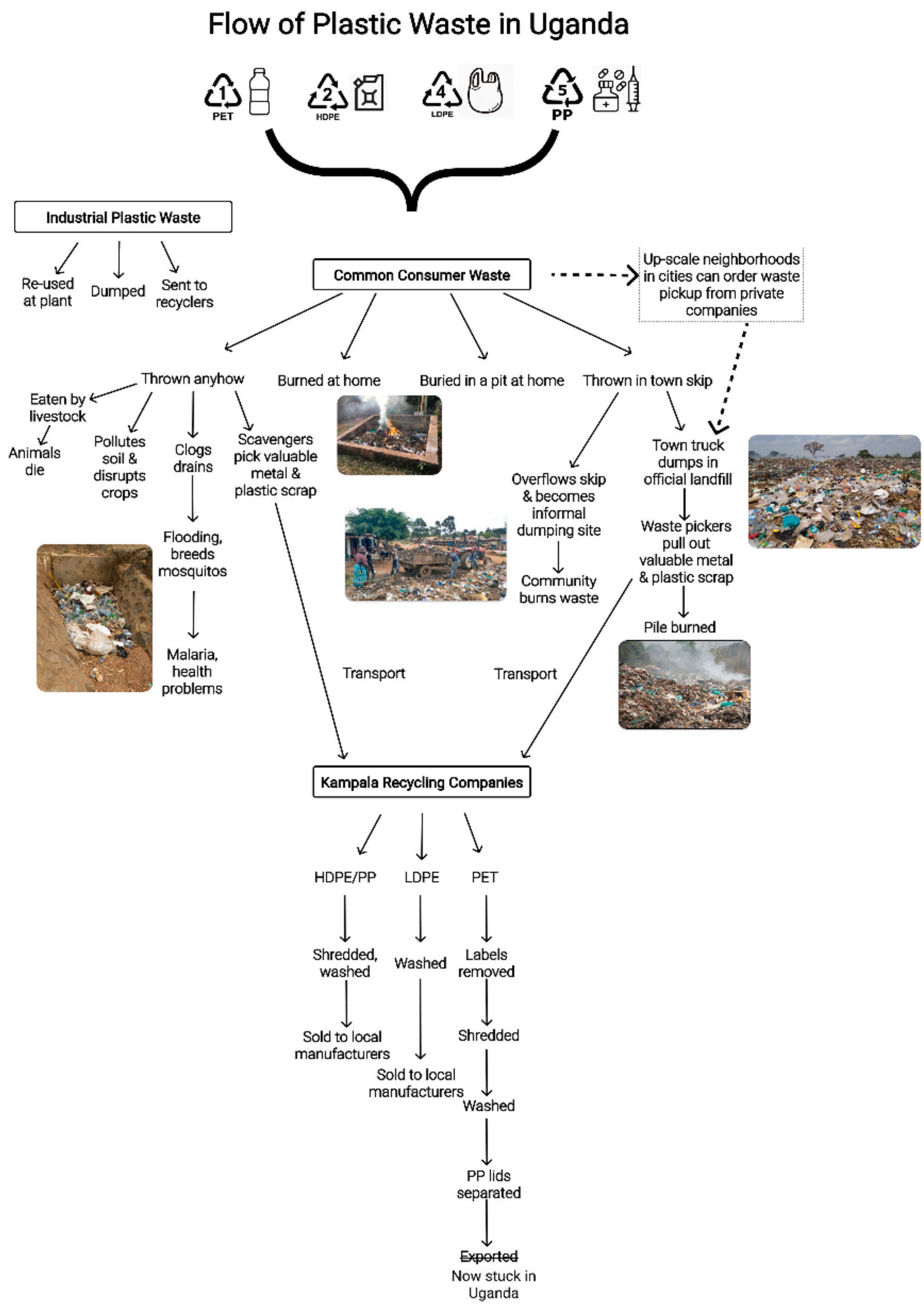

Fig. 1. Flow of plastic waste in Uganda.

Fig. 2. Resintile roof tiles.

industrial capacity of a developing country context. In this EEA, we analyze each disposal process and calculate the exergy needed for each step, including heating with electricity (hydropower), wood, plastic, recycled fuel oil, and diesel, to compare the different options and find means of efficiently using power and heat flow to conserve energy. We use exergy as a single metric to also calculate and compare virgin resources used, resources saved from replacing them with new recycled product alternatives, and the exergy needed to properly remediate all pollutants and by-products emitted. This complete picture includes resource conservation through recycling and gives insights into how to minimize the exergy input required to deal with handling and retiring the material in an environmentally sustainable way.

This paper adds to current literature by analyzing plastic waste disposal options appropriate to developing countries, such as Uganda. To our knowledge, no other paper compares resource or environmental cost of disposal options in Uganda and no other extended exergy analyses have been published on waste disposal methods for developing countries. Other studies have used life cycle analysis (LCA) (WRAP, 2010; Sommerhuber et al., 2017) and a few used exergy analyses (Dewulf and Langenhove, 2002; Jadhao et al., 2017; Zhou et al., 2011; Dewulf and Van Langenhove, 2004) to compare the resources used in landfilling versus incineration versus recycling but all in scenarios of developed countries with access to sophisticated, modern technology, and none specifically calculate the remediation costs. None consider only technologies available in developing countries. We devoted significant effort to researching what disposal methods are currently used in Uganda and their environmental effects. We also creatively conceived new disposal and remediation options that are currently not used in Uganda and present rationale for why they could be feasible. Additionally, our study examines plastic waste alone whereas most studies look at municipal solid waste (MSW) as a whole, which significantly influences results because the environmental effects of burning or otherwise disposing of solely plastic are much more detrimental than disposing of general MSW where plastic represents only a small percentage.

Additionally, our paper expands on the typical EEA approach by calculating the net avoided exergy of a disposal option. To give a complete picture, we include the exergy value of the resources saved from replacing fuel and products with recycled alternatives. None of the previously referenced works specifically calculate remediation costs, so we apply previous frameworks (Creyts and Carey, 1999; Rosen and Dincer, 1998) of defining two different ground states to calculate the costs of properly disposing of all pollutants and by-products according to environmentally acceptable standards.

Our results are directly relevant to discussions currently happening in Uganda and across the world about how to properly dispose of the plastic waste currently being burned or piling up all across the world. The Ugandan people, government, and multilateral aid organizations are increasingly concerned about the plastic waste crisis in their country. Recycling and SWM is a pressing topic in developing countries with many stakeholders interested in funding and searching for practical, cost-effective solutions to protect the environment. This extended exergy analysis can inform policymakers and project managers on the most resource efficient and environmentally friendly method of disposing of plastic waste in Uganda. It should be noted however, that this analysis does not apply to polyethylene terephthalate (PET) or polyvinyl chloride (PVC) plastic. Disposal options for PET in Uganda will be explored in future work.

2. Material and methods

2.1. Exergy analysis framework

When considering sustainability in an environmental and ecological sense, an appropriately defined exergy is a useful concept to analyze the overall use of resources in a process and its impact on the environment. Exergy differs from energy in that exergy considers the *quality* of energy with respect to the environment. Exergy differentiates energy that is actually available to do work from energy that is lost and cannot be recovered due to irreversibilities or technology limitations. When analyzing a manufacturing process, the thermodynamic inefficiencies stand out as destroyed exergy—energy that has lost quality or usefulness (e.g. wasted shaft work or waste heat that cannot be recovered). Exergy identifies energy that is low in entropy and helps engineers identify the amount, type, location, and causes of losses in a system to help identify means of improvements (Dincer, 2007).

Exergy for a closed system (non-flow) with mass *m* is defined in terms of physical, chemical, kinetic, and potential exergy as:

$$Ex_{non-flow} = Ex_{ph} + Ex_o + Ex_{kin} + Ex_{pot} \quad (1)$$

where

$$Ex_{pot} = PE \quad (2)$$

$$Ex_{kin} = KE \quad (3)$$

$$Ex_o = \sum_i (\mu_{io} - \mu_{ioo}) N_i \quad (4)$$

$$Ex_{ph} = (U - U_o) + P_o(V - V_o) - T_o(S - S_o) \quad (5)$$

The terms with 'o' subscripts are associated with the ground state. μ_{io} is the chemical potential of substance *i*, N_i is the number of moles of substance *i*, *U* is the internal energy, *P* is the pressure, *V* is the volume, *T* is the temperature, and *S* is the entropy.

For an incompressible substance, Equation (5) can be written as

$$Ex_{ph} = m * C_p \left(T - T_o - T_o * ln\left(\frac{T}{T_o}\right)\right) \quad (6)$$

where C_p is the specific heat. As outlined by Creyts (Creyts and Carey, 1999), there are two methods for calculating the exergy of a process: theoretically or with a process path. Since exergy represents the amount of reversible work that keeps a system from its ground state, the minimum exergy value of a process is the difference in exergy values between the initial and final state. However, this represents an ideal process and does not account for practical irreversibilities. Real exergy values can be calculated by applying a generic efficiency factor to the theoretical exergy change between initial and final states, but this does not provide detailed insights. The process method is a better approach where a series of reversible process steps are constructed between the initial and final states, so that the consumed and lost exergy can be calculated for each step. The process for each step can be an imagined, hypothetical approach (useful for identifying areas of potential research and development) or based on practical, existing technology (useful for identifying inefficiencies in an existing process).

2.2. Extended exergy analysis

The exergy value of a process or resource also depends on how the environment or ground state is defined because exergy is a property of both the system and the environment. Extended Exergy Analysis (EEA) was first introduced in 1998 by Sciubba to include the material and labor resources, environmental costs, and upstream processing of materials (Corrado and Fiorini, 2006; Sciubba, 1999) in traditional exergy analyses. Using EEA, the lifetime extended exergy of a product can be calculated as a sort of life cycle analysis (Hannemann et al., 2008). By conducting the same exergy calculations for a process with different ground states, one can calculate the exergy cost between different scenarios, such as at process release conditions versus at ambient conditions. In a manner similar to the approach taken by Creyts (Creyts and Carey, 1999), here we adopt a definition of Extended Exergy that embodies exergy relative to an *environmentally acceptable* ground state based on various health, occupational, and ecological criteria. Comparing exergy analysis results between different process release conditions and an environmentally acceptable ground state provides manufacturers and regulators insights into the cost of doing the right thing by achieving environmentally benign production (Sciubba, 1999; Rosen and Dincer, 1998).

The definition of EEA adopted here is an exergy analysis extended to include physically returning all streams of the control volume to the defined ground state. In this paper, we explore different process paths for disposing of Resintile recycled plastic/sand roof tiles that have reached the end of their life and use two different ground states to calculate the remediation costs of properly returning all materials, by-products, and pollutants to an environmentally acceptable end state.

Fig. 3 visually shows the difference between a traditional exergy analysis (as described in the authors' previous paper on the Resintile manufacturing process (Balcom and Carey, 2020)) and an extended exergy analysis (as presented in this paper). We define the initial state as the old plastic/sand tiles removed from the roofs but still at the site of the individual homes where they were installed. The homes are all in the Kampala region, up to 35 km from the Resintile manufacturing site. We considered the control volume to be all of the Resintile tiles sold in a year. One ground state does not consider environmental effects and releases all pollutants without remediation, while the second ground state is an environmentally acceptable ground state defined as standard atmospheric pressure, ambient temperature (25 C), and air, soil, and ground water quality standards as set by the EPA and WHO (EPA; WHO, 2000).

2.3. Net exergy avoided

In this paper, we introduce the concept of including avoided exergy costs to an EEA to find the net exergy cost of bringing a discarded product to an environmentally acceptable end state. Instead of simply calculating the exergy used in each disposal process as in a traditional EEA (Rocco et al., 2014), we also consider the products that the Resintile tiles are replacing in some of the disposal options and subtract the exergy value of those replaced products to give a full picture comparison of resources used. For instance, in the incineration disposal scenario, the tiles are burned as fuel in place of biomass, petcoke, and furnace oil, so we subtract the exergy value of the fuel that is not burned to get the net exergy cost because the natural resources embodied in the current fuel mix are saved. The products replaced in each disposal option are explained in their respective sections.

We represent the exergy value of the replaced resources with the Cumulative Exergy Consumption (CExC) measure. CExC is defined as the raw materials plus fuel and energy inputs required to produce a product (Szargut et al., 1987). Other researchers have calculated the CExC value for many substances using the chemical exergy formula which represents the inherent exergy embodied in the substance plus the fuel and other resource inputs needed to obtain, produce, or refine the substance. For instance, the CExC for gravel is calculated from the chemical exergy of the various minerals in the rock plus the fuel needed to run the machines to extract the rocks and grind them to gravel. In our analysis, we calculated the CExC for many substances from Tables 2 and 3 in Szargut et al. (1987). A few substances in our analysis are not listed in Szargut, so the alternative sources are noted and a description of how we calculated values for bitumen, sand, and concrete is included in the Calculations section. Table 1 summarizes the CExC values used.

Thus, we define the exergy net avoided as

$$Ex_{net\ avoided} = Ex_{net\ process} + CExC_{resources\ avoided} \tag{7}$$

$$\left\{Ex_{net\ process} = Ex_{pr\ current} - Ex_{pr\ w.\ tiles}\right\}^{1} \tag{8}$$

$$\left\{Ex_{net\ process} = Ex_{pr\ current} + Ex_{rem\ current} - \left(Ex_{pr\ w.\ tiles} + Ex_{rem\ w.\ tiles}\right)\right\}^{2} \tag{9}$$

Table 1
Summary of CExC values for materials.

Material	CExC (MJ/kg)	Source
Sand	0.12	Dewulf et al. (2001)
Concrete (for pavers)	3.99	calculated
Cement (wet method)	10.18	Szargut et al. (1987)
Coal	30.44	Szargut et al. (1987)
Coke	30.50	Szargut et al. (1987)
Bitumen	47.52	(Szargut et al., 1987; Berthiaume and Bouchard, 1999)
Diesel	51.74	Szargut et al. (1987)
Fuel Oil	51.74	Szargut et al. (1987)
Cellulose (used for biomass)	60.03	Szargut et al. (1987)
Plastic (PE)	92.30	Szargut et al. (1987)

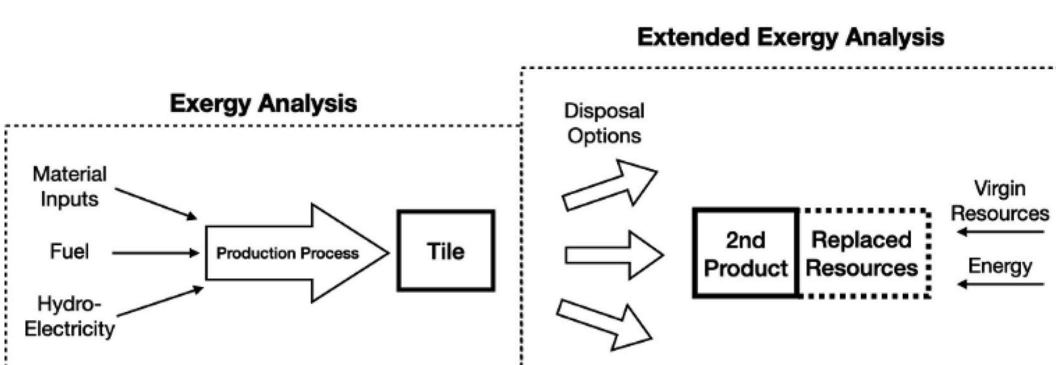

Fig. 3. Diagram of extended exergy analysis concept.

$$Ex_{net\ rem} = Ex_{rem\ current} - Ex_{rem\ w.\ tiles} \quad (10)$$

where $CExC_{resources\ avoided}$ is the exergy value of the virgin resources and the exergy cost of production of the products being replaced or saved in each disposal scenario. Ex_{pr} is the exergy cost of the process, and Ex_{rem} is the exergy cost of the remediation process to bring all inputs, by-products, and pollutants to an environmentally acceptable end state. The braces and exponents ^{1} and ^{2} refer to the ground states—the first with no environmental considerations and the second as an environmentally acceptable ground state as previously defined.

Our formula is based on the work presented by Dewulf (Dewulf et al., 2009) but modified to fit our specific scenario where the disposal option is not defined as one method but instead is the object of study. Dewulf adds a $CExC_{end-of-life\ disposal}$ value to account for the exergy avoided by no longer needing to dispose of waste (instead he assumes it is recovered or recycled into new products), but we do not include this term because the disposal option is the object of study in this paper, so it would be incorrect to assign a specific disposal method to obtain a value for exergy avoided from disposal. Additionally, the most common current disposal method in Uganda of piling up and leaving the roof tiles in an open space has negligible exergy cost.

Calculating the raw materials and energy inputs for disposal and remediation processes including waste residuals and pollutants compared to a consistent, environmentally acceptable ground state provides objective, big picture insights not available through other types of analyses. Including the CExC value of avoided resources and the exergy cost of production processes from products we are replacing takes most previous Extended Exergy Analyses a step further and makes our analysis even more holistically informative. To our knowledge, this is also the first extended exergy analysis for disposal options specifically for plastic waste (as opposed to all MSW) that considers what could be feasible in a developing country context, such as Uganda.

Thus, we employ equations (6)–(10) as the basis for our EEA as described in the Calculations section below. As noted in each calculation, we gathered the data from literature reviews and 10 months of field work in Uganda. Temperature data for various parts of the Resintile manufacturing process was obtained during a site visit, and the engineer and general manager at Resintile, LLC were especially helpful in providing other production data. Specific heat values for polyethylene and polypropylene at varying temperatures were taken from databases compiled by Gaur and Wunderlich (1981a,b).

3. Theory/model for EEA of various disposal options

We identified seven different end of life disposal options for the Resintile plastic/sand roof tiles that are either already practiced or could be feasible in the developing country context of Uganda. The general process of each option is shown in Fig. 4 and described below. This section presents the theory behind why and how we modeled each disposal option, and Section 4 presents the detailed calculations. In this section, each disposal method is introduced, the process for environmental remediation in each method is discussed, and the considerations for each process in the context of a developing country (specifically Uganda) are presented.

3.1. Open burning

The most common method of waste disposal in Uganda and developing countries is open burning. Homes and businesses in both rural and urban settings engage in this practice. Even in most landfills, waste is openly burned to reduce the size of the trash and make room for more. More than 40% of the world's garbage is burned in open piles emitting carbon dioxide, mercury, particulate matter, and polycyclic aromatic hydrocarbons (PAHs) (Wiedinmyer et al., 2014). The greenhouse gas emissions from burning trash are not counted in global inventories. PAHs are highly dangerous pollutants as they can cause cancer, birth defects, neurological disorders, and other health issues (R20 and "Open Burning of Was, 2019).

To determine if plastic/sand tiles can physically burn in an open burning scenario and assess if this disposal option is relevant to roofing tiles, we conducted an experiment to determine the flammability of the

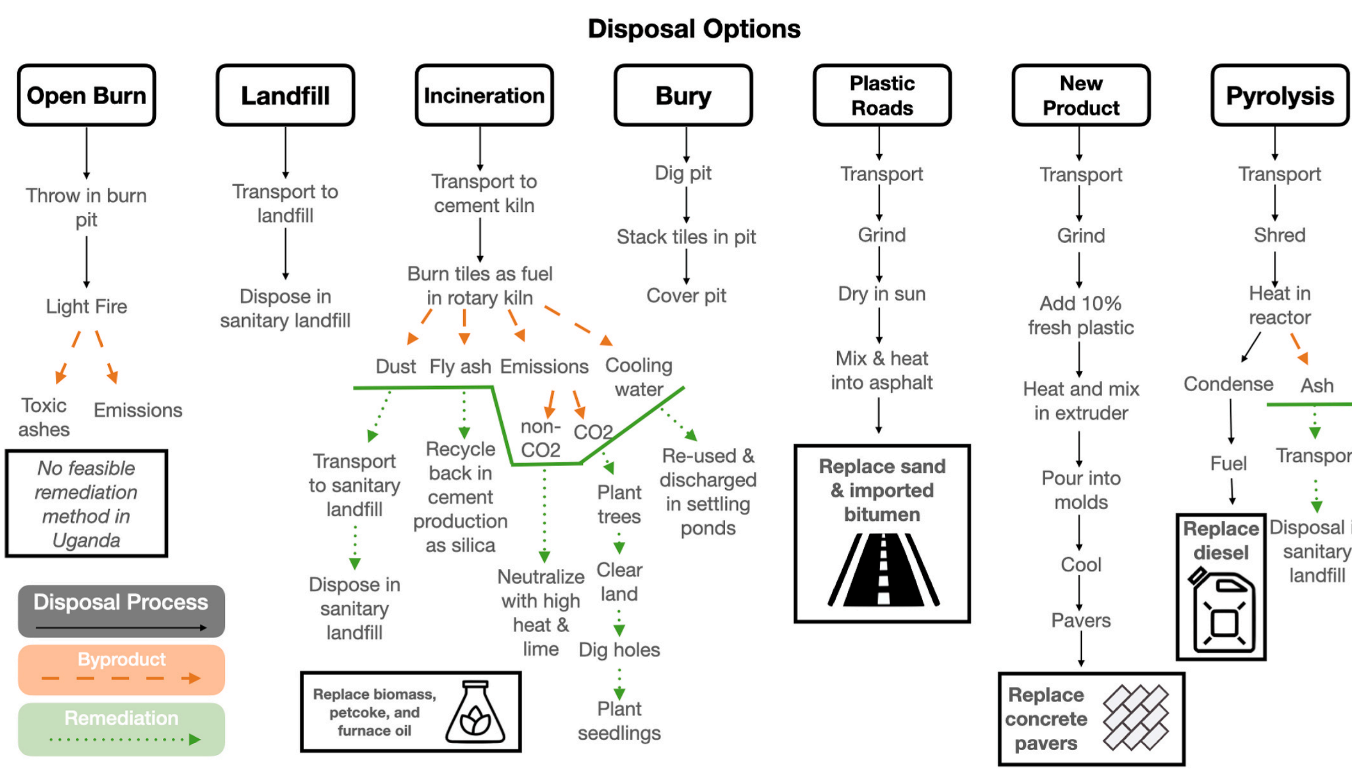

Fig. 4. Flow diagram of proposed disposal options for discarded resintile roof tiles.

Resintile tiles. Due to the significant amount of sand in the tiles, they do not continuously burn on their own. Even when kerosene is added, our experiments showed the fire extinguishes when the kerosene is finished burning, but when the tile is surrounded by organic material or other fuel, the fire sustains itself. Since burn pits in Uganda contain all types of waste (a large percentage being organic matter), we determined that the tiles could be burned. However, we estimated 10% of the energy required to burn the plastics in the tiles would be needed to start the fire.

3.1.1. Environmental remediation for open burning

We conducted extensive research to quantify the emissions and pollutants left in the ashes from open burning. We determined that CO_2, PAHs, particulate matter, lead, NOx, and SO_2 are the major pollutants (EPA; Valavanidis et al., 2008). According to experiments that simulated open burning conditions, carbon monoxide is not an issue because virtually no carbon is left in the ashes meaning that all carbon present in the polymer chains is converted to CO_2 (EPA, 2015). Only PET had 5% of its carbon remaining in the ashes; other plastics had 0% (Valavanidis et al., 2008). Therefore, the amount of CO_2 released from open burning of the tiles was calculated from the direct stoichiometry of each plastic present in the tile multiplied by the oxidation factors of 1 for HDPE, LDPE, and PP and 95% for PET. Section 3.1 discusses the various ways of remediating the CO_2 released to prevent negative environmental impacts.

For PAHs, Benzo [a]pyrene (BaP) was used as a proxy in accordance with procedures from other studies (WHO, 2000; Kwan and Takada, 2016). We compared the amount of BaP released from open burning of plastics with the World Health Organization 1 in 1 million cancer risk guideline (World Health Organization, 2000). The lead, NOx, SO_2, and particulate matter released from burning tiles was compared to the U.S. Environmental Protection Agency (EPA) critical air pollutant standards (EPA). The PAH, Pb, NOx, and particulate matter emissions from open burning of Resintile tiles far exceeded the WHO and EPA standards. Only the SO_2 emissions are within the guidelines. To properly remediate all of these pollutants to ensure no environmental damage, scrubbers and filters would be needed.

3.1.2. Ugandan context for open burning

Across the world, various Negative Emission Technologies (NETs) are utilized or under development to capture CO_2, such as direct carbon capture where CO_2 is chemically scrubbed from ambient air, magnesite—a carbon capturing mineral currently only made at lab-scale, iron spread on oceans to encourage the growth of carbon-absorbing phytoplankton, and tree planting (Workman et al., 2011). However, most of these technologies are not feasible in Uganda. For the developing country context, we identified tree planting as a possible carbon offsetting strategy and suggested growing algae on fish ponds as a new solution tailored for Uganda. Aquaculture is extensively practiced in Uganda, algae can be used as fish feed, and up to 50% of algal biomass weight can be carbon absorbed from the atmosphere (Kativu, 2011; Bux and Chisti, 2016). Algae can be intensively grown in bioreactors, but this technology is not available in Uganda (Nankabirwa, 2019). Ugandan aquaculture is limited primarily to open ponds, where algae cannot be grown intensively. We calculated that the surface area of open ponds necessary to grow enough algae to capture all the CO_2 released from burning Resintile tiles in a year exceeds the amount of land in the whole country of Uganda. Therefore, growing algae for CO_2 offsetting is not a feasible solution in Uganda. Cultivating trees is still a viable carbon sequestration option and is discussed more in Section 5.1.

The significant amounts of PAHs, Pb, NOx, and particulate matter can only be properly handled with extensive filter and scrubber systems which are not available in Uganda (Abdel-Shafy and Mansour, 2016). We explored the possibility of utilizing locally available filters, such as using catalytic converters from vehicles, but those only remove NOx and convert CO to CO_2. Additionally, it would not be feasible to erect filters over every burn pit across the region where tiles would be burned. Therefore, there is no feasible solution to realistically handle the emissions from open burning tiles, so exergy calculations were halted for this disposal option.

3.2. Landfilling

In Kampala, 40% of the city's waste is delivered to Kiteezi landfill (Komakech et al., 2014) located outside of the city 13.8 km from the Resintile factory. We therefore considered throwing the whole tiles in the landfill as a possible disposal option. The 2016/17 State of the Environment Report published by the National Environment Management Authority (NEMA) stated that Kiteezi landfill is full to capacity and plans are underway to open a new landfill site in Ddundu 40 km outside of the city (KCCA, 2017; NEMA, 2017). The site was scheduled to open in April 2019, but as of February 2020, a contractor to develop the project had not yet even been identified. All waste that is collected in Kampala is still being sent to Kiteezi landfill.

3.2.1. Environmental remediation for landfilling

The Kiteezi site 13 km outside of Kampala was designed to be a sanitary landfill with a leachate treatment plant, but it is currently not operating properly. There is no proper liner for the landfill (Project Teaser Kam, 2017), the daily chemicals for the leachate plant are often lacking (Nabukeera, 2015), and unstable slopes of the piled waste have reportedly breached the boundary of the landfill (Environmental Impa, 2008).

Although Kiteezi landfill is not operating properly, we still considered it a sanitary landfill because some of the infrastructure of a sanitary landfill is still in place and we deemed the environmental hazards from throwing the tiles into a landfill to be minimal. Leaching and microplastics are the only environmental risks in this scenario. There are no harmful leaching effects from the plastic polymers themselves—the risks come only from additives (Kwan and Takada, 2016). Since the tiles are made from post-consumer plastic waste, the additives are not highly dangerous. Additionally, EnviroShake, a Canadian company manufacturing roofing materials from plastic waste, conducted lab-certified toxicology tests proving that the rainwater runoff from their products is potable and there is no harmful leaching from the tiles (MTE, 2012). For the issue of microplastics, measuring microplastics is very difficult, so no conclusive studies have yet been done to determine the real environmental effects or to set acceptable standards.

3.2.2. Ugandan context for landfilling

We conducted extensive research on the state of Kampala's landfill as described in previous sections. These details enabled us to tailor our analysis to the Ugandan context. For future analyses outside of the Kampala area, other landfills across Uganda have even less infrastructure than Kiteezi and are more like open dumping and burn pits.

3.3. Incineration in cement kilns

Incineration was analyzed by using the tiles as fuel in cement kilns. Cement is a binder and the main ingredient in concrete. Its production requires a source of calcium which usually comes in the form of limestone and a source of silicon which comes in the form of clay or sand. The raw materials are ground, mixed, and then fed into a rotary cement kiln. Different sections of the kiln progressively heat up until they reach temperatures up to 1480 C. After the raw materials are completely melted, they cool and solidify into pellets called clinker. This clinker is then ground into a fine powder. Gypsum is added at the final stages of production during the grinding of the clinker to control the settling of the cement. Throughout the process, water is first used to cool the equipment, and then recycled and reused (Center for Health and Environment and Justice, 2011; Ghalandari and Iranmanesh, 2020; Jijesh et al., 2015; Afsar, 2012).

Many cement kilns use coal as their primary source of fuel to heat the rotary kiln (Chatziaras et al., 2016), but in Uganda, alternative sources are often used. For this study, we use Hima Cement Ltd, one of the largest and most advanced cement manufacturers in Uganda, as a case study. Hima uses a mix of agricultural waste, petcoke, and furnace oil to heat their kiln. In this EEA, we propose replacing the current fuel with the Resintile roof tiles made from recycled plastic and sand. Due to the high temperatures reached in the kiln, most types of waste can be burned in cement kilns as is already being done in India and encouraged by the Indian government (Central Pollution Control, 2017). The only major exception is PVC.

3.3.1. Environmental remediation for incineration in cement kilns

Cement manufacturing produces solid wastes and air emissions mostly in the form of cement kiln dust and gaseous emissions from burning fuel. Kiln dust consists of alumina, silica, clay, and metallic oxides with small traces of dioxins, furans, cadmium, lead, selenium, and radionuclides. However, the EPA determined that cement kiln dust is not hazardous to human health if disposed of in a properly lined landfill (Weber et al., 2011). Fly ash left behind after burning the fuel can be used as a source of silica in cement production or in concrete mixtures to substitute 15–35% of the cement (Jaturapitakkul et al., 2004).

Incinerating the plastic/sand tiles in the rotary kiln would release CO_2. We propose remediating the CO_2 released from incinerating the tiles by planting trees to absorb an equivalent amount of carbon dioxide. Other emissions, such as heavy metals and dioxins, are not an issue because the high temperatures (1250–1450 C), long residence time, and oxygen rich environment in the cement kiln destroy all waste and ensure complete combustion. Additionally, adding lime neutralizes pollutants to keep the emissions within accepted standards (Sustainable Recycling Ind, 2016; Theulen, 2015a). Water used to cool the equipment is reused and water used for equipment cleaning is discharged into settling ponds. The EPA does not consider this hazardous unless the pH of the waste water is less than 12.5 (Center for Health and Environment and Justice, 2011).

Cement kiln co-processing (burning waste as an alternative to fossil fuels to heat cement kilns) is approved by the Basel Convention for disposal of hazardous wastes and the Montreal Protocol for disposal of persistent organic pollutants (POPs). Co-processing plastic waste in cement kilns can be better for the environment than landfilling or incineration, and is encouraged by the Indian government (Central Pollution Control, 2017). India is even piloting co-processing hazardous plastic wastes containing bromide flame retardants in cement kilns (under specified emissions monitoring procedures) (Sustainable Recycling Ind, 2016).

3.3.2. Ugandan context for incineration in cement kilns

In developed countries, incineration in waste to energy plants is a common method of disposing of plastic waste. However, there are very few incineration plants near Uganda, and the ones available are not in operation. Incineration plants are costly to build and operate and are not a viable option for developing nations. Ugandan hospitals and health clinics often have incinerators for burning medical waste, but the furnaces are usually not well designed and there are no filters. Therefore, the emissions are not properly remediated, and the process is more like open burning.

To tailor our analysis to the Ugandan context, we identified cement kilns as a feasible alternative to traditional incinerators. The high temperatures required in cement kilns are representative of incinerators, and other studies have cited using plastic waste as fuel in cement kilns (Chatziaras et al., 2016). The cement production industry is already well established in Uganda with six different manufacturing plants across the country. Raw materials used in the manufacturing of cement such as lime and gypsum can be found in Uganda and Egypt respectively.

3.4. Pyrolysis

Researchers at the University of Kentucky and Makerere University developed a low-cost, locally fabricated reactor to transform plastic waste into fuel through pyrolysis (Joshi and Seay, 2016). Pyrolysis refers to the heating of plastic in the absence of oxygen to achieve thermal decomposition. The University of Kentucky Appropriate Technology and Sustainability (UKATS) reactor uses a rocket stove as the main source of heat and is insulated using vermiculite. The process begins by loading a propane cylinder, which acts as the reaction chamber, with shredded waste plastic. Next, the reaction chamber is placed inside the processor, covered with a lid, and heated steadily until it reaches 400 C–450 C. The vapor created is condensed in an ambient temperature water bath and the top fuel oil layer is separated from the water using gravity. After discussions, the designers of the UKATS reactor confirmed that their device can work with plastic roof tiles ground into pieces (Seay, 2019).

3.4.1. Environmental remediation for pyrolysis

The fuel produced by the UKATS reactor is similar to diesel or kerosene and the potential byproducts are wastewater, off-gases, and ash (Joshi and Seay, 2016). The water bath used in the reactor to condense the vapor can be reused for multiple batches, eliminating the need for wastewater disposal. The off-gases secreted are routed back into the heatbox using a pipe to increase system pressure to improve efficiency and eliminate air pollution. Approximately 1% of the mass of the original waste input is leftover as fine powder residue between batches (Seay, 2019). This residue is mostly caused by impurities in the plastic such as dyes, colorants, labels, and dirt. The residue is disposed of by burying it alongside the ash from the wood fire used to heat the process. According to the designers, no harmful environmental effects have been observed from this process. In this paper, we include the exergy cost of transporting and disposing of the ashes in a sanitary landfill to ensure all byproducts reach an environmentally acceptable end state.

3.4.2. Ugandan context for pyrolysis

The UKATS reactor was specifically designed for underdeveloped regions. It is simple, non-automated, and uses a local wood fueled rocket stove as the primary heat source. All of the materials needed to build the reactor can be sourced locally. Due to the regional limitations, the reactor has no precise temperature control, and it cannot be operated completely oxygen free. Since it is locally made without filters for emissions, PET and PVC plastics cannot be used, but polyethylene and polypropylene are acceptable. The UKATS reactor is still a small scale machine, but it proves the concept of pyrolysis as a valid approach for disposing of plastic waste.

Gasification was considered as a potential disposal option for the plastic/sand tiles. However, gasification plants in Uganda are small or medium scale machines designed to use biomass fuel. They would not be able to properly handle the pollutants and fuel separation of hydrocarbon-based plastic waste. We therefore decided gasification would not be a feasible option for disposal of plastic waste in Uganda.

3.5. Road paving

Across the world plastic waste has been used to replace bitumen when making roads (Singh and Sharma, 2016; Nkwachukwu et al., 2013). HDPE and LDPE carrier bags are generally used, but PP could also be possible because the bitumen is melted at 180 C. Laminated thin film plastics are avoided. The plastic modified roads are stronger than traditional asphalt roads and absorb less water, so the plastic roads last longer and require less maintenance (Pandi et al., 2017; Chavan, 2013).

In road construction, the wet method or the dry method can be used. The wet method, generally used in more developed regions, involves heating and mixing the bitumen, plastics, sand, and aggregates in a large mixer. The dry method is used in areas where such mixing equipment is not available or where rough road surfaces are required. In the dry method, the road is built in layers as hot bitumen is sprayed directly onto aggregate and rolled. An Indian professor invented an inexpensive way of melting plastic bags on hot stones and using them as plastic-coated aggregate (Vasudevan et al., 2012). The hot plastic-coated aggregate can then fuse with hot bitumen. India made plastic roads the default construction method in 2015, and as of 2017, the country had over 21, 000 miles of plastic-asphalt roads (Subramanian, 2016).

The Scottish company MacRebur produces plastic modified bitumen that has been implemented across the world. They take discarded plastic bags, extrude them into pellets, and mix them at 6% wt composition with bitumen and activator additives. Macrebur's products meet various worldwide road standards and have been installed in many countries (McCartney).

3.5.1. Environmental remediation for road paving

The potential environmental hazards associated with plastic roads are leaching and microplastics. In the wet method, there is less possibility of leaching because the plastic breaks down and completely mixes with the bitumen. Both plastic and bitumen are mostly hydrocarbons derived from petroleum. When heated together to a liquid state, they become an inseparable mixture of polymer modified bitumen with no risk of leaching or microplastics. Macrebur also adds an activator when heating the mixture to help the plastic fully degrade and compatibilize with the bitumen (McCartney). The compatibilizer helps the immiscible materials bond together to strengthen stability.

There is less conclusive evidence about the environmental effects of the dry method used on Indian roads. Since the bitumen is only sprayed on the hot plastic at 160–180 C, the plastic does not break down, so there is still a possibility of leaching and microplastics. Activists fear that the plastic roads exposed to sunlight, heat, and water could leach chemicals. However, no conclusive research has been done to prove if hazardous chemicals are leaching from the roads (Suriyani, 2017). In 2012, the technique of laying the plastic road was accepted by the Central Pollution Control Board in New Delhi (Vasudevan et al., 2012).

3.5.2. Ugandan context for road paving

Literature reviews and in-person interviews were conducted to verify the feasibility of plastic road technology in Uganda and other developing countries. As described previously, the dry method is already extensively used in India, although there remains some lingering questions about the environmental impacts. In Kampala, all roads are made with the wet method, except major highways that require a rough surface. Outside of Kampala, both methods are used depending on if the mixer and funds are available (the wet method is more expensive than the dry method) (Okello, 2020). Since this analysis focuses on Kampala, we based our calculations on the wet method which has less negative environmental impacts.

3.6. Local transformation to new products

Another disposal option is locally transforming old roof tiles into a new product. Since the tiles have been exposed to sunlight and weathering for many years, the polymer chains will be shortened compromising the strength of the plastic. We identified compound pavers as an appropriate product that could be made with the old tiles. Other companies in Uganda already make plastic/sand pavers with a composition similar to the Resintile roof tiles (Wazi Recycling and "Products, 2020). The thickness of the pavers (7 cm) and the compression-only loading compensates for the weakened state of the polymers and still delivers a functional product.

The pavers can be manufactured at the Resintile facility in nearly the same process as the roof tiles outlined in our previous paper (Balcom and Carey, 2020). Old roof tiles would be transported back to the Resintile factory, crushed into small pieces, fed into the extruder to be re-melted, and placed in molds to cool. The only difference from the roof tile process is that a hydraulic press is not needed to form the pavers and an extra 10% of fresh plastic waste should be added to the ground up tiles prior to extrusion to add additional bonding strength.

3.6.1. Environmental remediation for local transformation to new products

There are no harmful environmental effects from the production of the pavers because the melting temperature is precisely controlled with the extruder to prevent off-gasses. When the pavers are installed in compounds, there is a possibility of leaching and microplastics, but as described above, there is no conclusive evidence showing that these phenomena occur or what their impacts are. Several companies in Kampala are already marketing plastic pavers.

3.6.2. Ugandan context for local transformation to new products

Plastic/sand pavers are already made by several companies in Uganda, and the process we outlined in this analysis uses the Resintile machines. While these machines were expensive to import and are difficult to maintain in Uganda making them out of the reach of most developing country entrepreneurs, many large cities across Africa have industries with imported machinery. Smaller initiatives have made plastic pavers with improvised equipment by melting the plastics in an oil drum over a fire, but this is hazardous to the environment and workers' health. Since the temperature cannot be controlled, the process is virtually the same as open burning. Thus, the method we proposed to manufacture pavers with the Resintile extruder is safe and appropriate for large cities in developing countries with access to investor capital.

3.7. Pit Burial

Similar to landfilling, another disposal option is burying the roof tiles in a pit. The tiles from each house would be buried near the house to eliminate the need for transportation. The only cost is the labor of manually digging the pit and covering the tiles with soil.

3.7.1. Environmental remediation for Pit Burial

Plastics break down primarily through UV and thermal degradation and somewhat from water and oxygen exposure. Unlike organic materials that decompose by being eaten by naturally-present bacteria, if plastics are not exposed to sunlight or heat, they do not degrade (Selke et al., 2015). Therefore, burying plastics in the ground and covering them to create an anaerobic environment can be an environmentally acceptable disposal option. The only potential environmental hazard would come from pigments in the plastics containing heavy metals or other toxins. For the post-consumer waste plastics used by Resintile, this is not an issue. In our analysis, we based calculations on burying the roof tiles with 0.5 m of soil cover, deep enough below the zone heated by the sun's rays to ensure that the tiles are buried in a cool place.

3.7.2. Ugandan context for Pit Burial

In Uganda and other developing countries, digging a pit and burying waste is already a common disposal option. The only challenge comes when future development requires building on, planting in, or digging up the pit. For disposal of the roof tiles in this analysis, the site for burying must be carefully chosen to avoid this challenge. However, burying the tiles with 0.5 m of soil cover is deep enough to mitigate many of those challenges.

4. Calculations

4.1. Open burning

The exergy cost of open burning includes the energy to start combustion and the cost of properly remediating all of the pollutants released, including those in the ashes. To find the energy required to initiate combustion, we used Eqn. (11) based on the enthalpy required for thermal decomposition of plastic from Joshi and Seay's paper on pyrolysis (Joshi and Seay, 2019). The sensible heating of the plastic is broken up into a solid and liquid phase where T_m is the melting temperature of the plastic and T_{rxn} is the temperature at which the reaction occurs (in this case of combustion, we used the flash point of the plastic to find the heat needed to bring the plastic up to the temperature of ignition and then the combustion reaction could continue on its own if exposed to an open flame). ΔH_F is the enthalpy of fusion representing the energy required for the phase change from solid to liquid, and E_a is the activation energy of the reaction. Peterson gives experimentally measured activation energy values for thermal degradation of polyethylene and polypropylene in air as 80 and 90 kJ/mol respectively (Peterson et al., 2001). We also included sensible heating of the sand to bring the temperature of the sand up to the temperature of the reaction. Since the sand in the tiles is inert and slows the spread of flames, the tiles must be surrounded by other fuel, such as organic waste, to keep the fire going. We approximated this additional fuel as 10% of the energy needed for combustion of the plastic in the tiles.

Heat energy, Q, was converted to exergy as described by Eqn. (15) by imagining a theoretical heat engine could capture the heat and convert it into useable work. The carnot efficiency is calculated with the temperature values in Kelvin, and an η_{real} efficiency factor of 0.6 is included because in reality, heat engines generally operate at 60% of carnot efficiency depending on the type of modifications to the basic Rankine Cycle used (Sonntag et al., 2003).

$$Q_{plastic} = \sum_{i=1}^{n} m_i {*} C_{p\ solid_i} {*} (T_{m_i} - T_o) + m_i {*} \Delta H_{F_i} + m_i {*} C_{p\ liquid_i} {*} (T_{rxn} - T_{m_i}) + m_i {*} E_{a_i} / M_i \quad (11)$$

$$Q_{sand} = \sum_{i=1}^{n} m_i {*} C_{p_i} {*} (T_{rxn} - T_o) \quad (12)$$

$$Q_{extra\ fuel} = 0.1 {*} Q_{plastic} \quad (13)$$

$$\eta_{carnot} = 1 - \frac{T_o}{T_{rxn}} \quad (14)$$

$$Ex_{process} = \eta_{carnot} {*} \eta_{real} {*} \left(Q_{plastic} + Q_{sand} + Q_{extra\ fuel}\right) \quad (15)$$

Significant amounts of toxic fumes are released from burning plastic, so remediation is necessary to reach an environmentally acceptable end state. When plastic is burned in open environments, the carbon in the polymer chains breaks off and mixes with the oxygen in the air to form CO_2. Molecular weight and stoichiometry reveal the mass of CO_2 that is formed when all of the carbon in a polymer is converted to carbon dioxide. Depending on the amount of oxygen present during burning, some of the carbon can be converted to carbon monoxide instead of CO_2. We calculated the oxidation factor for open burning of the various polymers in the Resintile tiles based on the percentage of carbon left in the ashes from open burning experiments (Valavanidis et al., 2008). The remaining carbon in the ash represents the amount of carbon in the polymer chain that was not converted to CO_2, so the amount of CO_2 calculated from direct stoichiometry multiplied by the oxidation factor gives the real amount of CO_2 released by each polymer in open burning as described in the following equation where f_{ox_i} is the oxidation factor for polymer i, N_{C_i} is the number of carbon atoms in the repeat unit for polymer i, M_{CO_2} is the molar mass of CO_2, and M_i is the molar mass of one repeat unit of polymer i.

$$kg\ CO_2\ released = f_{ox_i} {*} N_{C_i} {*} M_{CO_2} / M_i \quad (16)$$

As shown in Table 2, we found that our calculated values agreed with

Table 2
Comparison of CO_2 emitted from burning plastic.

	PE	PP	PET
Oxidation Factor, Open Burning	1.00	1.00	0.95
Repeat Unit	C_2H_4	C_3H_6	$C_{10}H_8O_4$
CO_2 emitted (Eqn. (9)) [kg]	3.14	3.14	2.29
CO_2E emitted (EPA, 2015) [kg]	3.08	3.32	2.25

the EPA's values of kg of CO_2E (carbon dioxide equivalent) released per kg of plastic for each polymer type (EPA, 2015). It should be noted however, that the equivalent CO_2 in the EPA statistic includes impacts from other greenhouse gases emitted.

As described in Section 3.1, we identified growing algae and trees as potentially feasible options for remediating CO_2 in Uganda. Very little data exists on algae cultivation in East Africa, but an exergy analysis of growing algae in open raceways in India and harvesting for fuel reported that an open raceway could sequester 163,800 kg of CO_2/hectare/year (Sudhakar et al., 2012). If the CO_2 inputs required for cultivating, harvesting, and processing the algae into fuel are subtracted, a net 91,196 kg of carbon dioxide/hectare/year can be sequestered. In terms of exergy, the paper reports the exergy cost of cultivating and processing subtracted from the exergy value of the biofuel product gives a net exergy profit of 980,038 MJ/ha/year. However, open raceways are not currently available in Uganda. Another study on small Malaysian phytoplankton ponds is more applicable to the scenario in Uganda (Richardson and Jin, 1975). The paper reported that unenriched and enriched ponds could sequester 0.9 and 6.0 g C/m^2/day respectively. However, even with the enriched number, more hectares of ponds would be needed to sequester the CO_2 released from open burning of the Resintile tiles sold in one year than the land available in the whole country of Uganda. Thus, growing algae to sequester CO_2 is not yet a feasible option in Uganda.

However, growing trees to absorb CO_2 is a plausible option. Eucalyptus woodlots in Uganda can absorb 4 tonnes of carbon/ha/yr (Aune et al., 2005), and 2.35 tonnes of C/ha/yr is the average sequestration value for trees in Mt. Elgon and Kibale national parks in Uganda (Proforest, 2010). When planting woodlots, chain saws, pangas, and manual labor are used to clear the land, and manual labor is used to dig the holes and plant the seedlings (Bateham, 2019). In Uganda, one person can clear half an acre of land per day, dig 80 holes per day spaced 2.5 m apart, or plant 240 seedlings per day. Chain saws require approximately 6 L of petrol per acre cleared. Using 3483 kJ/person/day as the exergy cost for manual labor (Lu et al., 2006) and fuel exergy costs found using Equation (16) where V is the volume of fuel used, ρ is the density of the fuel, and b^{ch}_{fuel} is the specific chemical exergy, we calculated the exergy cost for planting trees is 11.1 kJ/m^2 of trees planted.

$$Ex_{fuel} = V {*} \rho {*} b^{ch}_{fuel} \quad (17)$$

To sequester 1 tonne of CO_2, we calculated 27.65 MJ and 47.06 MJ of exergy and 2500 and 4255 m^2 of land would be needed for eucalyptus woodlots and national parks respectively. There is no exergy loss from land use because land used to grow trees or other biomass is not taken into account when calculating land use exergy loss to avoid double-counting (Stougie et al., 2018).

Other pollutants emitted from burning plastic are smaller in mass but more toxic than CO_2. The amount of lead, NOx, SO_2, PAHs (BaP is used

Table 3
Extended exergy calculations for open burn disposal option.

Stage	Comments	Equations Used	Exergy Contribution (MJ/tonne tiles)
Heat	Sum the amount of sensible and latent heat and activation energy required to heat each material i in the tiles (sand, pigment, and three types of plastics) from 25 C to the flash point for PE of 341 C (Yaws, 2014). Convert the heat to exergy with an ideal heat engine multiplied by η_{real} of 60%. C_p values are 0.739 kJ/kg-K for sand (Yaws, 2014) and 0.650 kJ/kg-K for pigment (Lide, 2009). Property values for PE and PP are taken from (Joshi and Seay, 2019) except the activation energy for combustion is 80 and 90 kJ/mol for PE and PP respectively (Peterson et al., 2001).	$Q_{plastic} = \sum_{i=1}^{n} m_i * C_{p\ solid_i} * (T_{m_i} - T_o) + m_i * \Delta H_{F_i} + m_i * C_{p\ liquid_i} * (T_{rxn} - T_{m_i}) + m_i * E_{a_i} / M_i$ $Q_{sand} = \sum_{i=1}^{n} m_i * C_{p_i} * (T_{rxn} - T_o)$ $Q_{extra\ fuel} = 0.1 * Q_{plastic}$ $\eta_{carnot} = 1 - \frac{T_o}{T_{rxn}}$ $Ex_{process} = \eta_{carnot} * \eta_{real} * (Q_{plastic} + Q_{sand} + Q_{extra\ fuel})$	408
Net Process Exergy[a]	Sum all the exergy contributions to the process. $Ex_{pr\ current}$ equals 0 for open burning.	$\{Ex_{net\ process} = Ex_{pr\ current} - Ex_{pr\ w.\ tiles}\}^1$	**-408**
Remediation—Transport Ash	Transport ash (1% of plastic & 100% of all sand and pigment) to Kiteezi Landfill (avg 13.8 km). Use CExC transport value of 3.13 kJ/kg-km for 28t truck from (Dewulf et al., 2001). m is the mass of goods transported and d is the distance travelled.	$Ex_{rem} = CExC_{transport} * m * d$	30
Remediation—Landfill Ash	Dispose of all ash (1% of plastic & 100% of sand and pigment) in Kiteezi landfill. Use 0.35 MJ/kg CExC value for disposal of mixed debris in a sanitary landfill (Dewulf et al., 2009).	$Ex_{rem} = CExC_{landfill} * m$	247
Remediation—Emissions	Calculate m_i, the kg of airborne pollutant i emitted from burning tiles then multiply by the $AbatEx_i$ value for that pollutant. AbatEx is 0.028 MJ/kg CO_2 for absorption by trees in eucalyptus woodlots [calculated], 57.0 MJ/kg SO_2 scrubbing (Cornelissen, 1997), and 16.0 MJ/kg NO_x scrubbing (Cornelissen, 1997).	$Ex_{rem} = \sum_{i=1}^{n} AbatEx_i * m_i$	45
Net Remediation Exergy	Sum all the exergy contributions to remediation. $Ex_{rem\ current}$ is 0.	$Ex_{net\ rem} = Ex_{rem\ current} - Ex_{rem\ w.\ tiles}$	**-322**
Net Process Exergy[b]		$\{Ex_{net\ process} = Ex_{pr\ current} + Ex_{rem\ current} - (Ex_{pr\ w.\ tiles} + Ex_{rem\ w.\ tiles})\}^2$	**-730**
Avoided Resources	There are no avoided resources because burning does not replace any products.	N.C.	**N.C.**
Net Avoided Exergy[a]		$Ex_{net\ avoided} = Ex_{net\ process} + CExC_{resources\ avoided}$	**-408**
Net Avoided Exergy[b]		$Ex_{net\ avoided} = Ex_{net\ process} + CExC_{resources\ avoided}$	**-730**

N.C.: No Contribution.
[a] Ground State 1: current scenario of emitting all pollutants and by-products without remediation.
[b] Ground State 2: bringing all inputs, pollutants, and by-products to an environmentally acceptable end state as defined by EPA and WHO guidelines.

as a proxy), and particulate matter emitted from open burning of plastics was found from experiments reported in literature (Valavanidis et al., 2008; Courtemanche and Levendis, 1998) and was compared to the acceptable air standards set by the WHO and EPA (EPA; Boguski, 2006; World Health Organization, 2000). All pollutants except SO_2 were drastically over the acceptable limits.

As stated in Section 3.1, there is no realistically feasible way in Uganda to bring all the pollutants from open burning to an environmentally acceptable end state. However, in an attempt to quantify the exergy costs of this disposal option, we searched literature and found a couple of recent papers presenting AbatEx, abatement exergy, values for certain gaseous pollutants (González et al., 2020; Stougie et al., 2018). They define AbatEx as the internal energy needed to abate air emissions to an accepted limit for the environment using available technology. They report values of 5.9 MJ/kg for CO_2 from fossil fuel abatement based on CO_2 recovery via ethanolamine absorption and stripping followed by compression to 80 atm for underground storage (Stougie, 2014; Dewulf et al., 2000; Van der Vorst et al., 2011), 57 MJ/kg for SO_2 abatement based on 90% removal of SO_2 in a flue gas desulphurisation unit of a coal-fired power plant using limestone and converting to gypsum (Stougie, 2014; Cornelissen, 1997), and 16 MJ/kg for NO_x based on 80% removal in a $DeNO_x$ unit of a coal-fired power plant (Stougie, 2014; Cornelissen, 1997). None of these remediation technologies are feasible for Uganda, but they offer some idea of the exergy cost of burning recycled plastic roof tiles. However, the picture is further incomplete because no data yet exists for abatement exergy of other types of gaseous pollutants, which can cause misleading results because PAHs are the most toxic to human health of all the pollutants released from burning plastic, but no exergy remediation cost is available for PAHs. Results and comparisons are presented in Section 6.

Since open burning is one of the most common disposal methods currently used in Uganda, we provided the detailed calculations in Table 3 as an example of the calculations for the other disposal methods. The temperature measurements of the materials at various stages of the production process and the mass of the materials are the only measured values in our analysis. Other numbers are obtained from literature or calculated. The mass of the materials is estimated to 1 kg precision, and temperature measurements were obtained to 1 C precision with ± 0.5 C uncertainty.

4.2. Landfill

For the landfill calculations, we considered the fuel exergy cost of transporting the old tiles from the homes where they were installed to Kiteezi landfill (approximately 13.8 km) plus the cost of disposal in a sanitary landfill. The CExC value of transportation in a 28t truck is 3.13 kJ/kg-km (Dewulf et al., 2001), and the CExC value for disposing of mixed debris in a sanitary landfill is 0.35 MJ/kg (Dewulf et al., 2009). Since the tiles do not replace any product, there is no value added, so we do not consider the CexC value of any saved resources. In developed countries, biogas is often collected from degrading waste in landfills, but Kiteezi landfill does not have this technology. In the landfill scenario in Uganda, there is no new product gained from the waste; there is only the exergy cost of disposal.

4.3. Incineration in cement kilns

The exergy cost of incineration in cement kilns begins with the transportation of tiles from Resintile, lime from Hima lime plant, and Gypsum from Egypt. The transportation of materials, rotating of the kiln, heating of the clinker, and all other parts of the manufacturing process are the same regardless of if the current fuel mix or the tiles are burned, so the net exergy of the process is zero. We assumed the transportation of the tiles approximately equaled and negated the transportation of the current fuel. We equated the higher heating values of the tiles and the current fuel mix to calculate how many kilograms of the current fuel we could save by burning the tiles.

For this study, we used Hima Cement Limited as a case study because they are one of the largest and most advanced cement manufacturers in Uganda. They currently use a fuel mix of 60% biomass (coffee husks, rice husks, gnut husks, baggase and saw dust), 30% petcoke, and 10% furnace oil (Caroline, 2020).

The CO_2 emissions from burning plastic for fuel to heat the kiln are remediated by planting trees as explained in Section 5.1—we simply calculate the amount of CO_2 released from complete combustion of the plastic fuel and the exergy cost of planting enough trees to absorb that amount of CO_2. The CO_2 emissions from burning plastic are greater than the CO_2 emissions from burning Hima’s current fuel mix. 1.69 kg of CO_2 are released for every kg of the current fuel burned (EPA, 2018) while 3.14 kg of CO_2 are released for every kg of plastic burned. The exergy cost to plant trees to absorb those amounts of CO_2 were calculated according to the procedures outlined in Section 5.1 Open Burn then the remediation exergy cost with the tiles was subtracted from the current remediation exergy cost to get the net remediation cost. The fly ash and sand from the tiles can be added back to the cement during the ball mill process, and the wastewater is discharged to ponds on site which has negligible exergy costs (Theulen, 2015).

The product replaced by the plastic/sand tiles in cement kilns is the fuel currently burned. For Hima Cement, this fuel is biomass, petcoke, and furnace oil, but many cement plants burn coal. We calculated the higher heating value (HHV) of the plastic/sand tiles then found the kilograms of current fuel mix that would give an equal HHV. The resources saved by not burning the current fuel were calculated from their CexC values multiplied by the kilograms of fuel saved.

4.4. Pyrolysis

In the pyrolysis process, the tiles are first transported to the UKATS reactor at Makerere University and then shredded. The exergy cost of shredding the tiles was calculated using a CexC value of 22.2 MJ/tonne for crushing aggregate (Berthiaume and Bouchard, 1999). To calculate the exergy cost of heating the tiles in the UKATS reactor, we used equations (11), (12) and (14), (15) (without the $Q_{extra\ fuel}$ term) with T_{rxn} equal to 450 C. The condensation portion of the manufacturing process has no exergy cost because it lacks a temperature change. The ash leftover from the pyrolysis process—consisting of plastic residue (1% of all the plastic in the tiles), all the sand, and all the pigment (Seay, 2019)—is an environmentally harmful byproduct, so the exergy cost to landfill the leftover ash was calculated using the method described in Section 5.2.

Additionally, CO_2 is emitted by the fuel burned to heat the reactor. Joshi and Seay, the designers of the UKATS reactor recently published a paper on the emissions of their process (Joshi and Seay, 2019), so we used that data to calculate the kg of CO_2 that would be released from pyrolisizing the tiles and found the remediation exergy cost by multiplying by our calculated 27.6 kJ/kg of CO_2 remediation value for planting trees in eucalyptus woodlots. For the different fuels presented by Joshi and Seay, we calculated the exergy needed to remediate the CO_2 released in the production of recycled fuel oil from the Resintile tiles is 2.3, 0.8, and 0.9 MJ/tonne tiles for wood, propane gas, and recycled fuel oil respectively. We used the recycled fuel oil value for our calculations because it is the middle value and the most economical fuel choice for production. Financially, it makes sense to use some of the recycled fuel oil produced instead of buying fuel to heat the reactor.

The product produced by burning the plastic/sand tiles in the UKATS reactor can replace diesel. The CexC value of the diesel saved was calculated by multiplying the kg of diesel avoided (based on an equivalent LHV of recycled fuel oil) by the CexC value of diesel in Szargut et al. Detailed calculations and explanations are provided in Table 4 for the pyrolysis option as an example of the calculations performed for other disposal options.

Table 4
Extended exergy calculations for pyrolysis disposal option.

Stage	Comments	Equations Used	Exergy Contribution (MJ/tonne tiles)
Transport	Transport old tiles from homes where they were installed to Makerere University (~avg 35 km). Use CexC transport value of 3.13 kJ/kg-km for 28t truck from (Dewulf et al., 2001). *m* is the mass of goods transported and *d* is the distance travelled.	$Ex_{pr} = CExC_{transport}{*}m{*}d$	110
Shred	Shred the tiles into small pieces to make the heating process faster. Use CexC value of 22.2 MJ/tonne for crushing aggregate from (Berthiaume and Bouchard, 1999)	$Ex_{pr} = CExC_{crush}{*}m$	22
Heat	Sum the amount of sensible and latent heat and activation energy required to heat each material *i* in the tiles (sand, pigment, and three types of plastics) from 25 to 450 C. Convert the heat to exergy with an ideal heat engine multiplied by η_{real} of 60%. C_p values are 0.739 kJ/kg-K for sand (Yaws, 2014) and 0.650 kJ/kg-K for pigment (Lide, 2009). Property values for PE and PP are taken from (Joshi and Seay, 2019).	$Q_{plastic} = \sum_{i=1}^{n} m_i{*}C_{p\ solid_i}{*}(T_{m_i} - T_o) + m_i{*}\Delta H_{F_i} + m_i{*}C_{p\ liquid_i}{*}(T_{rxn} - T_{m_i}) + m_i{*}E_{a_i}/M_i$ $Q_{sand} = \sum_{i=1}^{n} m_i{*}C_{p_i}{*}(T_{rxn} - T_o)$ $\eta_{carnot} = 1 - \frac{T_o}{T_{rxn}}$ $Ex_{process} = \eta_{carnot}{*}\eta_{real}{*}(Q_{plastic} + Q_{sand})$	807
Net Process Exergy[a]	Sum all the exergy contributions to the process. $Ex_{pr\ current}$ equals 0 because there is no current pyrolysis option.	$\{Ex_{net\ process} = Ex_{pr\ current} - Ex_{pr\ w.\ tiles}\}^1$	**-938**
Remediation—Transport Ash	Transport ash (1% of plastic & 100% of all sand and pigment) from Makerere University to Kiteezi Landfill (10.8 km). Use CexC transport value of 3.13 kJ/kg-km for 28t truck from (Dewulf et al., 2001). *m* is the mass of goods transported and *d* is the distance travelled.	$Ex_{rem} = CExC_{transport}{*}m{*}d$	24
Remediation—Landfill Ash	Dispose of all ash (1% of plastic & 100% of sand and pigment) in Kiteezi landfill. Use 0.35 MJ/kg CexC value for disposal of mixed debris in a sanitary landfill (Dewulf et al., 2009).	$Ex_{rem} = CExC_{landfill}{*}m$	247
Remediation—CO_2 from fuel	Calculate *m*, the kg of CO_2 emitted from burning fuel to heat the reactor from (Joshi and Seay, 2019) then use our calculated value of 27.6 kJ of exergy required per kg of CO_2 absorbed for planting trees in eucalyptus woodlots.	$Ex_{rem} = AbatEx_{CO_2}{*}m_{CO2}$	0.9
Net Remediation Exergy	Sum all the exergy contributions to remediation. $Ex_{rem\ current}$ is 0 because there is no current pyrolysis option.	$Ex_{net\ rem} = Ex_{rem\ current} - Ex_{rem\ w.\ tiles}$	**-272**
Net Process Exergy[b]		$\{Ex_{net\ process} = Ex_{pr\ current} + Ex_{rem\ current} - (Ex_{pr\ w.\ tiles} + Ex_{rem\ w.\ tiles})\}^2$	**-1210**
Avoided Resources	Calculate a weighted average LHV of 41,482 kJ/kg for the recycled fuel oil produced based on the LHV's and mass ratios of the plastics in the tiles (Joshi and Seay, 2019). Use an experimentally measured LHV for diesel of 41,500 kJ/kg (Joshi and Seay, 2019) and CexC value of 51.74 MJ/kg (Szargut et al., 1987) for the resource being replaced. $m_{fuel\ oil}$ is found by multiplying the kg of plastic pyrolyzed by yield efficiency of 81.22% (Joshi and Seay, 2016).	$m_{avoided} = \frac{m_{fuel\ oil}{*}LHV_{diesel}}{LHV_{fuel\ oil}}$ $CExC_{resources\ avoided} = CExC_{resource}{*}m_{avoided}$	**12,513**
Net Avoided Exergy[a]		$Ex_{net\ avoided} = Ex_{net\ process} + CExC_{resources\ avoided}$	**11,575**
Net Avoided Exergy[b]		$Ex_{net\ avoided} = Ex_{net\ process} + CExC_{resources\ avoided}$	**11,303**

N.C.: No Contribution.
[a] Ground State 1: current scenario of emitting all pollutants and by-products without remediation.
[b] Ground State 2: bringing all inputs, pollutants, and by-products to an environmentally acceptable end state as defined by EPA and WHO guidelines.

4.5. Road paving

For the plastic road scenario in Kampala, we used the wet method of asphalt production for calculations. The road construction company has all of their equipment at the quarry and mixes the asphalt from there (Okello, 2020). The transportation of the tiles to the quarry was calculated based on the previously cited truck transportation CExC value of 3.13 kJ/kg-km. The tiles and aggregate are then crushed in a grinder with a CExC value of approximately 22.2 MJ/tonne (Berthiaume and Bouchard, 1999). The ground up tiles and aggregate are then dried in the sun to remove moisture. Bitumen is the most exergy-intensive element of asphalt roads because it requires extraction and extensive refining of petroleum. A tabulated CExC value of bitumen was not available, so we used a weighted ratio between the CExC value of coal and gasoline similar to Berthiaume & Bouchard's process for estimating the exergy value of bitumen (Szargut et al., 1987). We used 47.52 MJ/kg for the CExC value of bitumen because it should lie between the values for coal and gasoline but weighted more towards gasoline. We also added the exergy cost of transporting the bitumen because it cannot be made in Uganda. Uganda gets its bitumen from Kenya, but Kenya often imports bitumen from Egypt, Saudi Arabia, Iran, and Turkey (Kenya Bitumen , 2019). We used an exergy shipping transportation cost of 0.833 kJ/kg-km (an average of exergy shipping costs in (Hannemann et al., 2008; Dewulf et al., 2001)). We used nautical distance from the ports of Jeddah, Saudi Arabia to Mombasa, Kenya then trucking distance from Mombasa to Kampala. We chose Jeddah as an origin port because it is one of the top ports in the world and relatively in the center of all the countries from which Kenya imports bitumen. The bitumen, tiles, aggregate, and sand are then mixed and heated in a large mixer. The mixer consumes 751 MJ of exergy per m^3 of mixture (Berthiaume and Bouchard, 1999), and we used a mixture density of 2.5 tonnes/m^3 (McCartney). The exergy required for heating each of the individual materials was calculated according to equations (11), (12) and (14), (15) (without the $Q_{extra\ fuel}$ term) with T_{rxn} equal to 180 C.

Using the tiles in road construction saves a significant amount of resources because the tiles replace some of the bitumen and sand required to make the asphalt mixture. Macrebur reports plastic can comprise 0.3% of the total asphalt mixture, replacing 6% of the bitumen (McCartney). If the plastic in all the Resintile tiles sold in a year is transformed into asphalt at 0.3% plastic content, it could pave 111,826 m^2 of road at 10 cm thickness. Plastics also have a lower C_p value than bitumen, so some exergy is saved in heating when plastics are used. The total exergy saved is the CExC values of the replaced bitumen and sand, plus the transport of the bitumen from Saudi Arabia, plus the exergy saved in heating, minus the transport of the tiles to the quarry.

4.6. Local transformation to new products

The process of transforming the old tiles into compound pavers could be done at the Resintile factory. The required machines are already there except for the molds to make the pavers, but those can be easily fabricated by local metal workers. To calculate the exergy consumed in the process, we first consider the cost of transporting the tiles by truck from the various houses to the Resintile factory. The tiles are then crushed into small pieces with a crasher (we used a CExC of 22.2 MJ/tonne as reported in the road calculations for grinding gravel). The ground up tiles are then fed into the extruder and melted. In this analysis, we included an extra 10% of fresh plastic waste to be mixed with the tiles to provide extra binding strength. The exergy calculations for running the extruder screw and heaters are outlined in the authors' previous paper (Balcom and Carey, 2020). The melted plastic is then put into the paver molds and allowed to cool.

The plastic pavers would replace the pavers currently made with concrete. Using the ratio of cement and sand used to make concrete pavers in Uganda (38% cement and 62% sand) (Latong, 2020), we calculated a CExC value of 3.99 MJ/kg for this concrete mix from a weighted ratio of the CExC value for cement (wet method, med rotary kiln) in Szargut and a CExC value for limestone from DeWuluf (Dewulf et al., 2001) which we used to represent the CExC value for sand. We subtracted the CExC value of the 10% fresh plastic waste added to the plastic pavers to get the net CExC of virgin resources saved.

4.7. Pit Burial

For the scenario of burying the tiles, we assumed each home would dispose of their own tiles in their own pit, so the only exergy consumed is in digging the hole. In Uganda, pits are dug manually with a pickaxe. Lu et al. gives the exergy expended in digging as 3483 kJ/person/day (Lu et al., 2006). The average house where Resintile tiles are installed is a 3 bedroom bungalow with 250 square meters of tiles and 60 m of ridge tiles (Otai, 2015). The volume of all the tiles would occupy a 15.5 m^3 pit. In Uganda, it would take two men 5 days to dig a hole of that size assuming they hit some murram—if there is no murram, it would be faster.

Exergy can also quantify the cost of using land, but since the tiles would be covered with at least 0.5 m of soil, the land on top of the tiles could still be used for other purposes. Further research is needed to understand if the land could safely be used for growing crops or if it could support a large structure, but it could definitely be used for other purposes such as raising chickens, parking vehicles, cooking or washing, or relaxing in an open compound. The land could even be used as a football pitch or park. Therefore, we did not include the exergy cost of occupying the land.

5. Results & discussion

The comparison of various CO_2 abatement methods for open burning and the net avoided exergy for the whole process is presented in Table 5 and Table 6 respectively. In Table 5, the abbreviation "calc" means the numbers were calculated in this paper. As noted in Section 5.1, the abatement exergy values for scrubbing emissions are not representative of Ugandan conditions, but they help give an indication of the

Table 5
Comparing emissions abatement exergy costs and methods.

	AbatEx (MJ/kg pollutant)[a]	kg pollutant /kg fuel fed[b]	AbatEx (MJ/kg PE burned)	AbatEx (MJ/tonne tiles)	Source [a, b]
CO_2, planting trees eucalyptus woodlots	0.02764811	3.14	0.09	25.9	[calc, calc]
CO_2, planting trees Ugandan national parks	0.04706061	3.14	0.15	44.2	[calc, calc]
CO_2, scrubbing	5.9	3.14	13.0	5,535.7	(Dewulf et al., 2000; Van der Vorst et al., 2011), [calc]
SO_2, scrubbing	57	0.00014	0	2	(Cornelissen, 1997, Kim Oanh, 2017)
NO_x, scrubbing	16	0.0035	0	17	(Cornelissen, 1997, Courtemanche and Levendis, 1998)

Table 6
Comparison of net avoided exergy for open burning with different remediation methods.

All units reported as MJ/tonne of tiles						
Disposal Options for Plastic Tiles	Avoided Resources	Net Process Exergy[a]	Net Remediation Exergy	Net Process Exergy[b]	Net Avoided Exergy[a]	Net Avoided Exergy[b]
Open Burning, CO_2 abated w/eucalyptus woodlots	N.C.	-408	-322	-730	-408	-730
Open Burning, CO_2 abated w/trees in Ugandan parks	N.C.	-408	-341	-748	-408	-748
Open Burning, CO_2 abated w/scrubbing	N.C.	-408	-5,832	-6,240	-408	-6,240

N.C. No Contribution.
[a] Ground State 1: current scenario of emitting all pollutants and by-products without remediation.
[b] Ground State 2: bringing all inputs, pollutants, and by-products to an environmentally acceptable end state as defined by EPA and WHO guidelines.

Table 7
Comparison of net avoided exergy for different disposal options with and without remediation.

All units reported as MJ/tonne of tiles						
Disposal Options for Plastic Tiles	Avoided Resources	Net Process Exergy[a]	Net Remediation Exergy	Net Process Exergy[b]	Net Avoided Exergy[a]	Net Avoided Exergy[b]
Landfill	N.C.	-393	N.C.	-393	-393	-393
Pit Burial	N.C.	-7	N.C.	-7	-7	-7
Incinerate in Cement Kiln	84	N.C.	-61,839	-61,839	84	-61,755
Make Pavers	1579	-764	N.C.	-764	815	815
Pyrolisize into fuel	12,513	-938	-272	-1210	11,575	11,303
Road Paving	16,499	-37	N.C.	-37	16,462	16,462

N.C.: No Contribution.
[a] Ground State 1: current scenario of emitting all pollutants and by-products without remediation.
[b] Ground State 2: bringing all inputs, pollutants, and by-products to an environmentally acceptable end state as defined by EPA and WHO guidelines.

remediation cost for open burning (although the analysis is limited to only CO_2, SO_2, and NO_x emissions because of lack of AbatEx values for other pollutants). The method we proposed in this paper of planting trees to abate CO_2 emissions in a manner feasible for the developing country context of Uganda is worth exploring more because for every kg of plastic burned, our method could require only 0.7% of the exergy currently used by scrubbing techniques in developed countries. The precision of the calculations is noted by the number of significant digits presented in the tables. We maintained the precision reported in all sources and used the number of significant digits in the least precise value to report our calculation results.

A comparison of our other proposed disposal methods with remediation methods that are feasible in Uganda is presented in Table 7. The results show that when the exergy saved from replaced virgin resources and processes are considered, the net exergy cost is lowest for processes that recycle the tiles into a new product. This is consistent with DeWulf's

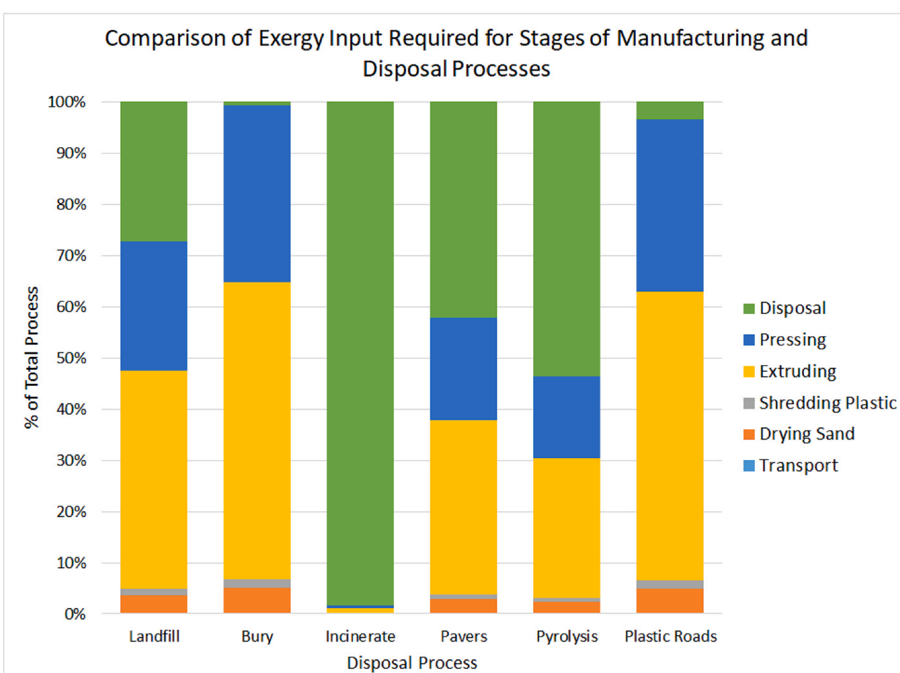

Fig. 5. Comparison of exergy input required for stages of manufacturing and disposal processes.

findings for developed countries that the exergy ratio of outputs to virgin resource intake for different disposal methods is highest for recycling plastics (Dewulf and Van Langenhove, 2004). In our results, mixing the tiles into asphalt to make roads and pyrolizising the plastic into fuel are the best scenarios. Melting and re-shaping the tiles into compound pavers also results in a positive net exergy avoided. The current disposal methods of landfilling, burying, and open burning require very little exergy input for disposal, but no new product is produced and no resources are saved in the process. The other options we propose replace products and materials currently being used, so they can have a net positive exergy saved (except incinerating in cement kilns because the remediation exergy cost is so high). Therefore, inputting thermal energy can add value to the waste and save net resources.

The net process exergy cost of making the tarmac/plastic mixture for paving roads is relatively small because most of the costs negate each other—they are the same regardless of if tiles are included or the current bitumen/sand mixture is used. The C_p value of plastic is lower than that of bitumen, so heating the mixture with tiles takes slightly less energy than the current energy required, but the exergy cost of transporting the tiles to the quarry where the mixture is produced makes the net process exergy negative. However, adding tiles to the mixture saves significant resources because bitumen has a high CExC value, and in Uganda, bitumen must be imported from as far away as Saudi Arabia making the transport exergy costs extremely high. Replacing some of the bitumen and sand with the tiles saves some of those resources. In other locations where the transport costs for bitumen are not as high, plastic roads could be a less favorable disposal option compared to other disposal options.

Pyrolysis is a desirable option because the product produced replaces diesel fuel, which has a very high CExC value (the exergy value of the virgin resource is high and the refining process is exergy-intensive). Heating the tiles and disposing of the ash in a landfill are the most exergy intensive parts of the process. The ashes and sand leftover after pyrolisizing the plastic should be remediated by disposing of them in a sanitary landfill, but the exergy cost of that is only 2.4% of the net exergy avoided. In terms of exergy cost, it is worth it to do the environmentally responsible option.

The process of turning the tiles into pavers is one of the most net exergy intensive of the options because the current process of making concrete pavers uses only manual labor while the plastic paver production process requires electricity for grinding and heating. However, a significant amount of virgin resources are saved if the cement and sand for concrete pavers are no longer needed. Thus the net exergy avoided is positive, making recycling the tiles into pavers an attractive disposal option.

For incinerating in a cement kiln, the exergy of the manufacturing process is the same regardless of if the tiles or the current fuel mix is burned, but the resources avoided and remediation costs depend on the type of fuel burned. In this scenario, where biomass, coke, and fuel oil all have CExC values lower than plastic, the replaced resource value is not very significant. The CO_2 emissions from burning plastic are roughly twice the emissions from the current fuel mix, so the net remediation exergy for burning the tiles is negative. Therefore, in this case, if remediation is considered, incinerating the tiles in a cement kiln is clearly the most exergy intensive disposal option.

The two non-recycling options—landfilling and burying—are negative because no products are produced that can replace and save virgin resources. (Syngas can be captured from more sophisticated landfills, but Kiteezi does not have this capability. The plans for Kampala's next landfill at Ddundu include the possibility of such syngas capture, but no plans have been finalized yet.)

Table 7 also shows the cost of changing the ground state from current, ambient conditions to an environmentally acceptable end state. Two of the disposal options require some form of remediation. Properly disposing of the ashes and sand after pyrolysis costs 2.4% of the net exergy avoided, but planting trees to remediate the CO_2 released from incinerating the plastic in a cement kiln is extremely costly and makes the option unfavorable if remediation is considered. The other disposal options have no remediation costs as explained in the Remediation subsections of Section 2.

When compared to the manufacturing of the tiles, the exergy input required for different disposal methods range from 0.6% to 98.3% of the whole cradle to grave process as shown in Fig. 5. The exergy inputs required for the different stages of the manufacturing process are explained in the authors' previous paper (Balcom and Carey, 2020), and Ground State 2 of bringing all the inputs, pollutants, and by-products to an environmentally acceptable end state was used for the disposal methods in this graph.

If all of Uganda's 600 tonnes of plastic waste generated per day was converted into Resintile roof tiles and disposed of according to our proposed methods, Uganda's current electricity resources would be enough, but Uganda would have to import more diesel. Although the 600 tonnes/day number technically includes PET and PVC plastics which should not be recycled using the exact processes described in this paper, no data is available on the exact percentages of PET, PVC, and other plastics in Uganda's country-wide waste stream. Thus we continue the following analysis using 600 tonnes of plastic per day to estimate if Uganda's resources are enough to recycle all of its plastic waste.

For the best disposal option of paving roads with the old tiles, 158,108,819 L of diesel would be needed per year to melt all the plastic and bitumen. Electricity could be used to melt the mixture, but many road construction sites do not have access to reliable three phase electricity, so a diesel generator is used. Approximately 30 L of diesel can melt 1800 kg of bitumen (Okello, 2020). Uganda imports all of its petroleum products; in 2018, Uganda imported and sold 1,012,541,798 L of diesel (Uganda Bureau of Statistics, 2019). The amount of diesel needed to heat all the plastic and bitumen to make roads with the old tiles from all of Uganda's plastic waste is 15.6% of the amount of diesel Uganda currently imports. For this disposal option, Uganda would have to import more diesel, but it would save importing 219,150,000 kg of bitumen per year by melting the tiles for roads.

If all of the old tiles from all of Uganda's plastic waste were made into pavers, 89.9 GWh of electricity would be needed per year to shred and melt the tiles. This is 2.2% of Uganda's current electricity generated because in 2018, Uganda generated 4038.8 GWh of electricity (Uganda Bureau of Statistics, 2019).

If the pyrolysis disposal option was used, some of the recycled fuel oil produced could be used to run the process to pyrolysize the tiles and make more fuel. The other disposal options do not require electricity or thermal energy inputs. Therefore, all of Uganda's plastic waste could theoretically be made into roof tiles and safely disposed of even with Uganda's limited infrastructure.

6. Concluding remarks

This paper utilized an extended exergy analysis (EEA) to quantify and compare the environmental effects of possible end of life disposal options for recycled plastic/sand roof tiles in the developing country context of Uganda. Our extended exergy analysis quantifies the energy-relevant resources used in the disposal process, resources saved from replaced virgin materials by recycling, and any additional resources needed to bring the tiles, byproducts, and pollutants back to an environmentally acceptable end state. We considered seven disposal options that are already used or could be appropriate for Uganda's less industrialized infrastructure. With a net exergy avoided of 16,462 MJ/tonne of tiles, mixing the tiles into asphalt roads proved to be the best option followed by pyrolysis with 11,303 MJ/tonne of net exergy avoided (including remediation). The remediation exergy cost for pyrolysis was predicted to be 2.4% of the net exergy saved. Recycling the tiles into pavers was the next best option with 815 MJ/tonne of net exergy avoided. Burying, landfilling, and incinerating in a cement kiln were all negative net exergy processes when remediation was considered with −7, −393, and −61,755 MJ/tonne of tiles respectively showing that inputting thermal energy can add value to the waste and save net resources. If all of Uganda's plastic waste was made into roofing tiles, Uganda theoretically has sufficient resources to safely dispose of all of the old tiles. The common practice of open burning was also considered, but we determined it is not practically feasible to bring all the pollutants from open burning to an environmentally acceptable end state with the limited technology available in Uganda. However, the method we proposed for remediating CO_2 by planting trees requires only 0.7% of the exergy used in CO_2 scrubbers currently used in developed countries.

This paper demonstrates how a thermodynamic extended exergy analysis can use empirical data to quantify the resource use of different disposal and recycling options for products made from plastic waste. Such a study focusing specifically on plastic products and disposal options applicable to developing countries has not been done before, so our paper can be useful to policy makers, multilateral organizations, and NGOs making decisions about solid waste management practices in less-industrialized nations. This paper presents results specifically for Kampala, Uganda, which cannot be accurately generalized to all developing countries because each nation's source of materials and technological infrastructure differ. However, with appropriate data, the calculations can be easily updated to provide accurate results for other countries. Additionally, the disposal options considered in this paper cannot be used for all types of plastic; for instance, pyrolyzing PET or PVC has negative environmental effects. The results from this paper are valid for HDPE, LDPE, and PP plastics.

Data availability

No large scale datasets were used in this paper. All data was obtained from literature or personal interviews in Uganda and is properly cited in the References. Our spreadsheet of specific calculations can be made available upon request to the corresponding author.

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.

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Glossary & Nomenclature

AbatEx	Abatement exergy
BAP	Benzo[a]pyrene
CExC	Cumulative Exergy Consumption
CO_2	Carbon dioxide
CO_2E	Carbon Dioxide Equivalent
Cp	Specific heat
ρ	Density
μ_{io}	Chemical potential of substance i
Ea	Activation Energy
η	Efficiency
EEA	Extended Exergy Analysis
Ex	Exergy
EPA	Environmental Protection Agency
f_{ox}	Oxidation Factor
HDPE	High Density Polyethylene
ΔH_F	Enthalpy of fusion
HHV	Higher Heating Value
LDPE	Low Density Polyethylene
LHV	Lower Heating Value
m	mass
M	Molar mass
MSW	Municipal Solid Waste
NGO	Non-governmental Organization
NC	Number of carbon atoms (in equation (9))
N_i	Number of moles of substance *i* (in equation (4))
NOx	Nitrous oxides
P	Pressure
PAH	Polycyclic Aromatic Hydrocarbons
Pb	Lead
PE	Polyethylene
PET	Polyethylene Terephthalate
POP	Persistent Organic Pollutants
PVC	Polyvinyl Chloride
Q	Heat
S	Entropy
b^{ch}	Specific chemical exergy

SO_2	Sulfur dioxide
SWM	Solid Waste Management
T	Temperature
U	Internal energy
UKATS	University of Kentucky Appropriate Technology and Sustainability reactor
V	Volume
WHO	World Health Organization

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