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Assessment of a Decentralized Solution for Waste Plastic Management in Developing Regions

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ASSESSMENT OF A DECENTRALIZED SOLUTION FOR WASTE PLASTIC MANAGEMENT IN DEVELOPING REGIONS

DISSERTATION

A dissertation submitted in partial fulfillment of the
requirements for the degree of Doctor of Philosophy in the
College of Engineering
at the University of Kentucky

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2021

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ABSTRACT OF DISSERTATION

ASSESSMENT OF A DECENTRALIZED SOLUTION FOR WASTE PLASTIC MANAGEMENT IN DEVELOPING REGIONS

Rapid population growth, urbanization and availability of pre-packaged consumer goods have led to increased generation and consumption of plastic – so much so that it has become ubiquitous in the environment. An affordable, durable, and lightweight material of construction, plastic is used in innumerable products in every country on earth. However, this explosion of consumption coupled with the material's significantly low degradability have led to serious plastic accumulation challenges, which are now an imminent threat to terrestrial and marine species globally. These challenges are especially acute in developing countries, where capital and infrastructure constraints, poor governmental regulation and lack of waste management education have led to post-consumer use plastic simply being discarded in unregulated dumps, open plots of land, streets, and waterways. As plastic accumulates in the ecosystem it poses significant negative health consequences due to improper disposal, release of harmful toxins from open incineration, and bioaccumulation of microplastic in the food chain.

To address this challenge, this research applies a holistic approach to waste plastic management in developing countries by incorporating the principles of sustainability, appropriate technology, and circular economy to develop a locally managed decentralized circular economy (LMDCE). In a LMDCE, communities in developing regions are empowered to manage waste plastic accumulation at the source of origin by encouraging and implementing locally engineered, simple, and low-cost solutions that reduce, reuse, repurpose, and recycle waste plastic for reentrance into the local economy. In this analysis, the trash to tank (3T) approach is advocated as a favorable LMDCE solution for eliminating waste plastic from the ecosystem altogether by converting it into plastic-derived fuel oil (PDFO) via thermal decomposition. The research further defines countries and communities most suitable for LMDCE; provides a tool for estimating waste plastic generation in regions lacking readily available waste management data; assesses the mass and energy balance of 3T in appropriate technology settings; assesses the composition and stability of PDFO; determines the generation and combustion emissions of PDFO; and identifies supply chain considerations necessary for sustainably implementing LMDCE and 3T. The proposed solution has also been tested in Kampala, Uganda as a case study.

KEYWORDS: Locally Managed Decentralized Circular Economy, Trash to Tank, Plastic Derived Fuel Oil, Sustainability, Appropriate Technology, Pyrolysis

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DEDICATION

To *my father and my grandfather. I miss you!*

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1. INTRODUCTION

Rapid population growth, urbanization and availability of pre-packaged consumer goods have led to increased generation and consumption of plastic – so much so that it has become ubiquitous in the environment. An affordable, durable, and lightweight material of construction, plastic is used in innumerable products in every country on earth. However, this explosion of consumption coupled with the material's significantly low degradability have led to serious plastic accumulation challenges, which are now an imminent threat to terrestrial and marine species globally. These challenges are especially acute in developing countries, where capital and infrastructure constraints, poor governmental regulation and lack of waste management education have led to post-consumer use plastic simply being discarded in unregulated dumps, open plots of land, streets, and waterways. As plastic accumulates in the ecosystem it poses significant negative health consequences due to leaching from improper disposal, release of harmful toxins due to open incineration, and bioaccumulation of microplastic in the food chain.

To address this challenge, this research applies a holistic approach to waste plastic management in developing countries whereby incorporating the principles of sustainability, appropriate technology, and circular economy, a simple, low-cost, and locally managed solution is created to empower communities to manage their waste plastic at the point of origin. This is accomplished via the establishment of a locally managed decentralized circular economy (LMDCE) in conjunction with a trash to tank (3T) approach for converting waste plastic to plastic derived fuel oil (PDFO) via thermal decomposition, or pyrolysis. In return, the proposed solution eliminates waste plastic from accumulating in the ecosystem, and aims to provide rural, or low-income communities in developing regions opportunities for economic growth, environmental well-being, and social equality. The proposed LMDCE and 3T solution has also been tested in Kampala, Uganda as a case study.

1.1 Research Objectives

The following objectives are proposed for this dissertation research:

1. Develop a road map for changing the perception of post-consumer plastic from waste to valuable resource by educating and incentivizing communities to collect, reuse, repurpose, recycle, and manage waste plastic instead of unsoundly discarding it. This road map will be based on the establishment of a LMDCE (Chapter 3). In areas with limited infrastructure and capital, LMDCE alleviates burdens placed on waste management municipalities by empowering communities to engineer waste management solutions that can be implemented readily using local resources. Based on existent country-specific population demographics and waste management data, determine countries most suitable for LMDCE applications (Chapter 3). A country-specific highlight is also provided for Uganda, where the application of LMDCE in the capital city of Kampala is summarized.
2. Determine how behavioral economics and sustainable behaviors support the establishment of LMDCE in developing regions and identify the benefits of LMDCE in terms of the three principles of sustainability (Chapter 4). This research objective underscores the importance of community participation in generating viable engineered solutions for waste plastic management that are posed for long-term success.

3. Determine the total impact of LMDCE implementation at a community level in regions lacking waste plastic generation data. This is accomplished through geographical information analysis and correlation of building density and size to population demographics, which in return influence plastic generation (Chapter 5). Subsequently, an open-sourced tool is developed for estimating waste plastic generation at a ~100m resolution in Sub-Saharan Africa. This tool can be used by researchers, recycling non-profit organizations, policy makers, and waste management municipalities to understand the breadth of waste plastic accumulation and how it can be appropriately handled.
4. Design a low-cost, easy to operate, and easy to deploy, appropriate technology-based solution for managing waste plastic locally in developing regions utilizing readily sourced construction materials. This will be accomplished via the 3T process, which performs pyrolysis of waste plastic to PDFO (Chapters 6 & 7). The technology developed through this approach is termed the 3T processor, and has been tested in Kampala, Uganda to perform thermal decomposition of waste plastic (Chapters 4 & 7).
5. Establish the environmental suitability of the proposed 3T process by determining the theoretical (Chapter 6) and actual (Chapter 7) carbon dioxide (CO_2) emissions generated during theoretical and actual implementation of 3T process. This will be accomplished by determining the pyrolysis reaction energy, measuring the energy content and CO_2 combustion emissions of PDFO, and by determining the mass and energy balance of the 3T process using

varying energy inputs. In return, the generation and combustion emission of 3T will be compared with traditional well-to-tank emissions of diesel.

6. Optimize 3T process for PDFO production in appropriate technology settings by characterizing the effects of temperature and time on PDFO composition and stability (Chapter 8). Since PDFO produced in the 3T processor has tradeoffs in efficiency, sophisticated distillation and condensation mechanisms are not available. Therefore, this objective aims to quantify the impact of temperature and time in appropriate technology 3T settings.
7. Establish the supply chain considerations needed for successfully implementing LMDCE via the 3T process in developing regions, including identifying the inherent uncertainty present in implementation. Consider the role of existent infrastructure, capital resources, waste plastic generation and management per population demographics, small-scale entrepreneurs, non-profit recycling organizations, PDFO use, operation costs, transportation logistics, and emissions generated for producing and combusting PDFO as variables in the supply chain management model (Chapter 9).

1.2 Research Novelty

This research offers a new, innovative, and simple method for effective waste plastic management in developing regions through the establishment and application of LMDCE. By considering waste management challenges, their sources, and their consequences in the rural or low-income regions of the developing world, LMDCE is built to reduce mismanaged waste plastic accumulation and help communities thrive economically, environmentally, and socially. In addition to advocating for LMDCE and defining the sustainability of LMDCE, this research contribution assesses the implementation of LMDCE at both the global scale (by identifying countries most suitable) and at the community scale (by geographical analysis of specific regions).

The LMDCE solution proposed in this research for eliminating waste plastic from the ecosystem is 3T, or conversion of waste plastic to PDFO via pyrolysis. Although, pyrolysis of plastics has been studied extensively, this research determines how pyrolysis can be conducted in an LMDCE and appropriate technology setting, including testing its implementation in Kampala, Uganda. Further, the PDFO is characterized in terms of its generation and combustion emissions, composition, and stability to understand its performance in comparison with traditional petroleum derived fuels, such as diesel and kerosene. Lastly, supply chain considerations of LMDCE and 3T are presented to assist future researchers in quantifying the overall impact and benefits of implementation.

CHAPTER 2. BACKGROUND AND LITERATURE REVIEW

2.1 The Global Waste Plastic Challenge

Plastics are used in every country on earth, and none is able to successfully collect and manage 100% of its waste plastic. Once produced, plastic enters the global supply chain and is used in all regions of the world. In fact, our world is generating, consuming, and discarding more plastic than ever, and the rates are increasing (Patni, *et al.*, 2013, Rochman, *et al.*, 2013, Wilcox, *et al.*, 2015, Li, *et al.*, 2016, Geyer, *et al.*, 2017). The rate of plastic production has increased at 5% per year worldwide (Patni, *et al.*, 2013). In 2010, approximately 270 million metric tons (MT) of plastic were produced, with 99.5 million discarded as waste by coastal populations living within 50 km of the coast (Jambeck, *et al.*, 2015). Additionally, it was estimated that of the waste plastic generated that year, 31.9 million MT were mismanaged on land and 4.8–12.7 million MT entered the oceans (Jambeck, *et al.*, 2015). If current trends continue, by 2050, 33 billion MT of plastic are likely to be produced, with approximately 12.2 billion MT disposed of as waste, 3.9 billion MT mismanaged on land, and 0.6–1.6 billion MT eventually entering the oceans (Rochman, et. al, 2013, Jambeck, *et al.*, 2015). This is a 122-fold increase in a matter of 40 years, meaning that global plastic production is increasing exponentially. Just between 2015 and 2026, we will make as much plastic as has been made since its production began (Wilcox, *et al.*, 2015).

There are numerous potential resting spots for waste plastic, including disposal in landfills, recycling, incineration, and unregulated dumping. Disposal on land is the most common option with previous studies showing that globally 60% of plastic municipal solid waste (MSW) is discarded in open space or in landfills (Patni, *et al.*, 2013). A key challenge is that in much of the world, appropriate waste disposal options are unavailable, including properly managed landfills, leading to waste plastic simply being dumped on open unestablished plots, accumulating on sides of roadways, and on outskirts of rural residential areas and slums. This accumulation of waste plastic on land can become a breeding ground for mosquitoes, cause clogged waterways and drainages, and reduce the general aesthetics of the community (Patni, *et al.*, 2013). As plastic can take thousands of years to decompose, both landfills and unregulated plots of land will remain unusable long after the dumping ends (Sarker, 2011, Sarker, *et al.*, 2012), and if not managed properly, chemicals can leach from the plastic into surrounding habitats (Rochman, *et al.*, 2013).

Common waste management problems in many resource-constrained or infrastructure limited parts of the world affect how waste is disposed, include lack of effective governmental policy, lack of municipal solid waste (MSW) management administration and planning, insufficient household education, economic pressures, limited perspectives on hazards associated with waste accumulation, and scarce stakeholder involvement (Troschinetz, 2008, Sujauddin, 2008). Other factors include growing economies, urbanization, and increased standards of living, which led to rapid increases in waste generation in developing countries (Mingha, *et al.*, 2009). In rural regions particularly, access to centralized collection and recycling methods are often unavailable. Consequently, uncontrolled growth coupled with lack of sufficient infrastructure and regulation in underdeveloped regions of developing countries compounds the waste management problem (Moghadam, *et al.*, 2009, Kalanatarifard, *et al.*, 2012, Seng, *et al.*, 2010, Mryyan & Hamdi, 2006). Because these factors include economic and social as well as environmental components, it is critical that proposed solutions include them as well.

Eventually, this waste plastic will be disposed of in, or migrate to surface waters, generating pollution and threatening both terrestrial and marine life. The impacts of plastic in the oceans are easily visible through natural ocean currents that have created 5 major gyres – huge rotating regions of open sea that collect floating waste materials (Jambeck, 2015). Once waste enters one of these gyres it is essentially trapped. Much attention has been given to what has been called "The Great Pacific Garbage Patch". This refers to waste, particularly plastic which has been trapped in the Pacific gyre. Although the Great Pacific Garbage Patch has received most of the attention, each of the ocean gyres is accumulating significant amounts of plastic (Jambeck, 2015). Current estimates suggest that the oceans hold more than 5 trillion pieces of plastic weighing more than 25,0000 tons (Eriksen, *et al.*, 2014). Between entanglement and ingestion of material that was mistaken for food, mismanaged waste plastic has been detrimental to marine and terrestrial life (Rochman, *et al.*, 2013, Wilcox, *et al.*, 2015, Li, *et al.*, 2016, Javasiri, *et al.*, 2013, Barnes, *et al.*, 2009, Barnes, *et al.*, 2011). In fact, it is estimated that 2/3 of the world's fish stock has ingested plastic (Wieczorek, *et al.*, 2018). Unfortunately, a single piece of plastic can kill over and over. The animal killed by the plastic eventually decomposes, but the plastic remains and can continue to cause harm. Additionally, through the consumption of fish, as well as food packaged in plastic, humans are also adversely impacted (Parker, 2018). For instance, plastic chemicals absorbed by the body have been found to alter hormones (Knoblauch, 2009). Another recent study from seven different European countries and Japan has revealed microplastics present in human feces (Parker, 2018). These findings verify the pervasiveness of plastic in the global environment.

Despite these concerns, plastic cannot be simply eliminated from the supply chain, nor is it practical or even always beneficial to do so. The alternatives to plastic goods and packaging include materials such as metals, glass, paper and cotton-based fabrics. As a result, an increased demand for metals would lead to increased mining and increased fuel demands for transportation of these heavy materials, resulting in increased prices and negative environmental impacts. Glass is heavy, energy intensive and prone to breaking. Increased cultivation of cotton and increased paper production will compete with land suitable for food crops, which is already in shortage due to population growth. Additionally, increasing land for cotton and paper production will lead to deforestation – a significant global threat. There are simply no suitable alternatives for plastic ready for deployment at an international scale, meaning that plastic is too cheap and efficient to be easily replaced. Thus, this phenomenon is currently leading to exponential growth in production, consumption, disposal, and accumulation of plastic, challenging its management globally. Therefore, without considering the three pillars of sustainability, waste plastic management solutions are unlikely to achieve long-term success.

2.2 Principles Governing Waste Plastic Management Solution in Developing Regions

This research applies the principles of sustainability, appropriate technology, and circular economy to generate the model of a locally managed decentralized circular economy (LMDCE) (Figure 2.1). Having sustainability and its applications, appropriate technology, and circular economy, as the foundation for the model, LMDCE aims to holistically target waste plastic management in developing regions by incorporating people, organizing tools to achieve prosperity, and working to benefit the planet. A detail overview of the core principles is presented in the following subsections.

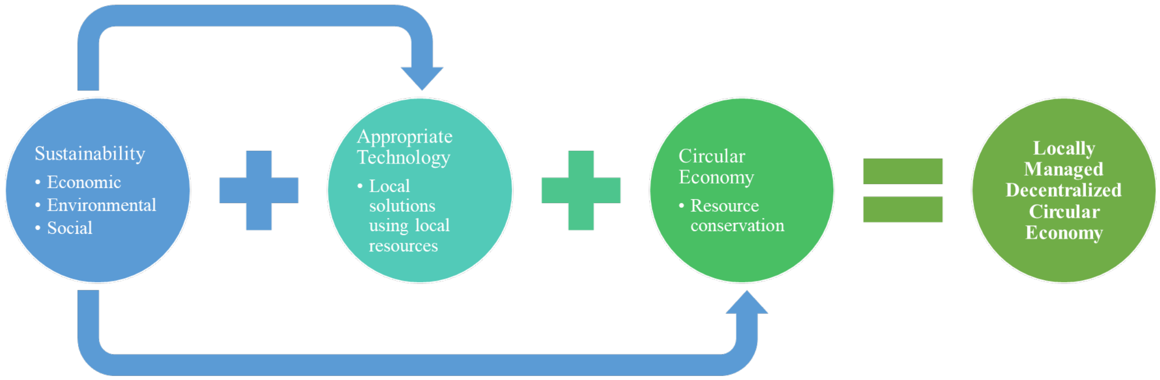

Figure 2.1. Principles governing the development of a LMDCE

2.2.1 Sustainability

According to the National Environmental Policy Act of 1969 (NEPA), sustainability means "to create and maintain conditions under which humans and nature can exist in productive harmony, that permit fulfilling the social, economic, and other requirements of present and future generations" (USEPA, 2020). Sustainability is often known by its three pillars – economic, environmental, and social sustainability. Economic sustainability is associated with production, distribution, and consumption of goods and services, including the creation and maintenance of jobs, promotion of incentives, promotion of informed supply and demand accounting, improvement of natural resource accounting, and positive impacts of costs and prices in the lifecycle of a product or service (USEPA, 2015).

Environmental sustainability relates to protection, maintenance, and restoration of ecosystems, air quality, water quality, and soil quality; reduction in environmental stressors such as pollutants and greenhouse gas (GHG) emissions; minimization of waste generation and importance of resource integrity; and design of processes, products, and services that are based on green engineering and chemistry (USEPA, 2015). Lastly, social sustainability relates to increased community and stakeholder participation, improved well-being (prosperity, safety, public health, access to proper waste management, food, water, and energy security), resource conservation and increased use of recyclable materials in a way that promotes societal fairness (including a full account of cradle-to-grave lifecycle of products and associated social costs), improved social organization systems, and positive contributions to rural development (increased access to education, workforce training, and technology) (Mohamed and Paleologos, 2021, Tang and Huang, 2017, Gnansounou and Pandey, 2017).

In the research included in this dissertation, the application of sustainability is deemed critical for design, maintenance, and longevity of waste plastic accumulation solutions. In particular, sustainable solutions modeling appropriate technology principles are favored to ensure that communities accept, use, and benefit from waste plastic management solutions.

2.2.2 Appropriate Technology

The concept of appropriate technology was first described by E.F. Schumacher in his book Small is Beautiful (Schumaker, 1973). This concept of appropriate technology is summarized by Hazeltine (Hazeltine, 1999) as "*Technological choices and applications that are small scale, decentralized, labor-intensive, energy efficient, environmentally sound, and locally controlled*." Appropriate technology is simply technology suitable for a specific region, designed to meet specific needs of certain individuals or communities (Joshi & Seay, 2016). Though the details of what constitutes appropriate technology can vary between regions and applications, the description from Hazeltine (Hazeltine, 1999) generally holds true. Appropriate technology does however require tradeoffs. In most cases, the tradeoffs include: efficiency for simplicity; convenience for low cost; and automation for manual operation. The key benefit of appropriate technology is that it is easily deployable because it does not rely on a sophisticated infrastructure. Appropriate technology is a way of achieving the societal benefits of sustainability, particularly in underdeveloped regions. This means that appropriate technology is not intended to reproduce industrial technology on a small scale but rather to design specific solutions appropriate for a given region or for a given community (Seay, *et al.*, 2012). Appropriate technology is the mechanism by which LMDCE principles overcome infrastructure challenges in developing economies.

2.2.3 Circular Economy

Breaking the Take → Make → Waste paradigm is an underlying principle and the first step towards building a circular economy. A circular economy applies the 3R's of sustainability (reduce, reuse, recycle) at the company or industry level by considering reducing resource consumption, reusing end-of-life products as feedstock, and/or recycling them back into the manufacturing supply chain. The circular economy's goals consist of focusing on designing out of waste and pollution, keeping of products and materials in use to support a cradle-to-cradle approach, and regenerating natural systems (Ellen MacArthur Foundation, 2021). Thus far, circular economy models for various waste types have been considered and applied in regions with sufficient infrastructure to collect and sort valuable waste products to reuse, recycle, or re-enter them into their respective manufacturing supply chains on an industrial scale (World Economic Forum *et al.*, 2016, Yuan, *et al.*, 2006). In addition to infrastructure, this approach requires capital and sophisticated equipment to reprocess the materials into their building blocks for entrance back into consumer products.

2.2.4 Locally Managed Decentralized Circular Economy

Since these necessities of infrastructure, capital, and equipment are often lacking at the rural or developing region level, this research contribution promotes the creation of a locally managed and decentralized, or distributed, circular economy for recycling, remanufacturing, and repurposing valuable waste products. In an LMDCE model, existent infrastructure, capital resources, equipment, and education of the general population are utilized to create local solutions for MSW and waste plastic management at the community or neighborhood level. When the solutions are created with active community participation, by understanding and prioritizing the needs, skills, and challenges of the community, solutions are targeted specifically to the community. The primary stakeholder responsible for implementing the solution is the community, and the primary beneficiary of the economic, environmental, and societal gains is the community.

Because communities differ in demographics, geography, size, and culture, LMDCE solutions for waste management are intended to vary from community to community. However, the general goal of achieving long-term, sustainable, appropriate technology-based solutions should be the focus of LMDCE implementations. Examples of LMDCE models for reducing plastic accumulation can include:

- A network of informal waste pickers that collect, clean, shred, and sell waste plastic downstream to recycling facilities (Plastics for Change, 2021),
- Building homes from waste plastic bottles (Upcycle Africa, 2021),

- Converting plastic into anti-slippery and recyclable floor tiles (the better home, 2021),
- Turning waste plastic packaging into handbags, wallets, wall paintings, welcome mats, and folders (Varier, 2017), or
- Converting waste plastic into fuel oil (Joshi & Seay, 2016).

Ultimately, by valuing waste, unsound consumption and disposal of waste is reduced at the local community level. In return, the diverse applications of LMDCE have the potential to benefit people, generate prosperity, and support the thriving of the planet.

2.3 Conversion of Waste Plastic to Fuel

Plastics commonly found in MSW such as High-Density Polyethylene (HDPE), Low-Density Polyethylene (LDPE), Polypropylene (PP), and Polystyrene (PS) can be converted into a liquid fuel oil via thermal decomposition, or pyrolysis. Plastics such as polyethylene terephthalate (PET) and poly vinyl chloride (PVC) are unfortunately not suitable for this process, due to the presence of oxygen and chlorine respectively in the polymers. The chemistry of converting plastics into a hydrocarbon fuel oil is simple and well established (Al-Salem, *et al.*, 2009, Demirbas, 2004, DeNeve, *et al.*, 2017, Joshi & Seay, 2016, Kumar & Singh, 2011, Miskolczi, *et al.*, 2004, Panda, *et al.*, 2010, Patil, *et al.*, 2017, Pinto, *et al.*, 1999, Santaweesuk & Janyalertadun, 2017, Sarker, 2011, Sarker, *et al.*, 2012, Singh and Ruj, 2016, Wong, *et al.*, 2015). Pyrolysis, or heating of the plastic in the absence of oxygen, is the most widely utilized approach for converting waste plastic, into fuel oil (Singh and Ruj, 2016, Demirbas, 2004, Pinto, *et al.*, 1999, Al-Salem, *et al.* 2009, Kumar and Singh, 2011, Miskolczi, *et al.*, 2004, Panda, *et al.*, 2010, Sarker, *et al.*, 2012). Since the molecules of this plastic are only made up of carbon-hydrogen chains, when thermally heated to temperatures of approximately 400°C-500°C (DeNeve, *et al.*, 2017, Joshi & Seay, 2016, Wong, *et al.*, 2015, Kumar and Singh, 2011, Singh and Ruj, 2016), the hydrocarbon chains break, decomposing the polymer, and yielding a hydrocarbon gas, which is then condensed to obtain the fuel oil product. In this contribution, the fuel oil generated is termed as plastic-derived fuel oil (PDFO). An objective of this research is to design, fabricate, operate, and test an appropriate technology-based solution for reducing plastic in municipal solid waste through what is termed as the trash to tank (3T) approach (Chapter 7).

2.3.1 Trash to Tank Approach

The goal of the 3T approach is to reduce waste plastic accumulation by providing rural, resource-constrained communities suffering from lack of municipal solid waste (MSW) infrastructure to manage their waste locally. 3T helps to alleviate the pressure placed on managed landfills and seeks to eliminate the practice of dumping or incinerating waste plastic in open plots of land in rural regions, which has led to sanitation, human health, and environmental concerns (Komakech, 2014, Patni, *et al.*, 2013, Rochman, *et al.*, 2013). In return, the eventual migration of unregulated waste plastic into waterways and oceans is reduced, decreasing endangerment of terrestrial and marine species (Geyer, 2017, Li, *et al.*, 2016, Wilcox, *et al.*, 2015).

The 3T approach applies the principles of sustainability, appropriate technology, and LMDCE to perform slow pyrolysis of waste plastic trash, converting it into PDFO. A simple technology has been developed by the University of Kentucky Appropriate Technology and Sustainability (UKATS) research for thermal decomposition of waste plastic in rural regions, known as the 3T processor, which is nonautomated, low-cost (approximately 800-1000 USD) and easily deployable, encouraging waste plastic management in small-scale solutions around the world (DeNeve, *et al.*, 2017, Joshi & Seay, 2016, Joshi, *et al.*, 2020). Since 2017, the UKATS team, in partnership with Makerere University in Kampala, Uganda and Beyond Uganda, a U.S. based NGO, has implemented six 3T processors in Uganda (Joshi, *et al.*, 2020).

The PDFO produced from the 3T processor has characteristics similar to diesel and kerosene, and is suitable for use in diesel generators, kerosene cookstoves, and lamps. PDFO has an additional advantage over traditional petroleum derived fuels in that it is sulfur free and generates no sulfur oxide (SOx) emissions when combusted. This can be attributed to the polymer chemistry of polyolefin-based plastic, often used for 3T applications, which contain only hydrocarbon bonds. As the waste plastic is converted to PDFO, it is wholly consumed and eliminated from the ecosystem.

Consequently, the 3T approach encourages waste plastic to reenter the LMDCE in underdeveloped regions by giving waste plastic a value. This promotes collection and management of waste plastic instead of simply discarding it. In addition, entrepreneurial opportunities are generated for sorting, collecting, and processing the waste plastic, providing a source of reliable, renewable energy for the community through its conversion to fuel oil. Since the plastic is converted to PDFO locally at an individual or community scale, an LMDCE for waste plastic is established. This practice has the potential to empower rural communities lacking capital, resources, technical education, and waste management infrastructure to repurpose the trash into valuable products, decrease MSW accumulation, and provide a roadmap for sustainable management of post-consumer plastic. Hence, this contribution studies in detail the sustainability of LMDCE and 3T processors in developing regions.

2.4 Tools Used to Assess LMDCE and Trash to Tank

The following tools were used in this research to determine and quantify the implementation of LMDCE in developing regions by proposing 3T as a viable option for waste plastic management.

2.4.1 Behavioral Economics and Sustainable Behaviors

Humans have evolved in concert with our ecosystem; however, rapid anthropogenic ecosystem changes are outpacing our ability to adapt. Our species is adapted to work in our own immediate self-interest. Groundbreaking research by George Ainslie in the 1970s concluded that behaviors that have a short-term payoff are favored over ones that only have benefits in the long term (Ainslie, 1975). This is known as hyperbolic discounting (Ainslie, 1975). The problem we are now facing, however, is that our behaviors with regard to consumption are causing severe damage to our ecosystem. The consequences of this behavior are discounted significantly by the general population. These problems associated with hyperbolic discounting are amplified in developing countries, since people have more immediate needs with regards to survival. Unstable governments, lack of strong institutions and lack of food, water and energy security make acting in the global best interest difficult or impossible.

Anthropogenic climate change, unsound waste disposal and loss of biodiversity are all happening at an alarming rate, but our global institutions have been unable to adequately address these problems. Much of the progress to date relies on altruistic behavior -

consciously consuming less than one otherwise could to minimize one's individual impact. Although altruism is a fundamental characteristic of human society (Brede, 2013), the problem with relying on altruistic behavior is twofold: first is the previously mentioned problem of our evolutionary predisposition to acting in our own self-interest, and second is the free rider problem. The free-rider problem describes our inherent distaste for others benefiting from our individual sacrifice. This problem has been observed in resistance to social programs, as well as resistance to sustainable consumption options that are perceived as being more expensive, less effective or less convenient than traditional options. Because of the issues that arise with both reliance on altruism and the fear of free-riders, many proposed solutions to environmental problems are rooted in the theory of neoliberal conservation. This theory posits individuals are rational actors who always act in their economic self-interest. Neoliberalism combines conservation with markets such that conserved land and resources become fungible commodities (Doane, 2014). The result of this line of thought is that economic incentives are required to advance environmental protection, however these practices do not necessarily benefit the poor, or the environment (Brockington & Igoe, 2006, Igoe & Brockington, 2006). This clearly indicates that a new model of behavior that benefits the rural poor is needed.

The neoliberal approach to conservation and environmental protection is based on the assumption that individuals are rational actors. The principle of the rational actor is based on three tenets: that individuals are self-interested and attempt to maximize their own benefits; that they only respond to economic incentives; and that economic markets are free, mutual, and rational (Peterson & Isenhour, 2014). However, recent research has suggested that new approaches are needed to model human behavior with regard to environmental protection (Doane, 2014, Isenhour, 2014, Peterson, 2014, Gowdy, 2007). This research argues that individuals are not simply motivated by economic gain alone. As asserted by Peterson (Igoe & Brockington, 2006), giving the ecosystem an economic value to ensure protection undermines the consideration of alternative values.

Additional research states that monetary incentives may be counterproductive (Gowdy, 2007, Berkes, 2004, Frey, 1997, Frey & Oberholtzer-Gee, 1997). These economic incentives are not only counterproductive to individuals, but outcomes based on the rational actor model can erode communities (Peterson & Isenhour, 2014). Contrastingly, motivation is multidimensional (Peterson & Isenhour, 2014) and recent research has shown that equity and empowerment are often more important than monetary incentives (Berkes, 2004). Therefore, to be effective, approaches must be rooted in all three pillars of sustainability, economic, environmental, and social equality.

2.4.2 Sustainability Indicators and Geographical Analysis

To determine which locations are suitable for LMDCE implementation, the behaviors associated with waste generation and disposal must be first understood to propose region specific management solutions. Previous research has highlighted waste and waste plastic generation at a global scale (Jambeck, 2015, Geyer, 2017, Eriksen, *et al.*2014). The data summarizes the behaviors associated with and the largest influencers of waste production at the global, or sub-continent scale (Hoornweg & Bhada-Tata, 2012, Kaza *et al.*, 2018). This data is an excellent tool for driving global and continent-specific policies for reducing and recycling waste generation. However, to understand what actions must be taken at the country-scale, a clear understanding of the demographics of the population and the current waste management practices must be assessed. This task can be challenging in developing countries where often waste management data is only available for urban cities and communities. Nonetheless, by correlating measured country-specific data such as gross domestic product, estimated total MSW generation, and population to the three pillars of sustainability, indicators alluding to the economic, environmental, and social well-being of a country can be inferred. By weighing the severity of a country's challenges in each of the sustainability indicators, the waste generation behavior of the country can be concluded, and in return, the countries most suitable for LMDCE implementation can be identified.

Furthermore, since LMDCE emphasizes a distributed, small-scale approach for implementation, the regions within a country most suitable for LMDCE implementation should also be identified. Often waste management is a priority in urbanized regions of developing countries, with little attention given to rural regions. As a result, the accessibility of waste generation data in rural, or low-income regions of developing countries is minimal. Challenges such as variation in income level, conditions of road infrastructure, and perception of communities toward waste, including education regarding hazards associated with waste influence the way waste is handled in rural and low-income regions. Specific waste management data such as the amount and composition of waste generated per region, along with the amount unsoundly disposed to the environment are often unknown.

In this aspect, the waste management behaviors of a region can be inferred from a close-up geographical analysis of the region. Previous contributions in this field are minimal and have analyzed data at ~1km resolution and have reported the total amount of current and projected waste plastic generation for the country and global scale (Lebreton

& Andrady, 2019). However, the reported data is not broken into region-specific, city, or village scale data for ready use by local entrepreneurs, non-profit organization, or other agencies interested in implementing waste management solutions, such as LMDCE and 3T approaches in small-scale applications. Thus, this contribution studies open-sourced geographical data such as number of buildings and the size of buildings present in a region at a ~100m resolution to correlate population density and estimated waste plastic generation.

2.4.3 Generation and Consumption Emissions of Trash to Tank PDFO

Energy consumption is directly correlated with the economic development of a nation as measured by the gross domestic product (GDP) (Dritsaki & Dritsaki, 2014). Hence, as world economies develop, a peak in energy demand is forecasted. This is especially true for the transportation energy sector, where approximately 159 quadrillion kilojoules (kJ) of energy consumption are predicted for the year 2040, a 46 quadrillion kJ spike from 2015 (Energy Information Administration [EIA], 2017). Consumption of diesel, the primary transportation fuel for medium- and heavy-duty vehicles in OECD (Organization for Economic Co-operation and Development) and non-OECD countries is also anticipated to grow from approximately 87 quadrillion kJ, surpassing 105 quadrillion kJ by 2040 (EIA, 2017). Furthermore, with increased energy usage, greenhouse gas (GHG) emissions are likely to increase, unless additional regulations for controlling the emissions are enforced (Dritsaki & Dritsaki, 2014). For instance, diesel emissions, consisting of carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NOx), sulfur oxides (SOx), polycyclic aromatic hydrocarbons, aldehydes, ketones, phenols, ammonia, carbonyl compounds, volatile organic compounds, and metals such as aluminum, calcium, iron, magnesium, nickel, silicon, sodium and vanadium are likely to build up in the atmosphere without the addition of effective emissions management technologies (Maricq, 2007, Morgan, *et al.*, 1997, Popovicheva, *et al.*, 2015, Sarvi, *et al.*, 2011, Wierzbicka, *et al.*, 2014, Wu, *et al.*, 2017, Zielinska, 2005).

Regions currently motorizing at unprecedented rates are often lacking or have minimal availability of existing effective transportation emissions reduction technologies, thus challenging sustainable development. Another contributing cause is the use of cheaper, second-hand vehicles imported to developing countries after years of use. This practice is termed as "exporting pollution" or "environmental dumping" as poorer economies have become a "pollution haven" for old cars with reduced fuel efficiencies and safety standards, higher GHG and particulate matter emissions, leading to respiratory concerns and smog (Edwards, 2017, Khan, 2013, Hutchinson, 2011, Davis & Khan, 2011).

One potential method for reducing the high rate of GHG emissions and particulate matter from diesel or petroleum derived fuels in developing countries is the use of fuel derived from waste plastic. This approach of trash-to-tank, or 3T, solves two problems simultaneously in developing economies – reduction of heavy metals from fuel combustion due to the hydrocarbon polymer chemistry of plastics and reduction in accumulation of waste plastic in areas with minimal waste management infrastructure through its conversion to PDFO. This contribution studies the environmental impact of PDFO from a LMDCE application, comparing it with the current standard, petroleum diesel. Previous studies have determined the emissions of plastic derived fuels obtained in a lab setting (Churkunti, 2015, Kalargaris *et al.*, 2018, Kalargaris *et al.*, 2017a, Kalargaris *et al.*, 2017b, Kumar & Sankaranarayanan, 2016, Mani, *et al.*, 2010, Rinaldinin, 2016). However, the environmental analysis of plastic derived fuels in rural, developing communities has not yet been performed. As a result, this contribution determines and analyzes the CO_2 emissions for generating and combusting the 3T fuels, comparing them alongside WTT petroleum derived diesel fuel emissions.

2.4.4 PDFO Composition and Stability

To assess the similarities of PDFO with diesel and kerosene, the composition and stability of the fuel were measured. The analysis of PDFO was performed in a gas chromatograph-mass spectrometer (GC-MS) and a thermogravimetric analyzer (TGA) for determining the composition and stability, respectively, as a function of temperature and time in the absence of a catalyst. This approach is consistent with literature analysis of PDFO generated from a variety of plastic feedstocks (Aboulkas & Nadifiyine, 2008, Achilias, *et al.*, 2007, Breyer *et al.*, 2017, Budsaereechai, *et al.*, 2019, Cai, *et al.*, 2008, Chandrasekaran, *et al.*, 2015, Miandad *et al.*, 2017, Miandad *et al.*, 2019, Phetyim & Pivsa-Art, 2018, Rahman, 2018, Xing *et al.*, 2019, and Zhou *et al.*, 2006). However, these contributions primarily focused on the pyrolysis of plastic with catalysts (Achilias, *et al.*, 2007, Budsaereechai, *et al.*, 2019, Chandrasekaran, *et al.*, 2015, Kunwar et. al, 2021, Liu, *et al.*, 2021, Miandad, *et al.*, 2017, Miandad, *et al.*, 2019), or coprocessing of plastic with oil producing biomass (Aboulkas & Nadifiyine, 2008 and Rahman, 2018), used lubrication oils (Phetyim & Pivsa-Art, 2018, Breyer *et al.*, 2017), coal (Cai, et. al, 2008), and semicoke (Xing *et al.*, 2019).

2.4.5 Supply Chain and Uncertainty

To effectively implement LMDCE in a developing region via 3T, supply chain considerations and their associated risks, or uncertainty, need to be quantified. In its simplest definition, supply chain management involves the planning, sourcing, procurement, conversion, and logistics of processing raw materials to finished products, and their distribution to customers (Badurdeen et. al, 2009, and Lee and Billington, 1993). The plastic supply chain at the industrial manufacturing level has been previously studied (Jiuping *et al.*, 2016, Vermeulen, et. al, 2016, Hongtao, et. al, 2019). However, in a LMDCE application, the waste plastic supply chain considerations more closely align with those of informal waste pickers in developing countries, who are a distributed network of individuals collecting, sorting, and selling recyclable materials to assist waste management practices in both urban and rural regions (Chikarmane, 2012, Dias, 2016, Gall et. al, 2020, Hayami, et. al, 2006, Medina, 2008, Moreno-Sanchez and Maldonado, 2006, and Navarrete-Hernandez and Navarrete-Hernandez, 2018). By incorporating individual, small-scale entrepreneurs such as informal waste pickers, local consumers, and recycling NGOs, the LMDCE supply chain considers the costs and benefits of gathering and transporting waste plastic within the community, converting it to PDFO via 3T, and selling it locally to the community. Additionally, the uncertainty present in the stochastic variables of the supply chain model is assessed to obtain the most probable outcomes for economic gains, jobs created, and emissions produced from generation and combustion of PDFO.

CHAPTER 3. A PERSPECTIVE ON A LOCALLY MANAGED DECENTRALIZED CIRCULAR ECONONMY

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3.1 Abstract

Waste plastic accumulation, especially at the detriment of water and land resources, is a global problem. Unsound post-consumer disposal is the primary pathway of waste plastic into the ecosystem. One way of addressing this problem is through the establishment of a circular economy for waste plastic. Unfortunately, much of the unsound disposal comes from economically disadvantaged regions where waste disposal and recycling infrastructure is limited or unavailable. Therefore, to be impactful, in rural or economically disadvantaged regions, the establishment of a circular economy for waste plastic must be locally managed and decentralized, meaning that the disposal, collection, remanufacture and use of waste plastic must all occur within the same community. Therefore, we suggest that waste plastic abatement strategies be targeted to reduce, reuse and recycle waste plastic at the local level, establishing a circular economy appropriate for infrastructure limited regions. To be effective, technologies for recycling plastic must be low-cost, economically viable, socially acceptable and not adversely impact the environment, but also produce a product that has a ready market in the local community. This is critical because although environmental concerns are important, unless proposed solutions are also economically viable and socially appropriate, they are unlikely to be successful, especially in underdeveloped regions. Using big data analysis, a simple metric for identifying countries that will have the most potential to benefit from a locally managed decentralized circular

economy (LMDCE) for plastic has been developed. Country specific data on municipal solid waste (MSW) generation, percent of MSW consisting of plastic, extent of unsound waste disposal practices and total environmental stress, along with economic and population indicators were used to develop this analysis. The information obtained from this metric will help researchers and policy makers promote a LMDCE of waste plastic for managing the accumulation of plastic on land and its eventual migration into waterways. Additionally, we present a case study of a proposed LMDCE waste plastic abatement strategy in the MSW infrastructure limited country of Uganda.

3.2 Introduction

Plastics are used in every country on earth, and none is able to successfully collect and manage 100% of its waste plastic. Once produced, plastic enters the global supply chain and is used in all regions of the world. In fact, our world is generating, consuming, and discarding more plastic than ever, and the rates are increasing (Patni, *et al.*, 2013, Rochman, *et al.*, 2013, Wilcox, *et al.*, 2015, Li, *et al.*, 2016, Geyer, *et al.*, 2017). The growth rate of plastic production has increased at 5% per year worldwide (Patni, *et al.*, 2013). In 2010, approximately 270 million metric tons (MT) of plastic were produced, with 99.5 million discarded as waste by coastal populations living within 50 km of the coast (Jambeck, *et al.*, 2015). Additionally, it was estimated that of the waste plastic generated that year, 31.9 million MT were mismanaged on land and 4.8 - 12.7 million MT entered the oceans (Jambeck, *et al.*, 2015). If current trends continue, by 2050, 33 billion MT of plastic are likely to be produced, with approximately 12.2 billion MT disposed of as waste, 3.9 billion MT mismanaged on land, and 0.6-1.6 billion MT eventually entering the oceans (Rochman, et. al, 2013, Jambeck, *et al.*, 2015). This is a 122-fold increase in a matter of 40 years, meaning that global plastic production is increasing exponentially. Just between 2015 and 2026, we will make as much plastic as has been made since its production began (Wilcox, *et al.*, 2015).

There are numerous potential resting spots for waste plastic, including disposal in landfills, recycling, incineration, and unregulated dumping. Disposal on land is the most common option with previous studies showing that globally, 60% of plastic municipal solid waste (MSW) is discarded in open space or in landfills (Patni, *et al.*, 2013). A key challenge is that in much of the world, appropriate waste disposal options are unavailable, including properly managed landfills, leading to waste plastic simply being dumped on open unestablished plots, accumulating on sides of roadways and on outskirts of rural residential areas. This accumulation of waste plastic on land can become a breeding ground for mosquitoes, cause clogged waterways and drainages, and reduce the general aesthetics of the community (Patni, *et al.*, 2013). Since plastic can take thousands of years to decompose, both landfills and unregulated plots of land will remain unusable long after the dumping ends (Sarker, 2011, Sarker, *et al.*, 2012), and if not managed properly, chemicals can leach from the plastic into surrounding habitats (Rochman, *et al.*, 2013). Eventually, this waste plastic will be disposed of in, or migrate to surface waters, generating pollution and threating both terrestrial and marine life. Specifically in major bodies of water, waste plastic is ingested by marine life and bird species, resulting in adverse health effects, entanglement, and death (Rochman, *et al.*, 2013, Wilcox, *et al.*, 2015, Li, *et al.*, 2016, Javasiri, *et al.*, 2013, Barnes, *et al.*, 2009, Barnes, *et al.*, 2011).

Figure 3.1 shows plastic bags collecting in a drainage canal in Kampala, Uganda due to unregulated dumping. This is a common problem in many resource-constrained or infrastructure limited parts of the world, where lack of effective governmental policy, MSW management administration and planning, along with insufficient household education, economic pressures, limited perspectives on hazards associated with waste accumulation and scarce stakeholder involvement affect how waste is disposed or managed (Troschinetz, 2008, Sujauddin, 2008). Other factors include growing economies, urbanization and increased standards of living, which have led to rapid increases in waste generation in developing countries (Mingha, *et al.*, 2009). In rural regions particularly, access to centralized collection and recycling methods are often unavailable. Consequently, uncontrolled growth coupled with lack of sufficient infrastructure and regulation in underdeveloped regions of developing countries compounds the waste management problem (Moghadam, *et al.*, 2009, Kalanatarifard, *et al.*, 2012, Seng, *et al.*, 2010, Mryyan & Hamdi, 2006). Because these factors include economic and social as well as environmental components, it is critical that proposed solutions include them as well. Therefore, in our view, without considering the three pillars of sustainability, MSW management solutions are unlikely to achieve long term success.

Figure 3.1. Waste plastic and other trash clog a spillway in Kampala, Uganda

3.3 A Perspective on a Locally Managed Decentralized Circular Economy

Unfortunately, there are currently no globally effective strategies to keep waste plastic out of the ecosystem that meet the challenges of both developed and developing countries. This is primarily because waste plastic is not a point-source pollutant. Since plastic enters the ecosystems from numerous points, it has been a major obstacle for control (Geyer, *et al.*, 2017). Moreover, low-income and low-to-middle income countries lack the resources to address this problem. In fact, in addition to lack of waste collection and management infrastructure in underdeveloped regions, researchers have identified that simply the lack of convenient waste disposal containers can affect household waste disposal decisions (Moghadam, *et al.*, 2009, Kalanatarifard, *et al.*, 2012, Seng, *et al.*, 2010, Mryyan & Hamdi, 2006, Tadesse, *et al.*, 2008). If people have to walk long distances to reach a suitable disposal location, they will simply dump the waste nearby on streets, underdeveloped plots of land, or burn it, leading to potentially toxic smoke, especially if plastics are present. This underscores our assertion that locally managed decentralized solutions – targeting waste where it is generated rather than focusing on centralized processing – may be more effective in communities where governmental waste solution efforts are minimal. This type of approach empowers individuals and small communities to adapt and invent solutions rather than waiting on central authorities to enact policies and regulations to address the problem. As a result, a LMDCE of plastic products is generated, encouraging direct users of plastic to consider and benefit from opportunities of providing waste plastic a value, or by generating new lifecycles for plastic products through a cradle-to-cradle approach (Ellen MacArthur Foundation, 2017).

We assert that a decentralized circular economy of plastic at the local level can have tremendous benefits in reducing the accumulation of waste plastic on land and its eventual migration to major bodies of water. An industrial circular economy replaces the produce-consume-discard model by reusing, recycling or reentering products into their manufacturing supply chain on an industrial scale (Ellen MacArthur Foundation, 2017, Parker, 2018, Yuan, *et al.*, 2006, Geng, *et al.*, 2009, Matthews, *et al.*, 2018, Preston, 2012, Preston & Lenhe, 2017, Geissdoerfer, *et al.*, 2017, Kaur, *et al.*, 2017). However, at the local level, especially in rural regions, remanufacturing of plastic products, or creating the infrastructure networks to reenter them into their respective supply chains is difficult. Traditional solutions, like centralized recycling of waste plastic, are also often impractical in remote regions, or regions lacking well developed infrastructure due to the transportation costs, making large-scale recycling operations uneconomical. Hence, a LMDCE functions to manage waste on small-scale in rural regions, without the need of industrial technologies or developed infrastructure. Viable solutions are those that are low cost, can be implemented utilizing the region's technical knowledge, and most importantly provide an incentive for local people to collect, reuse and recycle themselves.

In many economically disadvantaged regions, an informal local recycling sector exists via a system of waste pickers that sort through dumpsites to collect saleable materials such as metals, plastics, glass and papers (Parker, 2018, Medina, 2007, Medina, 2008, Rathi, 2007, Bari, *et al.*, 2012, Fergutz, *et al.*, 2011). Often, waste pickers travel throughout communities of rural regions and cities to collect recyclables from house-to-house as well, or set-up recycling drop-off locations, paying individuals a small incentive for valuable materials. Afterwards, the waste pickers will sort through collected materials, clean and sell them to recycling companies for a profit. These companies then shred and process the materials as desired by manufacturing organizations. In this way, rural communities and heavily populated urban centers of developing countries benefit from a decentralized circular economy of recyclable materials, including plastics.

However, not all plastics that are recyclable are of value to waste pickers due to a non-existent recycling market. For instance, polyethylene shopping bags are generated in large volumes globally, but are recycled in extremely low quantities (Parker, 2018), accumulating on sides of streets, dumps, and landfills in developing countries. Even in the United States, 380 billion plastic bags are consumed annually, with only 5.2% being recycled (Sarker, 2011, Sarker, *et al.*, 2012). So, unless waste plastic items, such as polyethylene bags can be given a value, they will continue to be unsustainably used and discarded. Therefore, we assert that a LMDCE with informal recycling playing a vital role in decreasing the accumulation of waste plastic is needed. Furthermore, we believe that including social and economic considerations in addition to environmental are critical to successful waste plastic abatement strategies in underdeveloped regions, which has been lacking in most plastic abatement strategies.

In Figure 3.2, we propose a strategy for establishing a circular economy at the local level by applying the three principles of sustainability to decentralized waste plastic management. This strategy is thermal decomposition of waste plastic to fuel oil at temperatures of 400-450°C (Joshi & Seay, 2016, DeNeve, *et al.*, 2017). High-density polyethylene, low-density polyethylene, polystyrene and polypropylene plastics [Sarker, 2011, Sarker, *et al.*, 2012, Joshi & Seay, 2016, DeNeve, *et al.*, 2017, Santaweesuk & Janyalertadun, 2017, Patil, *et al.*, 2017, Singh & Ruj, 2016, Demirbas, 2004, Pinto, *et al.*, 1999, Al-Salem, *et al.*, 2009, Kumar & Singh, 2011, Miskolczi, *et al.*, 2004, Panda, *et al.*, 2010, Wong, *et al.*, 2015) can be easily converted to fuel similar in composition to diesel and kerosene by individual entrepreneurs utilizing appropriate technology (AT), providing a potential path to a LMDCE. AT is simple, non-automated technology requiring little to no electricity, designed for a specific region to meet specific challenges according to available resources (Joshi & Seay, 2016). An AT solution for thermal decomposition of waste plastic is the UKATS Processor (Joshi & Seay, 2016, DeNeve, *et al.*, 2017). This invention is constructed locally utilizing existent construction materials, available infrastructure, technical knowledge of intended users and from easily acquired, locally generated waste plastics. For instance, the UKATS Processor is wood fired to allow for the skills of rural communities that operate wood fired cookstoves to be readily applied. Moreover, the desired plastics can be easily collected by waste pickers or entrepreneurs by either identifying the plastic recycling numbers (2, 4, 5 and 6, respectively) or by performing a simple density test of the shredded plastics in water. That is, if the waste plastics float on water, they are suitable for reprocessing to fuel oil.

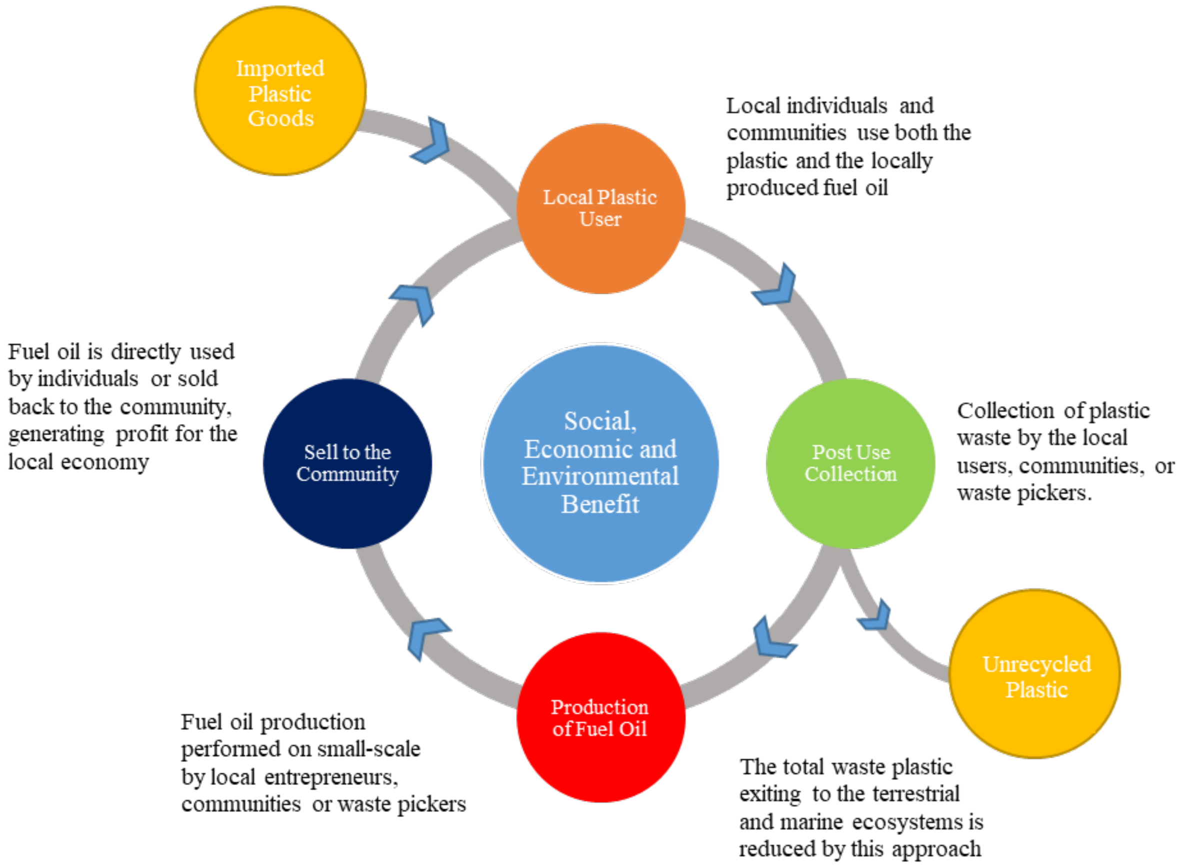


Figure 3.2. LMDCE for waste plastic in infrastructure limited regions

Consequently, a LMDCE gives waste plastic an economic value, which incentivizes people to collect and use it locally, reducing waste accumulation. It further significantly reduces the need for physical and technical infrastructure to implement an industrial circular economy of plastic by involving local community participation as shown in Figure 3.2. In addition, this approach is socially and environmentally appropriate. For instance, as accumulation of waste decreases, sanitation issues decrease, improving community health. Likewise, environmental benefits are reaped by decreasing waste leachate into soil and reducing toxic hazards associated with incineration of waste plastic – a commonly practiced alternative to managing accumulation in rural regions and near slums (Singh & Ruj, 2016, Demirbas, 2004, Pinto, *et al.*, 1999). The fuel oil itself also does not have sulfur dioxide emissions as sulfur is not present in the carbon-hydrogen plastic polymer chains, reducing greenhouse gas sulfur dioxide emissions in comparison with traditional petroleum derived fuels (Joshi & Seay, 2016).

3.4 Identifying Regions of Greatest Potential for a Locally Managed Decentralized Circular Economy

We propose that in order to identify countries that will have the greatest potential for a LMDCE, the three pillars of sustainability—environmental, economic, and social acceptability—should be incorporated. Hence, waste plastic abatement strategies cannot simply focus on the environment; they must also be economically viable and socially acceptable. We believe that unless solutions are targeted to be appropriate for the communities for which they are intended, they will ultimately be unsuccessful. To validate this perspective, we developed a simple metric that utilizes a big data approach to analyze countries' outlook in each of the three pillars of sustainability, highlighting regions where a LMDCE for plastic is likely to have the highest positive impact.

Today, data availability is better than it has ever been. Governments, private corporations, and NGOs are collecting ever increasing volumes of data, and much of that data is now publicly available and readily accessible via the Internet. This data is useful in conducting sustainability assessments for individual countries and regions. Here, it is organized and analyzed to identify countries which can potentially benefit from a plastic circular economy at the local level with decentralized waste plastic abatement strategies.

The purpose of this metric is therefore to identify countries that have specific challenges with any or all three of the pillars of sustainability in meeting their waste management challenges, in return directly affecting the way waste plastic is handled.

Often waste management is a priority in urbanized regions of developing countries, with little attention given to rural regions. Challenges such as variation in income level, conditions of road infrastructure, and perception of communities toward waste, including education regarding hazards associated with waste influence the way waste is handled in both urban and rural regions. As a result, wealthy communities experience regular waste collection, while slums outside of a city are perceived as dumping grounds for waste. Thus, our approach considers the challenges facing each country or region, in terms of economic, social, and environmental concerns to propose decentralized waste plastic solutions that are tailored to the region's availability of infrastructure, capital, and technical knowledge. Moreover, if community participation is prioritized, engineered AT solutions are more likely to be accepted, leading to intended uses and benefits, reducing the dependency on central waste collection and management for rural regions, specifically.

In this metric, a list of 200 countries was analyzed using nine indicators, representing the three pillars of sustainability—eco-nomic, social, and environmental. These indicators are described in Table 3.1 and were chosen because they identify countries with widespread poverty, underdeveloped infrastructure, weak governmental institutions, and an existing MSW management problem—key indicators for determining the suitability of a LMDCE. The development of the metric (see Equation 3.1) considers assigning specific and global weighting factors to each of the nine indicators mentioned in Table 3.1 to highlight the importance of each indicator and the environmental, economic, or social outlook of the countries. As a result, a country's specific and global weighting factors can be individually adjusted to ensure that the country's outlook, challenges, and advantages are equally highlighted. Afterward, the sum of indicators and respective weighting factors results in a comparison score of each country's viability for a LMDCE. Further details of this approach are described in the Appendix A.

$$\sum_{i=1}^{n} G_{EC}\ [(I_{EC1} * S_{EC1}) + (I_{EC2} * S_{EC2})] + G_{SC}\ [(I_{SC1} * S_{SC1}) + (I_{SC2} * S_{SC2}) + (I_{SC3} * S_{SC3})] + G_{EV}\ [(I_{EV1} * S_{EV1}) + (I_{EV2} * S_{EV2}) + (I_{EV3} * S_{EV3}) + (I_{EV4} * S_{EV4})] \tag{3.1}$$

Where:

G = Global weighting factor

I = Indicator type

S = Specific weighting factor corresponding to an individual indicator

Indicator Subscripts:

EC = Economic

SC = Social

EV = Environmental

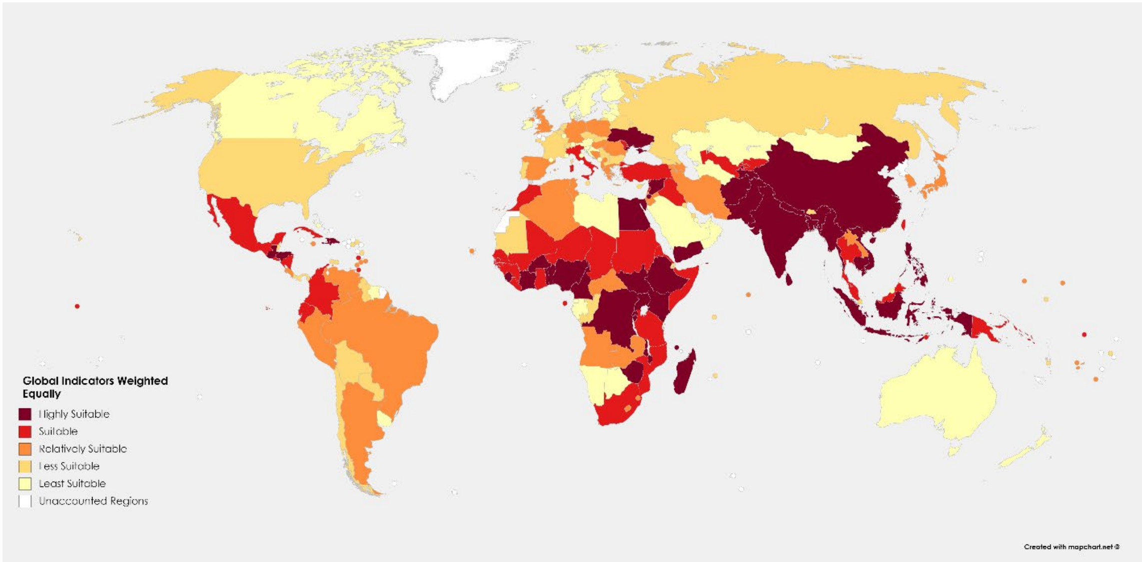
Table 3.1. Indicators used to develop metric for identifying regions most suitable for a consumer-focused decentralized circular economy

Sustainability Indicators	**Units**	**Justification**
Economic		
Gross Domestic Product (GDP)	Billion USD	This indicator gives a general overview of the wealth of the country, which is directly associated with the availability of developed infrastructure.
GDP per Capita	USD	Since GDP alone is not enough to characterize the economic wellbeing of a country's population, this indicator was included as well.
Environmental		
Estimated MSW Generation	MT/day	This indicator shows the magnitude of the MSW generated in a country.
Environmental Stress	MT MSW/km^2	This indicator shows the concentration of MSW by including the country's land area.
Estimated Waste Plastic in MSW	MT/day	This indicator is specific to the key focus of this perspective, which is waste plastic.
Estimated Unsound Waste Disposal	MT/day	This indicator provides an overview of the suitability of a locally managed decentralized solutions targeted at mismanaged waste.
Social		
Population	capita	This indicator shows how many people can be potentially impacted by proposed perspective and abatement solutions.
Population below Poverty Line	%	This indicator shows the general wealth of the population and how likely they are to benefit from entrepreneurial opportunities associated with waste management.
Population Density	capita/km^2	This indicator relates population to the rate of waste accumulation per land area, identifying hurdles of waste collection as crowded countries often have infrastructure challenges.

This metric can be utilized by researchers, policy makers, and other users to achieve an in-depth understanding of a country's waste management outlook, particularly with respect to the economic and social indicators, which are often over-looked. Users can adjust local or global indicator weighting factors according to a region's unique challenges or to emphasize a specific category that contributes to waste plastic mismanagement. Hence, opportunities for managing waste can be identified, with a LMDCE being a viable approach.

3.5 Utilization of the Metric

For the base case, all local and global weighting factors for each of the nine indicators were weighted equally. The results of the big data analysis metric for identifying key regions suitable for a LMDCE are illustrated in Figure 3.3. Darker colors represent countries that are most likely to benefit from this approach. It can be observed that sub-Saharan Africa, East Asia, Southeast Asia, and South Asia are the most promising regions for applying decentralized solutions to waste plastic management. This information indicates that typically, developing highly populated low-middle to middle income countries are the most important targets for locally managed decentralized waste plastic abatement strategies. The reason being that even though the citizens of these countries generate less waste per capita, the consequence of higher population density results in an overall larger amount of MSW generation than developed regions. Coupled with limited financial resources, lack of infrastructure and reliable access to energy [20], waste is increasingly susceptible to unsound disposal in open dumps, streets, and waterways, especially in rural communities. Contrastingly, developing nations considered by the metric that may consume greater amounts of energy and generate higher amounts of MSW per capita are not ideal locations for a LMDCE due to the reasons of improved collection, strong waste management infrastructure, controlled waste disposal, and an existent centralized, industrial circular economy, leading to reduction in unsound waste disposal.



Full scale image available at https://doi.org/10.1002/ep.13086.

Figure 3.3. Suitable regions for a LMDCE for waste plastic

The usefulness of this metric can be additionally demonstrated by weighting one of the three sustainability categories greater than the rest as per the user's interests. To illustrate this, the weighting of global sustainability indicators was varied by assigning a value of 50% to one, while the other two were set to 25%. This analysis is presented in Table 3.2 and signifies that when weighting the global economic indicator higher, countries with relatively low GDP per capita and high percentages of population living below the poverty line rise to the top as most suitable regions. In like manner, for social sustainability, countries with the greatest population numbers or population density are recommended. Meanwhile, estimated waste plastic in MSW 2016 and estimated unsound disposal of waste plastic in MT/day were found to be the biggest contributing factors for environmental sustainability highlighting regions suffering from uncontrolled waste accumulation. Lastly, the metric also depicts the impact of environmental stress, or the amount of waste generated per km^2 of land. Countries that rank highly in this category include the United States, many western European nations as well as high-income Southeast Asian countries, such as Hong

Kong, Macao, and Singapore, which have significant environmental stress due to either high generation of MSW, population density, and/or limited land area (Central Intelligence Agency [CIA], 2017a, CIA, 2017b).

As an example, India had the position of being 10th overall in this metric analysis, while being 52nd, 8th, and 5th most suitable country when global economic, social, and environ-mental indicators were respectively highlighted for implementation of a LMDCE. Therefore, it can be concluded that for India, the lack of waste management education, attitude toward environmental protection, and insufficient collection infrastructure combined with increased waste generation due to population density are the most probable causes of waste plastic accumulation, instead of capital constraints. It is also important to note that even though a circular economy is well established in China, the country currently practices a centralized industrial circular economy (Yuan, *et al.*, 2006, Geng, et. al., 2009, Matthews, *et al.*, 2018). Hence, it could likewise benefit from a locally man-aged decentralized circular economy approach in rural regions due to high waste generation associated large populations.

Although this analysis may appear to simply reinforce well-established beliefs, these results are used to make the point that developing urban and rural regions around the world are different, in return requiring different strategies for MSW and waste plastic abatement. The information obtained from the analysis suggests that African nations vary in their economic, social, and environmental stance compared with developing regions of Asia. This fact in itself alters the way waste management is approached in these countries, as cultural norms associated with perception of waste management vary. Another example is the data highlighting importance of waste recycling in the Americas versus in Europe.

Even though both regions are developed, environmentally benign waste management is practiced in many European nations via a variety of waste-to-energy solutions, while a large portion of waste in the United States goes to the landfill. Hence, the data are used to make the case for designing and developing technologies based on each region's outlook, suggesting a LMDCE in rural regions of developing countries.

Table 3.2. Comparison of 20 countries most suitable for decentralized waste plastic solutions according to different sustainability category weightings

Country Suitability	Global Indicators Weighted Equally	Economic Indicator Weighted Highest	Social Indicator Weighted Highest	Environmental Indicator Weighted Highest
1	Bangladesh	Burundi	Bangladesh	Bangladesh
2	Burundi	Malawi	Burundi	Pakistan
3	Haiti	Haiti	Nigeria	Vietnam
4	Pakistan	Rwanda	Pakistan	Nigeria
5	Malawi	Comoros	Haiti	India
6	Nigeria	Togo	Malawi	Philippines
7	Rwanda	Syria	Rwanda	Sri Lanka
8	Syria	Bangladesh	India	Syria
9	Vietnam	The Gambia	Syria	Haiti
10	India	Congo, Democratic Republic of the	Philippines	Guatemala
11	Philippines	Yemen	Vietnam	Burundi
12	Guatemala	South Sudan	Guatemala	Malawi
13	Yemen	Madagascar	Congo, Democratic Republic of the	Egypt
14	Congo, Democratic Republic of the	Pakistan	Togo	Rwanda
15	Togo	Sierra Leone	Yemen	China
16	Sri Lanka	Burkina Faso	Ethiopia	Yemen
17	Cambodia	Cambodia	Sri Lanka	Cambodia
18	Ethiopia	Afghanistan	Egypt	Thailand
19	Comoros	Benin	Myanmar/Burma	Congo, Democratic Republic of the
20	Myanmar/Burma	Liberia	Nepal	Myanmar/Burma

3.6 Uganda Case Study

The country of Uganda is positioned 32nd in the metric assessment, meaning that it has great potential for a LMDCE with informal recycling waste management approaches. Uganda has a population of 38.3 million, with a growth rate of 3.22% in 2016 (CIA, 2017c). The size of the country is slightly smaller in area than the U.S. state of Oregon (CIA, 2017a). The nation has abundant natural resources, fertile soil, sufficient rainfall, and small deposits of precious minerals and oil (CIA, 2017c). Consequently, agriculture and service sectors employ a combined 78.9% of the population, with coffee revenues accounting for the majority of the exports (CIA, 2017c). Nonetheless, the U.S. Central Intelligence Agency reports that Uganda is facing economic challenges due to sharp increase in refugees from South Sudan, high energy costs, inadequate transportation and energy infrastructure, insufficient budgetary discipline, and corruption (CIA, 2017c). Furthermore, during 2015 and 2016, the Uganda shilling depreciated 50%against the U.S. dollar (CIA, 2017c). Moreover, the nation's GDP per capita is equivalent to 2100 USD, with 9.4% unemployment rate and 19.7% of the population below poverty line (CIA, 2017c). This along with only 15% of the total population having access to electricity, and 19.1% population having access to sanitation facilities, has further led to very high risks of major infectious diseases (CIA, 2017c). Despite these challenges, the nation is poised as a good fit for implementation of decentralized waste management solutions, offering opportunities to recycle waste plastic locally, creating jobs and reducing the spread of diseases due to accumulation of trash.

A case study conducted in Uganda at the Kiteezi landfill in the capital city of Kampala reveals some insight on how the proposed metric has been employed for this region. In 2015, the population of Kampala was reported to be approximately 1.9 million, with 70% of the citizens living in informal settlements scattered around the city (CIA, 2017c, Serukka, 2017). However, as the country's capital, it is the home of major markets and a wide assortment of job opportunities which leads to a doubling of the city's population during the day (CIA, 2017c), increasing waste generation. Therefore, small-scale decentralized AT solutions to waste management are suggested for this city with both the community's and waste pickers' participation.

Currently, the Kampala Capital City Authority (KCCA), a governmental solid waste management organization, provides collection and cleanup services to the city's five divisions (a total 210 km^2 area) (CIA, 2017c), contracting collection of waste from affluent areas to private companies (Serukka, 2017, Komakech, *et al.*, 2014). Hence, the affluent areas are charged a waste collection fee, while the rest of the urban population is serviced by KCCA at no cost (Serukka, 2017). KCCA further manages the city's 36-acre 25-m tall landfill site at Kiteezi, where both KCCA and private sector waste collection vehicles unload MSW, excluding industrial waste, free of charge (Serukka, 2017, Komakech, *et al.*, 2014). At present, a total of 1300–1500 MT of MSW per day are landfilled, about half of the total waste generated by the city (Komakech, *et al.*, 2014). This means that the other half is openly dumped in areas inaccessible to waste collection vehicles, including drainage channels, wetlands, natural water courses, manholes, undeveloped plots, or on the roadside (Komakech, *et al.*, 2014, New Vision, 2015, Whitaker, 2007). This is a strong indication that consumer involvement and decentralized solutions to waste accumulation are needed. The composition of the waste mainly consists of bio-degradable food and garden waste (71.4%), stones and debris (8.6%), plastics (7.8%), paper (2.7%), glass and metals (1.5%), textiles (1.3%), and others (6.7%) (Patil, *et al.*, 2017). KCCA spends approximately 13.4 USD/MT for waste collection and disposal services (Serukka, 2017).

Waste to energy solutions and organized recycling services are not yet offered by KCCA. Nonetheless, small independently operated recycling drop-offs exist in the city's districts. As these recycling drop-offs are new to the city, each district only has one thus far, handling merely 3–4 tons of waste per week. Consequently, most of the waste is sent to the Kiteezi landfill, where it is informally sorted for recycling by waste pickers. With 500 in number, the organized community of waste pickers who live surrounding the landfill collect any-thing that has a well-developed market, such as construction tarps, plastic bottles, paper, glass, and metals (Serukka, 2017). More specifically, the waste plastic that is recycled by the waste pickers is purchased by domestic and international organizations that pay the pickers 500 UGX/kg. A waste picker typically collects around 40 kg/day of plastic, earning 20,000 UGX/day, which is higher than the average city dweller, who earns around 4,500 UGX/day (Serukka, 2017). However, the waste pickers do not collect soft plastics (composition 3.8% of total MSW) (Komakech, *et al.*, 2014) , such as polyethylene shopping bags—known locally as *kaveeras*—as they do not have a ready recycling market. Furthermore, despite the ban on production of plastic bags in the country, similar to 15 other African nations (Environment News Service, 2012, Iwuoha, 2017, Barigaba, 2017), lenient governmental enforcement allows for illegal selling of the polyethylene bags (Barigaba, 2017). Consequently, the *kaveeras* are likely to continue to accumulate in the Kiteezi landfill in the coming years unless action is taken.

Therefore, we recommend that close-coupled decentralized circular economy of plastic be encouraged via strategies such as conversion of polyethylene shopping bags and other soft plastics to fuel oil and similar products through AT (Sarker, 2011, Sarker, *et al.*, 2012, Joshi & Seay, 2016, DeNeve, *et al.*, 2017). This is a viable solution that can further create employment opportunities. Using the statistics previously mentioned, roughly 49,400 kg of soft plastics are brought to the Kiteezi landfill per day. If 40 kg/day of soft waste plastic can be picked by an individual, a resulting 1235 additional jobs could be created at the Kiteezi site. Because the number of soft plastics brought to the landfill are only half of that generated within the city, a similar opportunity exists for local citizens, entrepreneurs, and communities to recycle the waste plastic to fuel, creating additional jobs. The amount of fuel generated could be used as a substitute for kerosene and diesel applications, especially for cooking, lighting, generators, and farming machinery (Joshi & Seay, 2016). This establishment of a LMDCE could potentially have a monumental impact on the accumulation of nondegradable soft plastic accumulation at the Kiteezi landfill and in the Kampala city, improving the aesthetics of the region, and providing entrepreneurial and job opportunities, which will eventually benefit the entire nation (Joshi & Seay, 2016). Thus, by employing the perspective metric established in this research, the results of this case study serve as an example for other nations. The metric's use of sustainability-focused indicators can assist in identifying a region's potential suitability for a LMDCE for waste plastic management.

3.7 Conclusions

In conclusion, even though all developing countries encounter similar challenges to economic development, waste plastic management practices are likely to vary from region to region, requiring a detailed analysis approach based on the principles of sustainability to determine which nations would most benefit from a LMDCE for waste plastic. Often, due to lack of capital resources, centralized waste collection infrastructure, and the population's awareness of the consequences of global waste accumulation, rural and developing communities suffer from major sanitation issues and pose serious environmental concerns. Thus, it is our view that decentralized or distributed approaches with high levels of local participation be proposed for waste plastic abatement strategies to be successful. The metric established in this research has been utilized to glean insight for validating this assertion on the importance of including infrastructural, economical, societal, and environmental constraints in deciding how waste abatement strategies and resources should be prioritized. Thus, focusing on simple low-cost technologies, like thermal decomposition, which can be employed at a local level via AT methods, enable the development of a LMDCEs. This approach promotes community-managed collection and recycle of waste plastic directly where it is generated in a sustainable manner.

3.8 Supplementary Information

Details discussing the generation of the metric presented in this study are outlined in Appendix A, Supplementary Information – Metric Generation. For additional information, visit https://doi.org/10.1002/ep.13086.

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CHAPTER 4. BUILDING MOMENTUM FOR SUSTAINABLE BEHAVIORS IN DEVELOPING REGIONS USING LOCALLY MANAGED DECENTRALIZED CIRCULAR ECONOMY PRINCIPLES

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4.1 Abstract

Despite the current threat from climate change, plastic collecting in the world's oceans, and the steady loss of biodiversity, the world continually fails to take action with regard to our rapidly changing ecosystem. Unfortunately, waiting on governments to act is no longer a viable option. Rapid change is needed, and the pace of diplomacy is simply too slow. Democratic governments are reactionary and taking action to solve future problems is not a priority, even as the threat of potential ecological catastrophe draws ever closer. Change is in the hands of individuals, and it is our decisions and behaviors that will influence the future of our planet and our ability to inhabit it. Therefore, building momentum for sustainable behavior must begin with individuals. The neoliberal approach to environmental protection posits individuals are motivated by rational self-interest, and that economic incentives are necessary to achieve environmental goals. However, recent research suggests that monetary gain alone actually negatively impacts behavior, and often neglects the rural poor. As a result, models for projects designed to benefit the environment need more than just a monetary incentive, they must incorporate all three pillars of sustainability: environment, economy and society. One approach for building momentum for sustainable behavior with regard to municipal solid waste management, particularly in the developing world, is by implementing Locally Managed Decentralized Circular Economy (LMDCE) principles. This contribution will describe the role behavioral

economics plays in the choices made by producers and consumers. The results of a case study on applying LMDCE principles in Uganda to manage waste plastic accumulation by conversion to fuel oil will be presented.

4.2 Environment and Waste Plastic

4.2.1 Ecosystem Deterioration and the Tragedy of the Commons

As the global population continues to grow, the impacts of human activities have overwhelmed the resiliency of the ecosystem. Climate is rapidly changing with serious adverse consequences (Intergovernmental Panel on Climate Change [IPCC], 2018) and mismanaged waste plastic has infiltrated every ocean (Jambeck, 2015) and every link of the food chain, including humans (Parker, 2018). This paradigm is well described by the scenario of the tragedy of the commons. This scenario was first described in 1833 by William Forster Lloyd (Hardin, 1968) and is based upon the public usage of common grazing land in England. The scenario unfolds with a herdsman as a rational being seeking to maximize his personal gain via his access to common grazing land. This is accomplished by adding more animals to his herd. The benefit to the herdsman is obvious – additional profit from a larger herd. However, the additional animals grazing on common land reduces resources available to everyone, including the herdsman himself. Nonetheless, the loss of grazing capacity is shared by everyone, whereas the benefit is gleaned by the herdsman alone. The outcome of course is that the use of common resources works well when there is plenty for everyone but leads to degradation and eventual conflict when the capacity is diminished. The tragedy of the commons is currently playing out with our current global ecosystem. For instance, in the past, lower human populations and less consumption meant the ecosystem was able to easily absorb the impact of human activity and treating it as a common resource was sustainable. However, with the dual pressures of population growth and increasing consumption, the tragedy of the commons is becoming a global reality.

4.2.2 The Global Plastic Challenge

The impacts of plastic in the oceans are easily visible. Natural ocean currents create 5 major gyres – huge rotating regions of open sea that collect floating waste materials (Jambeck, 2015). Once waste enters one of these gyres it is essentially trapped. Much attention has been given to what has been called “The Great Pacific Garbage Patch”. This refers to waste, particularly plastic which has been trapped in the Pacific gyre. Although the Great Pacific Garbage patch has received most of the attention, each of the ocean gyres is accumulating significant amounts of plastic (Jambeck, 2015). Current estimates suggest that the oceans hold more than 5 trillion pieces of plastic weighing more than 250,000 tons (Eriksen, *et al.*, 2014). Between entanglement and ingestion of material that was mistaken for food, mismanaged waste plastic has been detrimental to marine life. In fact, it is estimated that 2/3 of the world’s fish stock has ingested plastic (Wieczorek, *et al.*, 2018). Unfortunately, a single piece of plastic can kill over and over. The animal killed by the plastic eventually decomposes, but the plastic remains and can continue to cause harm. Additionally, through the consumption of fish, as well as food packaged in plastic, humans are also adversely impacted (Parker, 2018). For instance, plastic chemicals absorbed by the body have been found to alter hormones (Knoblauch, 2009). Another recent study from seven different European countries and Japan has revealed microplastics present in human feces (Parker, 2018). These findings verify the pervasiveness of plastic in the global environment.

Despite these concerns, plastic cannot be simply eliminated from the supply chain, nor is it practical or even always beneficial to do so. The alternatives to plastic goods and packaging include materials such as metals, glass, paper and cotton-based fabrics. As a result, an increased demand for metals would lead to increased mining and increased fuel demands for transportation of these heavy materials, resulting in increased prices and negative environmental impacts. Glass is heavy, energy intensive and prone to breaking. Increased cultivation of cotton and increased paper production will compete with land suitable for food crops, which is already in shortage due to population growth. Additionally, increasing land for cotton and paper production will lead to deforestation - a significant global threat. There are simply no suitable alternatives for plastic ready for deployment at an international scale, meaning that plastic is too cheap and efficient to be easily replaced. Thus, this phenomenon is currently leading to exponential growth in production, consumption, disposal, and accumulation of plastic, challenging its management globally.

Previously, much of the world's recyclable plastic was shipped to China to be re-manufactured. However, in January 2018, the country announced that it would no longer be a "dumping ground" for what it calls "foreign garbage" from other countries (Cole, 2017). China's ban covers imports of 24 kinds of solid waste, including plastic. Prior to the ban, China had been processing much of the world's exports of waste metals, papers and textiles, as well as more than half of the world's plastic scraps at nine million metric tons per year (Cole, 2017, Freytas-Tamura, 2018). This sudden action has left Western countries scrambling to deal with a buildup of plastic and paper garbage while looking for new markets for the waste (Freytas-Tamura, 2018, Kottasova, 2018, Yosufzai, 2018). However, the ban doesn't only influence Western economies, developing economies have also been impacted. Unfortunately, infrastructure limitations have left governments in developing countries with no outlet for waste, an especially problematic scenario as previous research has demonstrated that many of the top 20 contributors to marine plastic debris are coastal developing countries (Jambeck, 2015). Hence, for waste plastic to be managed on land, governmental action is simply not enough. Waste plastic must be considered as an imminent threat to the environment by all individuals, who must be presented with readily accessible, viable solutions to target waste accumulation within their communities. Subsequently, the behavioral economics of individual citizens along with their interactions with, perceptions of, and influences on their community should be analyzed to propose viable solutions for plastic management.

4.3 Economics & Sustainable Behaviors

4.3.1 Behavioral Economics

Humans have evolved in concert with our ecosystem; however, rapid anthropogenic ecosystem changes are outpacing our ability to adapt. Our species is adapted to work in our own immediate self-interest. Groundbreaking research by George Ainslie in the 1970s concluded that behaviors that have a short-term payoff are favored over ones that only have benefits in the long term (Ainslie, 1975). This is known as hyperbolic discounting (Ainslie, 1975). The problem we are now facing, however, is that our behaviors with regard to consumption are causing severe damage to our ecosystem. The consequences of this behavior are discounted significantly by the general population. These problems associated with hyperbolic discounting are amplified in developing countries, since people have more immediate needs with regards to survival. Unstable governments, lack of strong institutions and lack of food, water and energy security make acting in the global best interest difficult or impossible.

Anthropogenic climate change, unsound waste disposal and loss of biodiversity are all happening at an alarming rate, but our global institutions have been unable to adequately address these problems. Much of the progress to date relies on altruistic behavior - consciously consuming less than one otherwise could to minimize one's individual impact. Although altruism is a fundamental characteristic of human society (Brede, 2013), the problem with relying on altruistic behavior is twofold: first is the previously mentioned problem of our evolutionary predisposition to acting in our own self-interest; and second is the free rider problem. The free-rider problem describes our inherent distaste for others benefiting from our individual sacrifice. This problem has been observed in resistance to social programs, as well as resistance to sustainable consumption options that are perceived as being more expensive, less effective or less convenient than traditional options. Because of the issues that arise with both reliance on altruism and the fear of free-riders, many proposed solutions to environmental problems are rooted in the theory of neoliberal conservation. This theory posits individuals are rational actors who always act in their economic self-interest. Neoliberalism combines conservation with markets such that conserved land and resources become fungible commodities (Doane, 2014). The result of this line of thought is that economic incentives are required to advance environmental protection, however these practices do not necessarily benefit the poor, or the environment (Brockington & Igoe, 2006). Quoting Igoe and Brockington (Igoe & Brockington, 2007):

"... neoliberalism's emphasis on competition, along with its rolling back of state protection and the social contract, create spaces in which local people are often not able to compete effectively."

This clearly indicates that a new model of behavior that benefits the rural poor is needed.

4.3.2 Environmental Protection and the Fallacy of the Rational Actor Model

The neoliberal approach to conservation and environmental protection is based on the assumption that individuals are rational actors. The principle of the rational actor is based on three tenets: that individuals are self-interested and attempt to maximize their own benefits; that they only respond to economic incentives; and that economic markets are free, mutual, and rational (Peterson & Isenhour, 2014). However, recent research has suggested that new approaches are needed to model human behavior with regard to environmental protection (Doane, 2014, Isenhour, 2014, Peterson, 2014, Gowdy, 2007). This research argues that individuals are not simply motivated by economic gain alone. As asserted by Peterson (Igoe & Brockington, 2006), giving the ecosystem an economic value to ensure protection undermines the consideration of alternative values. Gowdy (Gowdy, 2007), further asserts that:

"*It is no longer tenable for economists to claim that the self-regarding, rational actor model offers a satisfactory description of human decision making.*"

Additional research states that monetary incentives may actually be counterproductive (Gowdy, 2007, Berkes, 2004, Frey, 1997, Frey & Oberholtzer-Gee, 1997). These economic incentives are not only counterproductive to individuals, but outcomes based on the rational actor model can actually erode communities (Peterson &

Isenhour, 2014). Contrastingly, motivation is actually multidimensional (Peterson & Isenhour, 2014) and recent research has shown that equity and empowerment are often more important than monetary incentives (Berkes, 2004). Therefore, to be effective, approaches must be rooted in all three pillars of sustainability, economic, environmental and social.

4.3.3 Breaking the Take → Make → Waste Paradigm

When it comes to consumption, the traditional Take → Make → Waste paradigm is firmly rooted in our collective human behavior. If something can't be immediately reused to our economic advantage, our first inclination is to dispose of it. As previously described, this behavior is well described by the concept of the tragedy of the commons (Hardin, 1968). In applying this principle, we see that the benefits to the individual of the Take → Make → Waste paradigm far outweigh the consequence to the individual since the adverse effects of ecosystem deterioration are shared among the entire population over an extended time horizon. This is particularly problematic with wastes which linger in the ecosystem, like plastic. Many researchers globally are studying the accumulation of waste plastic and its impact on marine and terrestrial life. A recent study complied data from 192 countries bordering major bodies of water (Jambeck, 2015). This study concluded that 2.5 billion metric tons of solid waste were produced in 2010 by these countries and of that waste, 8 million metric tons of plastic entered the ocean (Jambeck, 2015). This plastic threatens sea life, birds and human health (Jambeck, 205, Eriksen, *et al.*, 2014, Knoblauch, 2009). Without regulatory intervention, which seems increasingly unlikely, breaking this paradigm will fall on the backs of consumers. New models of production, consumption and waste management that act in concert with, rather than in opposition to, established modes of human behaviors will be required.

4.3.4 Building Momentum for Sustainable Behaviors

Sustainable behaviors are those that are economically beneficial, environmentally benign and socially responsible. If we are able to move past the paradigm of the rational actor model, we can propose potential solutions that rely on more than economics alone as motivating factors. Successful strategies will include environmental protection and social responsibility as well. To achieve these goals, a LMDCE model is proposed for combatting the problems of wasteful consumption and mismanaged municipal solid waste. As will be described, LMDCE focuses on all three aspects of sustainability, meaning that it moves beyond the narrow confines of neoliberal conservation approaches.

4.4 LMDCE Principles

4.4.1 Impacts of infrastructure limitations on circular economy development

Breaking the Take → Make → Waste paradigm is an underlying principle and the first step towards building a circular economy. Thus far, circular economy models for various waste types have been considered and applied in regions with sufficient infrastructure to collect and sort valuable waste products to reuse, recycle or re-enter them into their respective manufacturing supply chains on an industrial scale (World Economic Forum *et al.*, 2016, Yuan, *et al.*, 2006). In addition to infrastructure, this approach requires capital and sophisticated equipment to reprocess the materials into their building blocks for entrance back into consumer products. Likewise, a waste plastic circular economy is also encouraged to reduce the production of virgin plastics. However, only 9% of plastics produced have been recycled (Geyer, 2017) by both developed and developing countries to date. Developing countries have relied on an informal recycling sector via waste pickers to sort through dumpsites and unmanaged landfills to collect recyclable waste plastics (Parker 2018, Medina, 2007, Medina, 2008]. These plastics were previously shipped to China for remanufacturing. However, due to the recent bans from China on "foreign garbage", waste picker jobs are currently being jeopardized (Cole, 2017, Freytas-Tamura, 2018, Kottasova, 2018, Yosufzai, 2018).

Hence, there is a need for a locally managed and decentralized, or distributed, circular economy for valuable waste products in regions lacking infrastructure, capital and tools to erect an industrial circular economy. In spite of these constraints, the solutions to waste management must rely on the involvement of local consumers, encouraging them to take ownership of their waste management, instead of relying on governmental and industrial assistance. This further requires a fundamental change in behaviors of individuals and their perception of waste. To change behaviors, an incentive is needed - one that is locally available and pays dividends in the local community. However, many projects designed to benefit and protect the environment have neglected their subsequent impact on local communities, decreasing citizen involvement and ownership of the projects (Brockington & Igoe, 2006). This failure to consider the impacts on local communities has negatively affected municipal solid waste (MSW) management in developing countries.

Due to infrastructure limitations, MSW often has no perceived value and is simply discarded after use. In return, this waste ends up on the streets, in waterways, or on open dumps. As a result, projects designed to manage MSW must give the waste a value so that it is considered as a resource by communities and will not be discarded. Moreover, in resource limited regions, supply chain constraints favor local solutions. For the case of MSW, this means applying decentralized collection and decentralized utilization. To address the aforementioned challenges by inclusion of community members, the concept of a LMDCE is proposed, as shown in Figure 4.1.

Using this approach, imported manufactured goods enter the circular economy cycle as the initial feed source. They are then used, reused, and collected after post use to generate value-added products. Here, the participation of waste pickers is highly recommended and needed to decrease waste accumulation. The waste products, then, serve as local raw materials to produce goods, which once sold back to the community, generate entrepreneurial opportunities and boost the local economy. The only output from this cycle is any waste that cannot be reused, collected, or recycled by the community. Therefore, the waste stream exiting to the environment from the community is reduced. Additionally, the key of this decentralized approach is that everything is local and waste management is designed around and operated by the community. That is, collection, production and use are all managed in the local community. Of course, this limits the scope of remanufacturing in rural regions, but this approach has a higher likelihood of success when implemented. The real benefit is that this approach does not require sophisticated infrastructure and provides needed locally focused incentives for decreasing waste accumulation.

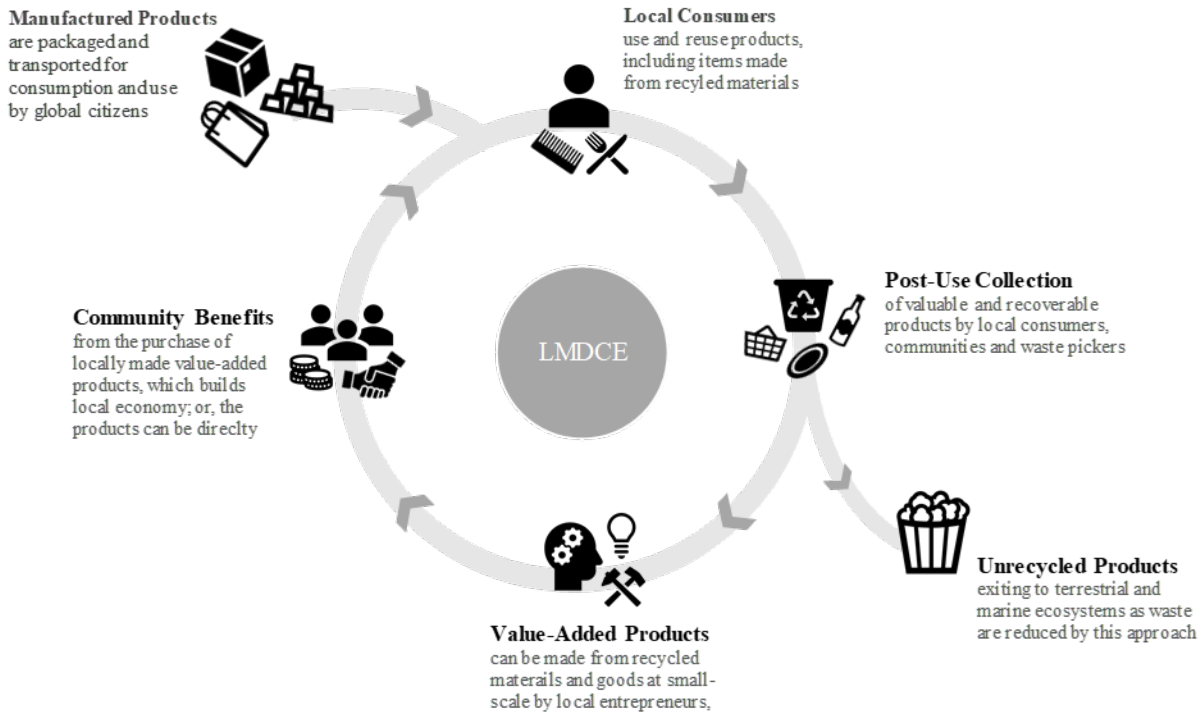

Figure 4.1. Illustration of a LMDCE for infrastructure limited regions

Using this approach, imported manufactured goods enter the circular economy cycle as the initial feed source. They are then used, reused, and collected post use to generate value-added products. The waste products, then, serve as local raw materials to produce goods, which once sold back to the community, generate entrepreneurial opportunities and boost the local economy. The only output from this cycle is any waste that cannot be reused, collected, or recycled by the community. Therefore, the waste stream exiting to the environment from the community is reduced. Additionally, the key of this decentralized approach is that everything is local and waste management is designed around and operated by the community. That is, collection, production and use are all managed in the local community. Of course, this limits the scope of remanufacturing in rural regions, but this approach has a higher likelihood of success when implemented. The real benefit is that this approach does not require sophisticated infrastructure and provides needed locally focused incentives for decreasing waste accumulation.

4.4.2 Appropriate Technology

The concept of appropriate technology (AT) was first described by E.F. Schumacher in his book Small is Beautiful (Schumacher, 1973). This concept of AT is summarized by Hazeltine, (Hazeltine, 1999) as:

"*Technological choices and applications that are small scale, decentralized, labor-intensive, energy efficient, environmentally sound, and locally controlled.*"

AT is simply technology suitable for a specific region, designed to meet specific needs of certain individuals or communities (Joshi & Seay, 2016). Though the details of what constitutes AT can vary between regions and applications, the description from Hazeltine (Hazeltine, 1999) generally holds true. AT does however require tradeoffs. In most cases, the tradeoffs include efficiency for simplicity; convenience for low cost; and automation for manual operation. The key benefit of AT is that it is easily deployable because it does not rely on a sophisticated infrastructure. AT is a way of achieving the societal benefits of sustainability, particularly in underdeveloped regions. This means that AT is not intended to reproduce industrial technology on a small scale but rather to design specific solutions appropriate for a given region or for a given community (Seay, *et al.*, 2012). AT is the mechanism by which LMDCE principles overcome infrastructure challenges in developing economies.

4.5 Applying LMDCE Principles in Uganda

4.5.1 Converting Waste Plastic to Fuel Oil

A method that can potentially be deployed using the LMDCE approach is the conversion of waste plastic into fuel oil, suitable for use as an alternative to diesel or kerosene fuels. Polyolefin plastic polymers like High- and Low-Density Polyethylene and Polypropylene and be converted into a liquid fuel at temperatures of 400°C - 500°C via thermal decomposition in the absence of oxygen, or through a process called pyrolysis (Joshi & Seay, 2106, DeNeve, *et al.*, 2017). This process does not require catalysts to breakdown the plastic polymer chains; instead, it simply utilizes a viable heating source to decompose the plastic. Using this process, 1 kg of waste plastic can be converted to 1 liter of fuel oil (Joshi & Seay, 2016). The chemistry is simple and via the application of AT, this process can be carried out on a small, local-scale in resource constrained regions (Joshi & Seay, 2016). Employing this chemistry and technology as a case study, the application of LMDCE principles are illustrated.

4.5.2 LMDCE Case Study

The University of Kentucky Appropriate Technology & Sustainability (UKATS) research group has designed and lab tested an AT based technology for converting waste plastic into fuel. This technology is completely non-automated, requires no electricity to operate and is designed according to the availability of resources, capital, infrastructure and technical knowledge of individuals in developing countries. The technology is constructed from repurposed metal (preferably stainless-steel drums) and has two parts – a batch retort vessel for conducting the thermal decomposition reaction that converts waste plastic to fuel oil, and an efficient, institutional sized, biomass fueled cookstove that provides the necessary heat to drive the reaction. A photo of the process is illustrated in Figure 4.2. As can be seen, the retort (inner barrel) is housed inside the cookstove (outer barrel). The process is initiated by igniting waste wood or other biomass sources in the cookstove to generate a steady fire. The plastic then melts, decomposes and vaporizes in the retort according to the energy provided by the fire. Vapor phase products from this process exit through a vent pipe, as shown in Figure 4.2, and the pipe is submerged in water to condense the products to fuel oil. This process is well described in previous literature as well (Joshi & Seay, 2016, DeNeve, *et al.*, 2017).

Further, this process was tested for two years in Uganda at the Makerere University Agriculture Research Institute in Kabanyolo (MAURIK) to determine its feasibility and effectiveness. Specifically, operational and maintenance training was provided to local students, and the technology was tested to determine its success in converting locally sourced waste plastic, such as kaveeras (polyethylene grocery bags), jerry cans and plastic containers to fuel oil. The quality of the fuel generated was tested in a local multi-purpose utility vehicle operated by a diesel engine. The goal of the initial testing was to identify operational and maintenance issues, resolving them to prepare the technology for deployment in a real-life scenario, such as for use by an entrepreneur to establish a business in the local community based on this process.

After initial testing, the process was provided at no cost to a local entrepreneur in the Mukono region, identified by the Rotary Club of Kampala, to convert post-consumer waste plastic into fuel oil. The process was typically operated 4-5 times per week by a homemaker, collecting on average 20-25 liters of fuel from a feedstock of 20-25 kg of waste plastic. The temperature of the process was maintained between 450°C - 500°C. The plastic feedstock was collected from personal household waste or purchased from neighbors at a price of 500 UGX/kg. The biomass source utilized for heating the process was wood, purchased at 250 UGX/kg, and the fuel was sold to diesel truck drivers in the region at a price of 2500 UGX/liter. After performing a simple economic assessment by factoring the costs of raw materials and the revenue generated from fuel sales, a 158% profit was obtained on average. The profit earned was almost double the daily average income of citizens in the nearby capital city of Kampala, having a lasting positive societal benefit on the entrepreneur's family. Furthermore, it is noteworthy to mention that since these were preliminary field trials, the fuel was sold at a 30% discount when compared with the retail price of petroleum derived diesel fuel in the city, meaning there is an even greater profit potential present in this process, making it economically viable.

Figure 4.2. Photograph of the UKATS process for converting post-consumer waste plastic into fuel oil

4.6 A Sustainable Path Forward

Finding a sustainable path forward for our global society is a significant challenge. However, this path forward must be firmly grounded in the three pillars of sustainability and must not rely on the outdated rational actor model. As illustrated in Figure 4.3, LMDCE provides a roadmap for this sustainable path forward.

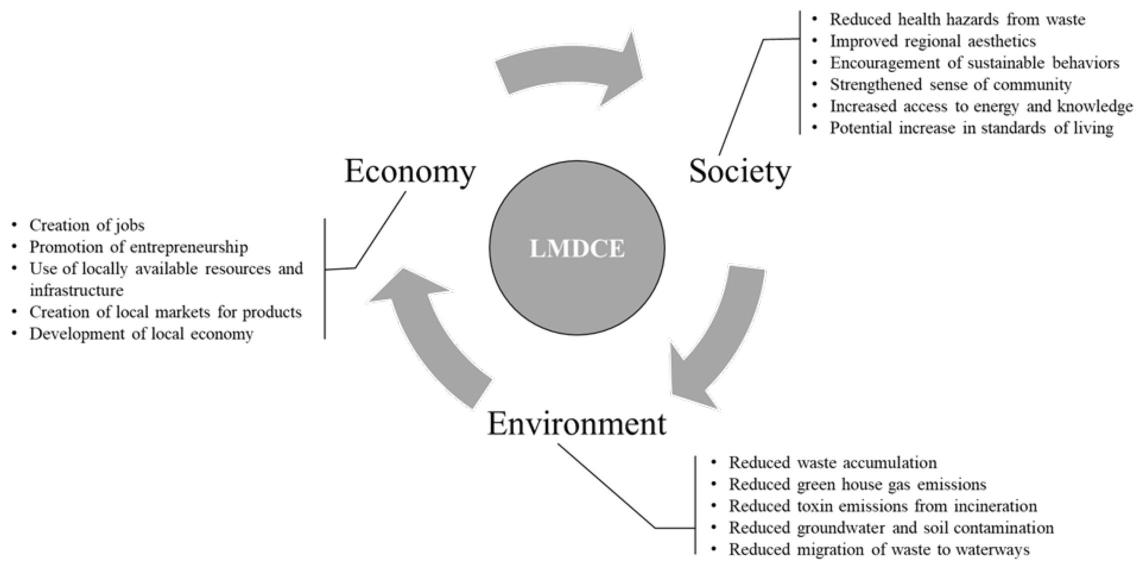

Figure 4.3. LMDCE principles provide a sustainable path forward for global waste management

LMDCE is a potential path that results in benefits for rural or developing economies without relying on the tenets of neoliberal conservation. Each step in the LMDCE has a local benefit. The local economy, the local environment and the local community see a direct benefit from successful implementation of a LMDCE. It is this feature of the LMDCE approach that provides the best chance for success in MSW management in infrastructure limited regions.

The waste plastic to fuel LMDCE provides a model for a sustainable path forward, as detailed in Figure 4.3. The case study clearly demonstrates this path. First, the process provides entrepreneurial opportunities and direct benefits to the economy by incentivizing collection of waste plastic and through the sale of generated fuel. Next, it provides environmental benefits by decreasing waste accumulation. Lastly, it encourages the community to take ownership of waste management, providing societal benefits that are shared by the entire community.

4.7 Conclusions

In conclusion, it is not the planet that needs saving - the earth will continue to turn with or without us - it is we humans who need saving from ourselves. Without a new approach to conservation, the tragedy of the commons awaits us. As previous research in the field of behavioral economics asserts, economic incentives alone are not enough to ensure success of environmental protection projects. Projects must be rooted in the three pillars of sustainability: environmental protection, economic viability and social acceptability. LMDCE is an approach that departs from neoliberal conservation and the rational actor model and incorporates all three aspects of sustainability. LMDCE is particularly suited to environmentally focused projects. The case study conducted in Uganda on converting post-consumer waste plastic into an economically viable fuel oil illustrates how the LMDCE approach can be successfully deployed in an infrastructure limited region. The results of the case study therefore demonstrate a local homemaker converting waste plastic to fuel oil in rural setting utilizing an AT based non-automated, low-cost technology. In return, perception of waste plastic is likely to be changed from that of simply waste accumulating on the side of the street to something valuable that should be picked up and repurposed via LMDCE, benefiting the environment, the local community and the entrepreneur socially and economically.

4.8 Acknowledgments

The contributions of Noble Banadda, Professor and Chair of Agricultural and Biosystems Engineering and Mr. Ronald Kizza, graduate student at Makerere University are gratefully acknowledged. The resources provided at Makerere University Agricultural Research Institute in Kabanyolo (MAURIK) for testing the waste plastic to fuel oil technology are also gratefully acknowledged. Funding for the Kampala case study was provided by the Rotary Club of Paducah, Kentucky and the technology was disseminated through the assistance of Rotary Club of Kampala, Uganda.

CHAPTER 5. ESTIMATION OF WASTE PLASTIC GENERATION IN DEVELOPING CITIES UTILIZING GEOGRAPHICAL ANALYSIS

5.1 Introduction

In 2016, an estimated 174 million metric tons of waste was generated in Sub-Saharan Africa by a population of approximately 1 billion people (Kaza *et al.*, 2018). As the region continues to experience rapid population growth and modernization, waste generation is projected to increase to approximately 700 million metric tons annually by 2050 (Kaza *et al.*, 2018). Waste collection in rural areas, slums, and lower-income neighborhoods of urban cities is a significant challenge in Sub-Saharan African countries due to infrastructure constraints. The lack of proper waste disposal containers and waste management education for households, reduced access to narrow streets for door-to-door waste pickup by local municipalities, and haphazard dumping has led to 70% of the waste being openly dumped (Ayeleru *et al.*, 2020).

However, waste collection practices are slowly improving in Sub-Saharan Africa in pursuit of sustainable development, where landfilling and recycling practices are beginning to become more prevalent (Kaza *et al.*, 2018). Through the investment of industry and an informal, decentralized, network of waste pickers, recycling of valuable materials such as plastics, glass, and metals is increasing. Yet, in order to determine the economic, environmental, and social benefits of recycling practices and decentralized solutions used for optimizing waste collection and disposal, region-specific waste generation data is needed. For instance, per capita waste generation varies from approximately 0.11 kg/day to 1.57 kg/day in developing countries of Sub-Saharan Africa based on the development of the region and the demographics of the population (Kaza *et* *al.*, 2018). In addition, local municipalities lack the capital resources needed to measure waste generation at specific pickup points throughout their regions of operation. In most cases, the amount of waste collected from a pickup route is only measured once the pickup vehicle arrives at the dumpsite (Komakech, *et al.*, 2014, Kinobe, *et al.*, 2015) reducing the clarity of how much waste is generated amongst business sectors and income groups.

Therefore, this research presents a model that correlates population demographics (particularly income level) and geographical data of a region to estimate waste generation at a ~100 m resolution. In addition to municipal solid waste, corresponding waste plastic generation per capita is also estimated. This model was developed utilizing the capital city of Kampala, Uganda and is applicable for use in similar urbanized cities within Sub-Saharan Africa. The model serves as a screening tool for local municipalities, private investors, non-profit organizations, and researchers interested in understanding total waste generation within a subset portion of an urban city for implementing targeted waste management solutions. The results of the model were validated using Entebbe, Uganda as a case study.

5.2 Materials and Methods

5.2.1 Materials

5.2.1.1 QGIS Geographical Information System

Quantum Geographical Information System (QGIS) is a free, open-sourced geographical information system (GIS) software (QGIS 2021a). An official project of the Open Source Geospatial Foundation, QGIS operates under the General Public License and allows users to "*create, edit, visualize, analyze and publish geospatial information*" (QGIS 2021b). For this research application, QGIS version 3.8 Zanzibar was used (QGIS 2019).

5.2.1.2 OpenStreetMap

OpenStreetMap is a free, open license world map operated by the OpenStreetMap Foundation. It is created by a global community of mappers that contribute to, maintain, and validate regional infrastructure data (OpenStreetMap, 2021). An OpenStreetMap extension was added to QGIS to analyze the regional, geospatial data of Kampala, Uganda.

For the purposes of this research, free, widely available geographical data analysis tools were utilized to allow future implementation of the model in additional developing regions.

5.2.1.3 Kampala, Uganda

Waste generation and population data for Kampala, Uganda were used to develop and test the model. Kampala is the capital city of Uganda, located in the central region of the country on the shores of Lake Victoria. It is divided into five residential divisions namely: Central, Kawempe, Makindye, Nakawa, and Rubaga (also known as Lubaga). These divisions are further divided into 96 parishes, covering a total land area of 169 km^2 (Kampala Capital City Authority [KCCA], 2019). The city is a national center for administration, commerce, finance, education, services, culture, sport, and tourism (KCCA 2019).

The residential, commercial, and industrial waste generated within the city is collected by KCCA and private waste collection companies. KCCA offers free waste pickup within the city to residential sectors and markets. Private companies generally service affluent neighborhoods and businesses at a fixed rate. Waste collected from the city is transported to the Kiteezi landfill, which is operated and maintained by KCCA (Komakech, 2014, Kinobe, 2015). The overall waste collection efficiency for the city of Kampala is 64% (Aryampa *et al.*, 2019).

The waste generation data for Kampala was obtained from KCCA for the year 2017 as published by Aryampa *et al.*, 2019. The reported data states that KCCA collected 263,126 metric tons of municipal waste throughout the five divisions of the city, while private waste collection companies collected 217,956 metric tons for a total of 481,081 metric tons (Aryampa *et al.*, 2019). Although KCCA details the amount of waste generated at the divisional level, waste disposed at Kiteezi landfill by private companies is generated from all divisions within the city and is not segregated at the landfill [Komakech, 2014]. Hence, waste generated from KCCA and private companies was combined as a single date point for the purposes of this study.

The percentage of waste collected from low-income residential, upscale residential, markets, and commercial areas was estimated to be 62%, 18%, 9%, and 11%, respectively for the entire city of Kampala by Kinobe *et al.*, 2015. The total percentage of plastics (hard and soft) in the municipal solid waste varied in literature from 3.72% to 11.8% at the Kiteezi landfill between 2006-2012 (Katusiimeh, 2012, Komakech, 2014, Kinobe, 2015). As a result, KCCA provided plastic composition of 7.8% was utilized for this study (Serukka, 2017). This estimate more closely aligns with World Bank data for Sub-Saharan Africa, which determined a plastic composition of 8.6% in 2016 (Kaza *et al.*, 2018).

The residential population data for Kampala's divisions and parishes was obtained from Uganda Bureau of Statistics' (UBOS) country-wide census in 2014 (UBOS 2019, KCCA 2019). UBOS also provided population projections for 2015-2018 at the divisional level in Kampala (UBOS, 2019) The population projections at the parish level were linearly extrapolated from 2014 to 2017 utilizing UBOS divisional data. This translated to a residential population increase from 1,507,080 in 2014 to 1,590,100 in 2017. This account does not reflect the daytime population of the city, which doubles as citizens from neighboring regions migrate for employment, education, and entertainment (Gollin & Haas, 2016). However, since UBOS provided residential population projection for 2017, this data was correlated to the latest waste collection data provided by KCCA for 2017.

Lastly, the administrative divisional boundaries and parish boundaries for Kampala were provided by KCCA in the form of GIS shapefiles for direct use in QGIS.

5.2.2 Methodology

The methodology for this model assumes that that an increased building density correlates to an increased residential density, and the size of a residential building is an indication of household income level. For instance, highly crowded small buildings in the outskirts of city centers signal slums, whereas large, fenced-in buildings with in-ground swimming pools in secluded neighborhoods indicate affluent communities, as depicted in Figure 5.1. Commercial and industrial sectors are classified based on a high density of businesses and the size of respective facilities. Hence, if the number and size of buildings could be determined for a given region, classification could be made as to whether the buildings are within a slum, lower-income, middle-income, upper-income, commercial, or an industrial sector. Multiplying the number of buildings in each classification by the average household size provides an estimation of population density. Here, the model further assumes that individuals employed in the commercial and industrial sectors generate waste similar to residents of a household. Lastly, dividing the total waste generation of a region by the population density, provides estimated waste generation and waste plastic generation per capita. This approach was applied to the city of Kampala at a 100 m resolution to correlate geographical data to waste generation.

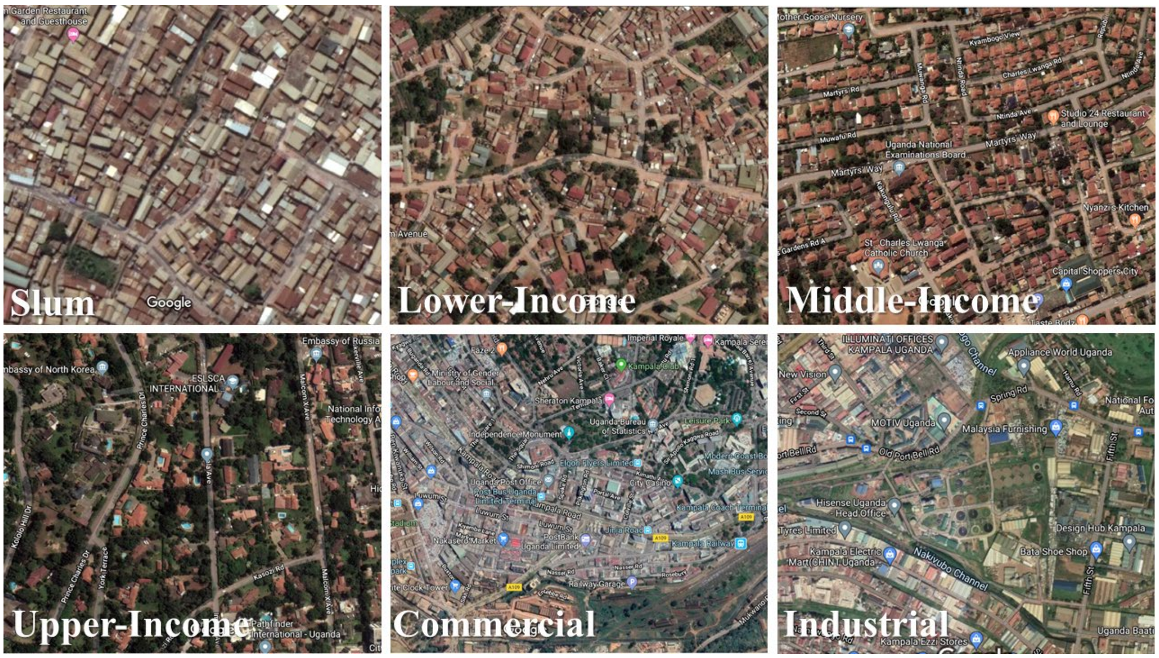

Figure 5.1. Building classification according to income level and business sectors. Image courtesy of Google Maps obtained 2019.

5.2.2.1 Determining the Number and Size of Buildings

The OpenStreetMap extension within QGIS enables viewing the buildings on a map as polygons. These polygons could further be counted using the *OSM (OpenStreetMap) Downloader* tool within QGIS, which downloads OpenStreetMap data into a QGIS vector file. Once downloaded, each polygon is assigned a unique numerical identifier, and the sum of the polygons is equivalent to the total number of buildings and geographical features present within the region. Since the application of this research focused on counting buildings, non-waste generating features such as grasslands and bodies of water were excluded from the data analysis.

Utilizing the QGIS *Assign Geometry* tool, the area and perimeter of each polygon in meters was calculated via an ellipsoidal projection of the data contained within the vector file. This procedure was repeated for each of the 96 parishes of Kampala at a resolution of 100 m to determine the size of each building. Note, since QGIS relies on a top-view of each building, the area of the building is in reference to only length and width of each building; the height of the building is not considered.

5.2.2.2 Classifying Buildings according to Building Size

To determine the average range of building sizes within each classification category, 125 random 100 m x 100 m grids within Kampala were analyzed. These grids were selected using the Random Select in Extent tool present within QGIS. Each grid was assigned a predetermined classification according to the geographical representation in Figure 5.1, and by following the above-mentioned steps, the size (area) of each building within that grid was calculated. Compiling the data for the 125 grids, 95% confidence intervals were calculated for the building classifications: slums, lower-income, middle-income, upper-income, commercial, and industrial. The calculated upper and lower 95% confidence intervals for building classifications are presented in Figure 5.2. Although not depicted in Figure 5.2, the building size range for the industrial sector was determined to be between 929.18 m and 1738.79 m^2.

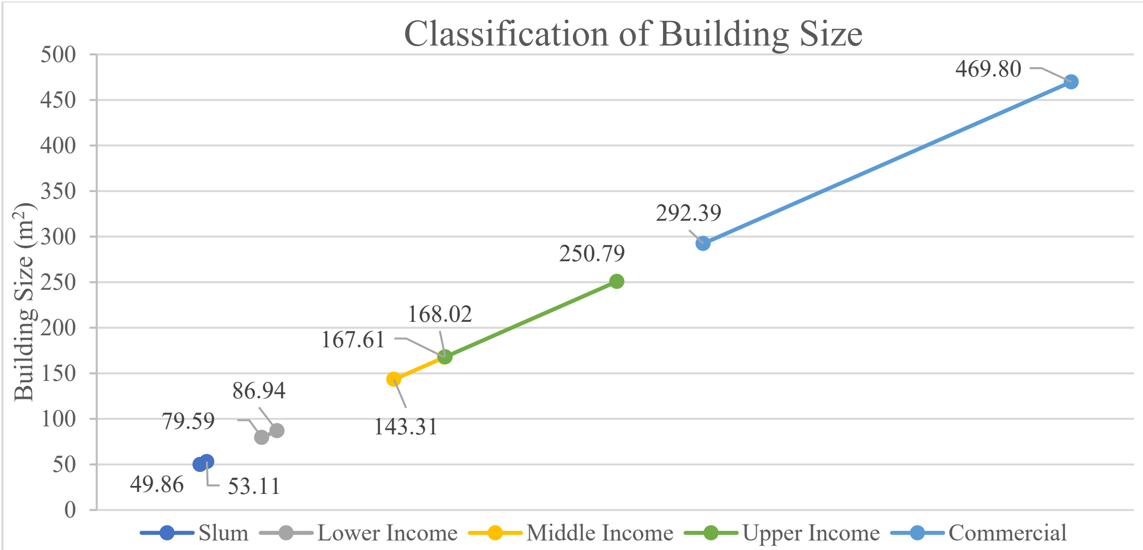

Figure 5.2. Building size ranges per 95% confidence interval of building areas in each classification

5.2.2.3 Correlating Building Classifications and Population

The buildings within each parish were classified according to the building ranges identified in the above section. This translated the total number of polygons into total number of buildings present within each classification in each parish of Kampala. The fraction of buildings in each classification were then calculated and multiplied by the total population of the parish. This yielded the number of people residing within in each building classification in each parish. The number of buildings in each classification were plotted against the calculated number of people residing within each classification for the 96 parishes of Kampala, providing a set of equations that correlated the number of buildings to population per building classification (Figure 5.3). Outliers within the dataset were not removed as they represented actual parishes within the city that may be either more or less densely crowded based on the geography, scale of development, and use of the buildings.

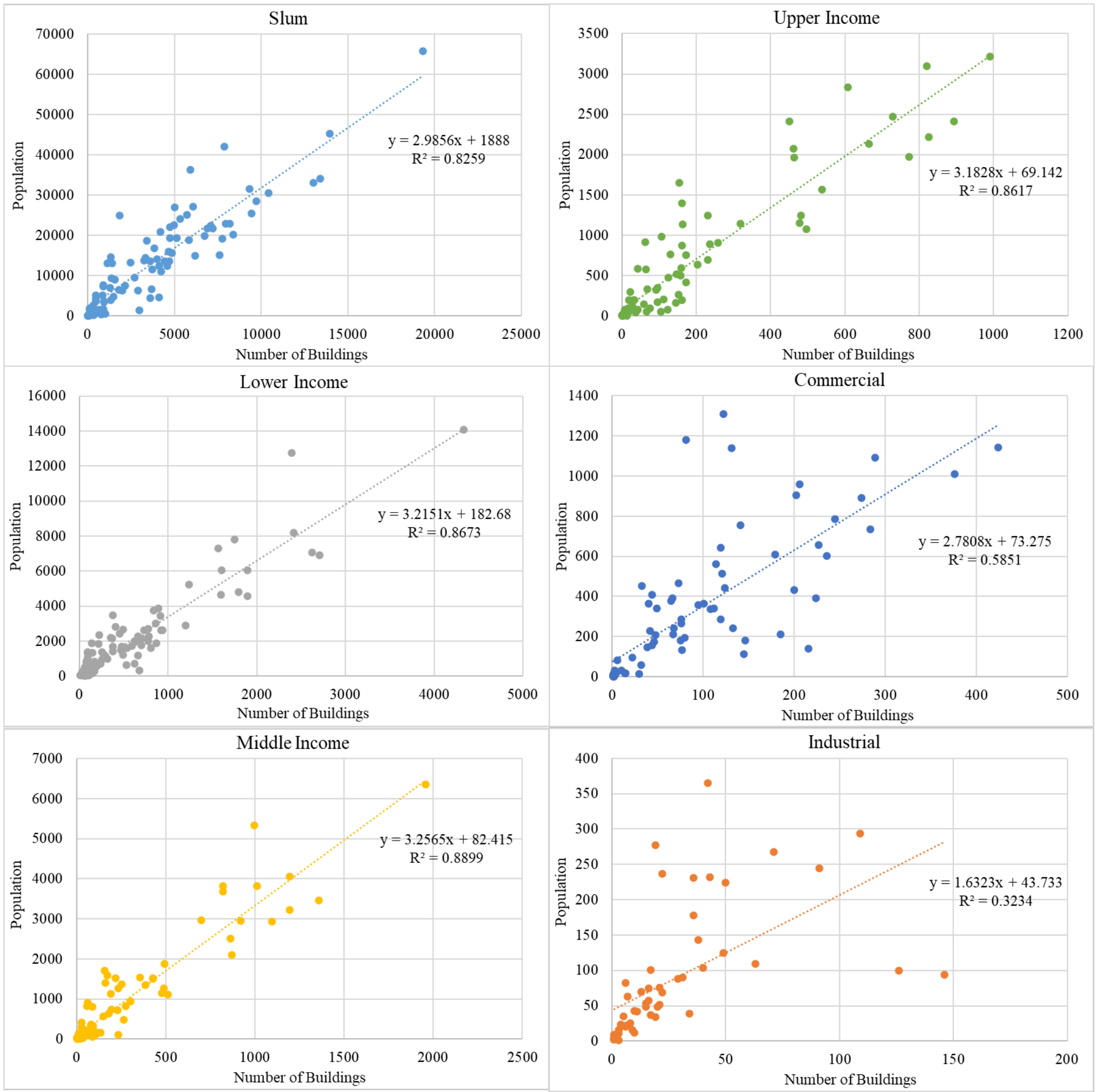

Figure 5.3. Model equations for estimating population from building size within each building classification

5.2.2.4 Estimating Waste and Waste Plastic Generation

Because the availability of waste generation data was limited to the city as a whole and not its individual parishes, similar to that available for population, model equations for plastic generation per building classification could not be easily developed without a high level of uncertainty. In fact, in this case, literature reported that the high population density of Kampala contributes to a majority of the waste generation within the city (Aryampa, *et al.*, 2019, Kaza, *et al.*, 2-18, Kinobe *et al.*, 2015, Serukka, 2017). Therefore, the literature reported waste generation percentages by Kinobe *et al.*, 2015 were employed, where 62% of the waste generation was allocated to slums and lower-income neighborhoods, 18% to middle-income and upper-income neighborhoods, and 20% commercial and industrial sectors. Although, Kinobe *et al.*, 2015 indicate that 11% is generated from businesses and 9% from markets, these two categories are compiled into commercial and industrial sectors for this study as further clarity on type of businesses is not provided.

After allocation of total waste generation into the generalized income and commercial/industrial categories, the amount of waste was divided by the total number of buildings within each category, i.e., 62% of total waste generated in Kampala was divided by the total number of buildings classified as slums and lower-income in Kampala. Further dividing the annual waste generation by the number of days in a year, waste generation per capita per day for slums/lower-income, middle/upper-income, and commercial/industrial sectors was calculated. Waste generation per capita was finally multiplied by a plastic composition of 7.8% for Kampala to obtain per capita waste plastic generation per day.

5.3 Model Limitations

Model limitations primarily involved the precision of data and tools used to calculate the geographical analysis model. First, the 2019-2020 version of OpenStreetMap was used for determining the total number of buildings within Kampala. As a result, the QGIS model is likely to include an increased number of buildings than those present in the base year 2017, reflecting the development within the city between 2017 and 2019. In occasions when high-quality base imagery is not available, as is in the case of slums, OpenStreetMap also identifies objects as polygons. These objects were deleted from the building analysis when easily identifiable, but due to the low-quality resolution of the base maps, objects functioned as noise within the building-counting model. In like terms, in areas of new construction, OpenStreetMap may not have been updated in time to identify recently erected buildings as a polygon. In such cases, OpenStreetMap misses a very small portion of buildings.

Second, the UBOS 2014 and 2017 population projections only represent the residential population of the city. Since the population of the city doubles during the day and aggregates in the business-centered regions of the city, the impact of migrating population in the commercial and industrial sectors is not accurately reflected. Instead, the amount of waste generated by the migrating population is averaged throughout both the residential and commercial/industrial sectors.

Third, the lack of waste generation data at the parish level for 2017 reduces the efficiency of the model in predicting the impact of population demographics in waste generation. Although this model was simplified from four to two income categories, waste generation generally increases with income level (Kaza *et al.*, 2018). Lastly, the waste generation data for all sectors within the city is primarily classified as municipal solid waste. Special wastes such as industrial, hazardous, and electronic waste are not distinguished in this model due to the lack of waste characterization data for these categories at Kiteezi landfill.

5.4 Results & Discussion

Using the equations developed for correlating Building Classifications and Population, the population of each of the five divisions of Kampala was calculated. The calculated 2017 population varied 4.59% to 27.79% from the UBOS projected 2017 population for the five divisions. Furthermore, the overall population of Kampala was calculated to be 1,380,595 which is 13.18% lower than the UBOS project 2017 population of 1,590,100. The difference in the calculated and UBOS projected population can be attributed to the R^2 regression analysis values of the equations, which vary from 0.32 to 0.89. The regression analysis suggests that the model is not a best fit for industrial areas ($R^2 = 0.32$) and commercial sectors ($R^2 = 0.56$). The probable cause for these trends is due to the high variability in the size and type of waste generated by industrial and commercial sectors. In like terms, the model predicted the lowest R^2 (0.83) for slums in the residential sector. This can be attributed to the low-resolution of base map for slums, which reduce the accuracy in identifying individual buildings in densely crowded slums.

Dividing the calculated population for slums/lower-income, middle-income/upper-income, and commercial/industrial sectors by the waste allocated to those sectors, the per capita waste generation is 0.66 kg/day, 1.94 kg/day, and 12.12 kg/day, respectively; and the waste plastic generation is 0.05 kg/day, 0.15 kg/day, and 0.95 kg/day, respectively. These predictions are higher than the average and maximum waste generation per capita for Sub-Saharan Africa, which were reported to be 0.46 kg/day and 1.57 kg/day, respectively (Kaza *et al.*, 2018). The global average for per capita industrial waste is 12.73 kg/day but varies between 0.36 kg/day for low-middle income countries and 5.72 kg/day for middle income countries (Kaza *et al.*, 2018).

However, when doubling the UBOS 2017 projected population to account for the daytime population of Kampala, and by considering the 36% of uncollected waste generation within the city, the total waste generation of Kampala was estimated to be

654,271.38 metric tons/annum. Allocating this amount by the population estimated for each income level and business sector, the results presented in Table 5.1 were obtained. The resulting estimates more closely align with the reported per capita waste generation for Kampala at 0.46 kg/day (Aryampa *et al.*, 2019).

Table 5.1. Model estimations of waste and waste plastic generation per capita/day in Kampala, Uganda

Classification	Waste Generation/ Classification (%)	Total Waste Allocation (tons/year)	Waste Generation (kg/capita/day)	Plastic Generation (kg/capita/day)
Commercial/Industrial	0.2	130,854	8.24	0.64
Upper/Middle	0.18	117,769	1.32	0.10
Lower/Slum	0.62	405,648	0.45	0.04

This model can be further improved and updated with most recent population and waste generation data at both the divisional and parish levels for Kampala to reflect current trends in income level and waste generation. Nonetheless, via the use of free, open-sourced geographical analysis tools and published population and waste generation data, the model can be similarly applied to additional Sub-Saharan urban cities to estimate waste generation for region-specific applications. This model reduces the need for in person collection and measurement of waste generation in areas with infrastructure limitations, providing a basic estimation of waste and waste plastic generation at the household level.

5.5 Model Implementation in Entebbe, Uganda: A Case Study

Entebbe is a small urban city located on a peninsula into Lake Victoria, 37 km south of Kampala. The city has two divisions, four wards, and 24 villages/cells, covering a total land area of 56.2 km^2 (Entebbe Municipal Council, 2016). The city is home to Uganda's international airport, Uganda Wildlife Education Center, and is the official residence of

Uganda's President (Entebbe Municipal Council, 2016). Due to the international airport and the proximity of the city to beaches, the city features several hotels and shopping centers. The UBOS population of Entebbe was 69,958 for 2014 and the project population was 84,400 for 2017 (UBOS, 2019). Like Kampala, the daytime population of Entebbe doubles during the day. The estimated waste generation within the city was 150-200 metric tons/day in 2014-2015, with approximately 31% of the waste generation allocated to households, 46% to the international airport, and 23% to hotels and beaches (Entebbe Municipal Council, 2016). Waste generation in Entebbe is anticipated to increase to 250-300 metric tons/day by 2021 (Entebbe Municipal Council, 2016).

Via the implementation of the geographical analysis model developed for Kampala, the total number and size of buildings within Entebbe were determined using QGIS and OpenStreetMap. The base year of 2017 was chosen for this case study to reflect the 2017 data inputs used for Kampala. The buildings were classified according to their sizes, and the population of each classification was calculated using the equations provided in Figure 5.3. The model predicted that 59% of the population resided in slums, 18% resided in lower-income neighborhoods, 10% resided in middle-income neighborhoods, 8% in upper-income neighborhoods, 4% in the commercial sector, and 1% in the industrial sector. The resulting calculated population estimate for 2017 was 85,011, which is 0.72% higher than the 2017 UBOS projected population.

In multiplying the calculated population projections by the waste generation amounts determined for Kampala (in kg/capita/day for the UBOS 2017 residential population), waste generation for the residential population of Entebbe was estimated to be 97.12 metric tons/day for slums/lower-income neighborhoods, 31.24 metric tons/day for middle-income/upper-income neighborhoods, and 39.38 metric tons/day for commercial/industrial sectors. This is equivalent to a total of 7.58 metric tons/day of waste plastic for slums/lower-income neighborhoods, 2.44 metric tons/day of waste plastic for middle-income/upper-income neighborhoods, and 3.07 metric tons/day of plastic for commercial/industrial sectors. The total waste generation for Entebbe was determined by the model to be 167.74 metric tons/day for 2017. This is 13.02% less than the linearly projected, low estimate of 192.85 metric tons/day for the city (projecting 150 metric tons in 2014-2015 to 250 metric tons in 2021) (Entebbe Municipal Council, 2016).

The 13% difference in waste generation in Entebbe can be attributed to the higher influence of the commercial sector within the city, especially in regard to the international airport and tourism. In contrast to Kampala, which receives merely 20% of its waste from the commercial/industrial sectors, Entebbe receives approximately 70% of its waste from the commercial sector. For this reason, the impact of household waste generation in Entebbe is minimized, leading to a 10% decrease in the model's prediction of estimated waste generation.

5.6 Conclusions

The methodology presented in this research application allows local municipalities, private investors, non-profit organizations, and researchers to initially screen the amount of waste generated in a Sub-Saharan African region at an in-depth resolution of ~100m. The model serves to assist in making informed decisions on how to improve waste collection, disposal, and recycling in urban cities of Sub-Saharan Africa. By correlating geographical analysis with population demographics and waste generation data, the model can be further applied to study the economic, environmental, and social impacts of waste management solutions at the regional level.

CHAPTER 6. TOTAL GENERATION AND COMBUSTION EMISSIONS OF PLASTIC DERIVED FUELS: A TRASH TO TANK APPROACH

As Published in *Environmental Progress & Sustainable Energy*, 39(5), 2020

Chandni Joshi, Jeffrey Seay

6.1 Abstract

Trash to Tank (3T) is a concept based on the conversion of waste plastic trash into a liquid fuel, suitable for use in any diesel or kerosene fuel application. This contribution compares total carbon dioxide (CO_2) emissions from generation and combustion of petroleum derived diesel fuel with plastic derived fuel oil. Generation emissions for diesel are obtained from literature values for well-to-tank (WTT) CO_2 emissions, while 3T CO_2 emissions for plastic are calculated based on a locally managed decentralized circular economy (LMDCE) for waste plastic management. Specifically, this analysis applies a novel approach based on local, small-scale decomposition of waste plastic to fuel in an appropriate technology setting, with consumption of the fuel locally in rural, developing communities to completely remove waste plastic from accumulating in the global ecosystem. Results from 3T CO_2 emissions for both the generation and uses of the fuel oil are reported based on a combination of literature review, laboratory experiments and theoretical calculations. Four plastic derived fuels – low-density polyethylene, high-density polyethylene, polypropylene and polystyrene – were individually compared with petroleum derived diesel fuel to depict a positive reduction in total CO_2 emissions. Hence, this contribution will demonstrate that the 3T approach is a sustainable solution to waste plastic management in developing regions, where mismanaged waste plastic is an ongoing environmental and social challenge. Potential benefits to the global environment,

particularly in developing regions, from the use of plastic derived fuels as replacements for petroleum based is additionally discussed in this study.

6.2 Introduction

Energy consumption is directly correlated with the economic development of a nation as measured by the gross domestic product (GDP) (Dritsaki & Dritsaki, 2014). Hence, as world economies develop, a peak in energy demand is forecasted. This is especially true for the transportation energy sector, where approximately 159 quadrillion kilojoules (kJ) of energy consumption are predicted for the year 2040, a 46 quadrillion kJ spike from 2015 (Energy Information Administration [EIA], 2017). Consumption of diesel, the primary transportation fuel for medium- and heavy-duty vehicles in OECD (Organisation for Economic Co-operation and Development) and non-OECD countries is also anticipated to grow from approximately 87 quadrillion kJ, surpassing 105 quadrillion kJ by 2040 (EIA, 2017). Furthermore, with increased energy usage, greenhouse gas (GHG) emissions are likely to increase, unless additional regulations for controlling the emissions are enforced (Dritsaki & Dritsaki, 2014). For instance, diesel emissions, consisting of carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NOx), sulfur oxides (SOx), polycyclic aromatic hydrocarbons, aldehydes, ketones, phenols, ammonia, carbonyl compounds, volatile organic compounds, and metals such as aluminum, calcium, iron, magnesium, nickel, silicon, sodium and vanadium are likely to build up in the atmosphere without the addition of effective emissions management technologies (Maricq, 2007, Morgan, *et al.*, 1997, Popovicheva, *et al.*, 2015, Sarvi, *et al.*, 2011, Wierzbicka, *et al.*, 2014, Wu, *et al.*, 2017, Zielinska, 2005).

Regions currently motorizing at unprecedented rates are often lacking or have minimal availability of existing effective transportation emissions reduction technologies, thus challenging sustainable development. Another contributing cause is the use of cheaper, second-hand vehicles imported to developing countries after years of use. This practice is termed as "exporting pollution" or "environmental dumping" as poorer economies have become a "pollution haven" for old cars with reduced fuel efficiencies and safety standards, higher GHG and particulate matter emissions, leading to respiratory concerns and smog (Edwards, 2017, Khan, 2013, Hutchinson, 2011, Davis & Khan, 2011).

One potential method for reducing the high rate of GHG emissions and particulate matter from diesel or petroleum derived fuels in developing countries is the use of fuel derived from waste plastic. This approach of trash-to-tank, or 3T, solves two problems simultaneously in developing economies – reduction of heavy metals from fuel combustion due to the hydrocarbon polymer chemistry of plastics and reduction in accumulation of waste plastic in areas with minimal waste management infrastructure. This 3T approach alleviates the pressure placed on regulated landfills and recycling facilities in urbanized areas, while providing rural, resource-constrained communities suffering from lack of municipal solid waste (MSW) infrastructure to manage their waste locally. 3T also helps to eliminate the practice of dumping or incinerating waste plastic in open plots of land in rural regions, which has led to sanitation, human health and environmental concerns (Komakech, 2014, Patni, *et al.*, 2013, Rochman, *et al.*, 2013). Because the waste plastic is converted to fuel and wholly consumed, 3T completely eliminates the accumulation of plastic in the ecosystem, which current recycling practices have failed to do with remanufacturing of recycled plastics. Thus, in current approaches, accumulation of waste plastic is only delayed. Eventual migration of unregulated waste plastic to local waterways or discarding of the plastic in the ocean due to lack of landfill space is also reduced via 3T, decreasing endangerment of marine and bird species (Geyer, 2017, Li, *et al.*, 2016, Wilcox, *et al.*, 2015).

Therefore, the 3T approach encourages waste plastic use in underdeveloped regions by giving waste plastic a value. This promotes collection and management of waste plastic instead of discarding it as the material holds an economic value. In return, entrepreneurial opportunities are generated for sorting, collecting and processing the waste plastic, providing a source of reliable, renewable energy for the community through its conversion to fuel oil. Plastic can be converted to fuel oil in rural and urban regions via the method of thermal decomposition, or pyrolysis. Waste plastic polymers, particularly low-density polyethylene (LDPE), high-density polyethylene (HDPE), polypropylene (PP) and polystyrene (PS) can be converted into fuel oil through this process (Al Salem, *et al.*, 2009, DeNeve, *et al.*, 2017, Joshi & Seay, 2016, Kumar & Singh, 2011, Miskolczi, *et al.*, 2004, Panda, *et al.*, 2010, Patil, *et al.*, 2017, Santaweesuk & Janyalertadun, 2017, Sarker, 2011, Sarker, *et al.*, 2012, Wong, *et al.*, 2015). An example of such a simple technology has been developed by the University of Kentucky Appropriate Technology and Sustainability (UKATS) research for thermal decomposition of waste plastic in rural regions, known as the UKATS Processor, which is non-automated, low-cost and easily deployable, encouraging waste plastic management in small-scale solutions around the world (DeNeve, *et al.*, 2017, Joshi & Seay, 2016, Joshi, *et al.*, 2020). The fuel produced is similar in characteristics to petroleum-based fuels such as diesel fuel and kerosene. As a result, it can be directly used in diesel generators, kerosene cookstoves, lamps and motor vehicle applications (Joshi & Seay, 2016). Since the plastic is converted to fuel oil locally at an individual or community scale, and the fuel has a ready market within the community, a locally managed, decentralized circular economy for waste plastic is established. This practice empowers rural communities lacking capital, resources, technical education and waste management infrastructure to repurpose the trash into valuable products, decreasing MSW accumulation.

The novelty of this contribution lies in considering the environmental impact of plastic derived fuel from a locally managed, decentralized circular economy, comparing it with the current standard, petroleum diesel. Previous studies have determined the emissions of plastic derived fuels obtained in a lab setting (Churkunti, 2015, Kalargaris *et al.*, 2018, Kalargaris *et al.*, 2017a, Kalargaris *et al.*, 2017b, Kumar & Sankaranarayanan, 2016, Mani, *et al.*, 2010, Rinaldinin, 2016). However, the environmental analysis of plastic derived fuels in rural, developing communities has not yet been performed. As a result, this contribution determines and analyzes the CO_2 emissions for generating and combusting the 3T fuels, comparing them alongside WTT diesel fuel emissions. This analysis is essential for promoting the use of plastic fuel oil in rural regions to decrease MSW accumulation and its negative environmental and health consequences (Komakech, *et al.*, 2014, Patni, *et al.*, 2013, Rochman, *et al.*, 2013, Geyer, *et al.*, 2017, Li, *et al.*, 2016, Wilcox, *et al.*, 2015).

6.3 Materials and Methods

Figure 6.1 illustrates the overall methodology employed for calculating total CO_2 emissions from generation and combustion of plastic fuel types as well as petroleum diesel. The reaction energy, lower-heating value (LHV) and higher-heating value (HHV) were initially utilized to calculate the total process energy requirement, as shown by

Equation 6.1. This was combined with literature reported CO_2 combustion factors and experimentally measured CO_2 emissions to calculate the equivalent amount of CO_2 generated by the pyrolysis process using three different energy sources, wood, propane gas and recycled fuel oil. These three energy sources were selected because they are all readily available in underdeveloped or developing regions.

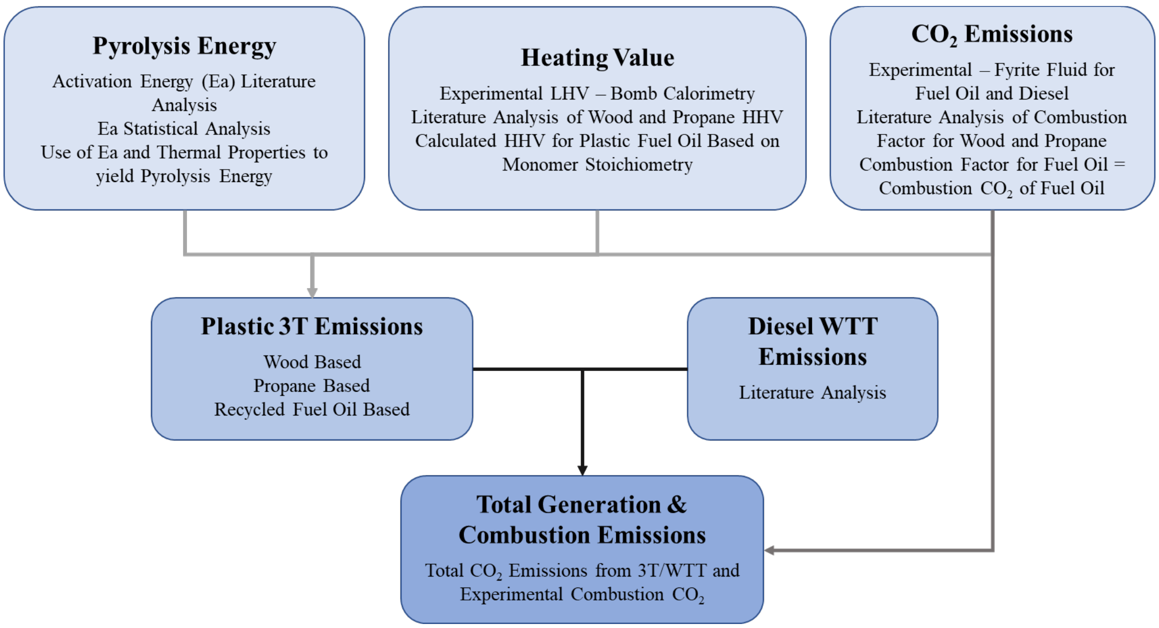

Figure 6.1. Methodology chart depicting the approach taken to calculate total generation and combustion emissions for plastic derived fuels and diesel

Next, 3T generation emissions for plastics were calculated according to Equations 6.2-6.3, which consider the amount of CO_2 released per process energy requirement by factoring in the CO_2 combustion factors of each pyrolysis energy source. Diesel generation emissions were collected from literature values for WTT emissions, which were reported to be 20.43 g CO_2/MJ fuel (Air Resources Board, 2009). Here, it is important to note that 3T transportation emissions are excluded due to the locally managed, decentralized circular economy approach in rural communities. Meaning, the cost and emissions generated by transportation of raw waste plastic feedstock to a centralized processing facility, similar to that present in petroleum derived diesel WTT considerations, is eliminated. Lastly, experimentally measured CO_2 combustion emissions of plastic fuels and diesel were added to generation emissions to obtain total generation and combustion emissions. The details of this methodology are discussed in the following sub-sections, beginning with the production of fuel oil from waste plastic.

$$Process\ Energy\ Requirement\ = \frac{Pyrolysis\ Reaction\ Energy}{HHV\ of\ Energy\ Source} \tag{6.1}$$

$$\begin{aligned} 3T\ CO_2\ Emissions\ Mass\ Basis \\ &= Pyrolysis\ Energy\ Source\ CO_2\ Factor \\ &\cdot Process\ Energy\ Requirement \end{aligned} \tag{6.2}$$

$$3T\ CO_2\ Emissions\ Energy\ Basis = \frac{Pyrolysis\ Energy\ Source\ C0_2\ Factor}{LHV\ of\ Fuel\ Oil\ Produced} \tag{6.3}$$

Where the units are:

Process Energy Requirement:	*kg Energy Source/kg Fuel Oil*
Pyrolysis Reaction Energy:	*MJ/kg Fuel Oil Produced*
HHV of Energy Source:	*MJ/kg Energy Source*
3T CO_2 Emissions Mass Basis:	*kg CO_2 Emitted/kg Fuel Oil*
Pyrolysis Energy Source CO_2 Factor:	*kg CO_2/kg Energy Source*
3T CO_2 Emissions Energy Basis:	*kg of CO_2 Emitted/MJ Fuel Oil*
LHV of Fuel Oil Produced:	*MJ/kg Fuel Oil*

6.3.1 Waste Plastic Pyrolysis

Fuel oil was produced from LDPE, HDPE, PP and PS plastic samples via slow pyrolysis at 450°C in a lab-scale apparatus using the methodology described by DeNeve, *et al.* (2017). An image of the four fuel oil samples studied along with the starting material is shown in Figure 6.2. The LDPE fuel oil was produced from shredded plastic shopping bags, HDPE fuel oil was produced from shredded plastic milk jugs, PP fuel oil was produced from virgin pellets from a hobby store and PS fuel oil was produced from shredded plastic cutlery.

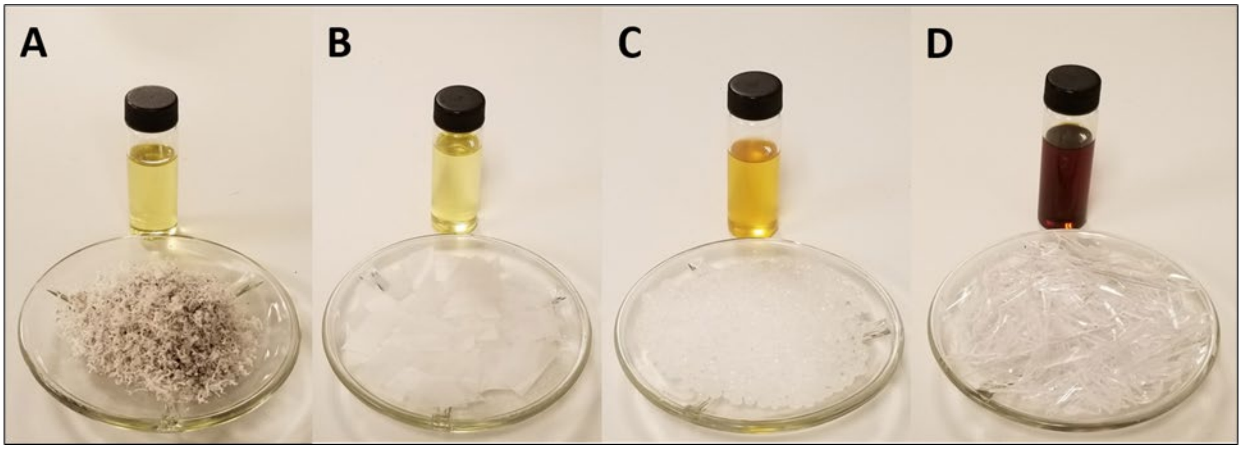

Figure 6.2. Fuel Oil samples and starting waste plastic material

A) LDPE fuel oil from shredded milk bags (obtained from research application in India), B) HDPE fuel oil from shredded milk jugs, C) PP fuel oil from hobby pellets and D) PS fuel oil from crushed test tubes.

6.3.2 Reaction Energy Determination

The total energy required for the thermal decomposition process includes the activation energy (Ea) for the reaction itself as well as the sensible heat required to raise the temperature of the plastic to the melting point, the heat of fusion and the sensible heat required to raise the temperature of the plastic to the reaction temperature. This process is described in Equation 6.4, below. Table 6.1 reports the compiled literature reported Ea values in kJ/mol (Sorum, *et al.*, 2001, Westerhout, *et al.*, 1997, Ceamanos, *et al.*, 2002, Yang, *et al.*, 2001, Peterson, *et al.*, 2001, Aboulkas & Bouadili, 2010, Silvarrey & Phan, 2016, Encinar & Gonzalez, 2008, Wu, *et al.*, 1993, Biswas, *et al.*, 2013, Saha & Ghoshal, 2007, Kim, *et al.*, 2008, Tuffi, *et al.*, 2018) and the kinetic methods utilized by the respective researchers. When given, the statistical uncertainty provided in the previous studies was included to capture the spread of the data. Results of this analysis are reported in Table 6.1.

$$\Delta H_{Process} = Cp_{solid} \cdot \Delta T_{solid} + \Delta H_F + Cp_{liquid} \cdot \Delta T_{liquid} + E_a \qquad (6.4)$$

Where:

$\Delta H_{Process}$ = *enthalpy required for thermal decomposition*

Cp_{solid} = *solid average heat capacity*

Cp_{liqid} = *liquid average heat capacity*

ΔT_{solid} = *Temperature change from ambient conditions to the melting point*

ΔT_{liquid} = *Temperature change from the melting point to the reaction temperature*

ΔH_F = *Enthalpy of Fusion*

Ea = Activation Energy

To check for outliers in the data, statistical analysis was performed using five-number summary (minimum, quartile 1-3 and maximum), inner quartile range, and upper and lower fence calculations. If data values exceeded upper and lower fence limitations, they were identified as outliers, and highlighted in blue as seen in Table 6.1. A box and whiskers plot representation of the gathered dataset and outliers is also shown in Figure 6.3. Next, excluding the outliers, a new 95% confidence interval was calculated for the dataset. This was lastly converted from mol basis (kJ/mol) to mass basis (kJ/kg) using the molecular weight of each polymer repeat unit (Crow, 2015a, Crow 2015b, Crow, 2015c). These results are represented in Table 6.2.

Table 6.1. Literature reported Ea (kJ/mol) for pyrolysis reaction of pure plastic polymers after year 1990.

Ea (kJ/mol)						
LDPE	HDPE	PP	PS	**Refernce**	Method	Notes
340.8	445.1	336.7	311.5	32	Model Fitting	
241	220	244	204	33	Model Fitting First Order	Two samples of LDPE & PP were used
201		188				
	248.7			34	Ozawa-Flynn-Wall	
222	240	126	176	35	Model Fitting DTG (differential thermogravimetry) Curve Fitting	
		150	200	36	Vyazovkin	PP range provided used as high and low values
		250				
221	247	188		37	Friedman	95% confidence interval range utilized
218	252	182				
224	242	194				
215	238	179			Ozawa-Flynn-Wall	
207	227	171				
223	249	187				
218	243	183			Kissinger-Akahira-Sunose	
211	232	175				
225	254	191				
267.61	202.4	261.22	192.61	38	Kissinger-Akahira-Sunose	95% confidence interval range utilized
264.38	211.87	266.35	193.37			
270.84	192.93	256.09	191.85			
	375.59				Friedman	95% confidence interval range utilized
	415.28					
	335.9					
285.74		169.35	136.64	39	Model Fitting First Order	Isothermal case only
206.27	233.05	183.68	171.96	40	Friedman	Converted from kcal/mol to kJ/mol
	171			41	Kissinger-Akahira-Sunose	95% confidence interval range utilized
	223.1					
	118.9					
	175				Ozawa-Flynn-Wall	95% confidence interval range utilized
	125.27					
	224.73					
		120		42	Vyazovkin	
		168				
		130		43	Model Fitting Reduced-Time-Plot	Low-temperature reactions (678-693K)
		111				
		149				
		99				High-temperature reactions (723-738K)
		97.4				
		100.6				
		227	205	44	Kissinger-Akahira-Sunose	95% confidence interval range utilized
		225	202			
		229	208			

Outliers present in the dataset are shaded.

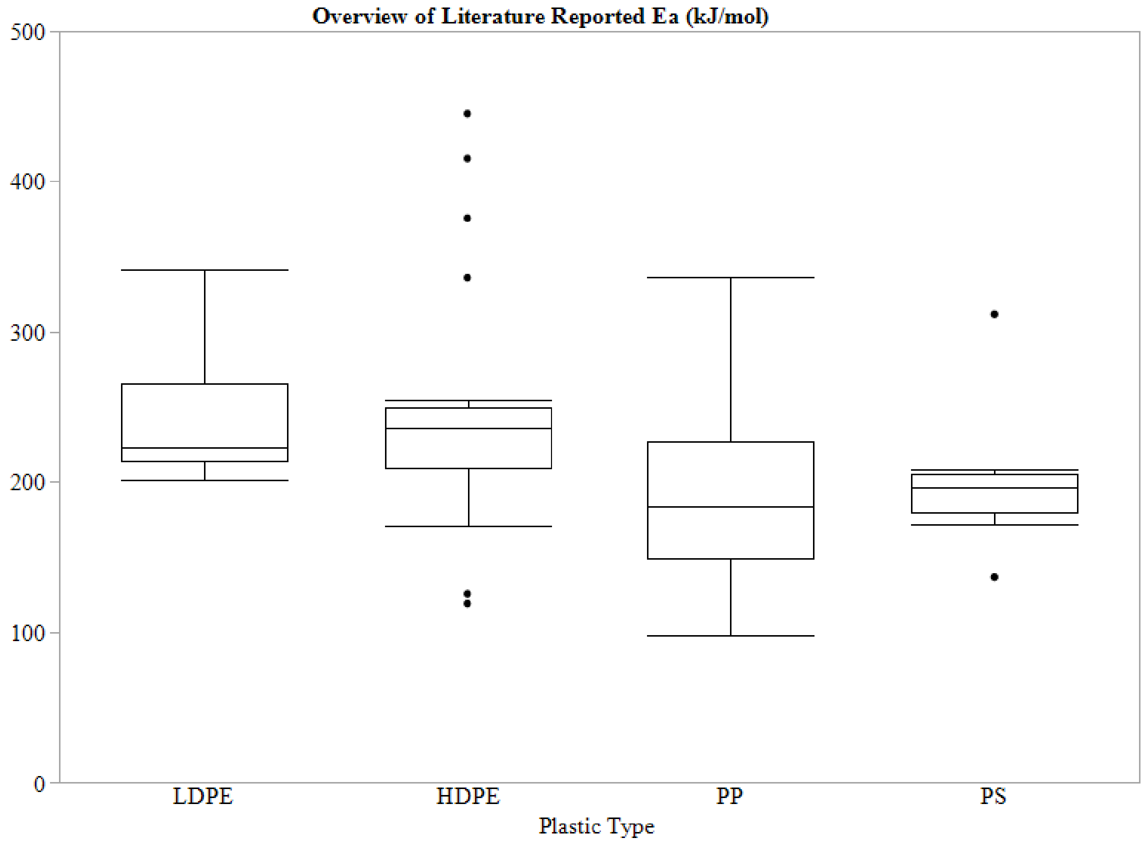

Figure 6.3. Box and Whiskers plot overview of literature reported Ea with outliers present

Table 6.2. 95% confidence interval for Ea dataset excluding outliers, presented on a mol basis and the corresponding pyrolysis energy in mass basis

	Plastic Type			
	LDPE	**HDPE**	**PP**	**PS**
Cp_{solid} (kJ/kg-K)[1]	1.65	1.65	1.64	1.21
Cp_{liquid} (kJ/kg-K)[2]	2.24	2.24	2.13	1.70
ΔT_{solid} (K)	116	116	154	217
ΔT_{liquid} (K)	309	309	271	208
T_{melt} (K)[1]	414	414	452	515
T_{rxn} (K)	723	723	723	723
ΔH_F (kJ/kg)[2,3]	146.52	146.52	206.75	80.36
Ea (kJ/mol)	236.76 +/- 16.62	226.34 +/- 10.75	185.08 +/- 19.86	194.48 +/- 7.54
Molecular Wt (g/mol)	28.05	28.05	42.08	104.15
Ea (kJ/kg)	8440.57 +/- 592.60	8069.12 +/- 383.34	4398.22 +/- 471.85	1867.30 +/- 72.38
Process Energy (kJ/kg)	9468.29 +/- 592.60	9097.29 +/- 383.34	5433.66 +/- 471.85	2563.15 +/- 72.38

[1]Polymer Science, 2019. [2]Wunderlich, 1990. [3]Bangs Laboratories, 2019.

6.3.3 Heating Value Determination

6.3.3.1 LHV

LHV experiments were conducted in a Parr Model 1108 Oxygen Combustion Bomb Calorimeter. The calorimeter was calibrated using a 99.9wt% methanol standard from Sigma-Aldrich. A sample of each fuel was loaded into the oxygen bomb and pressurized with bottled analytical grade oxygen to a pressure of 50 psig. The sample was then ignited, and the resulting temperature and pressure increase was noted. From this information, LHV was calculated for each plastic derived and petroleum derived fuel sample using Equation 6.5.

$$LHV = m_w Cp_C \Delta T \tag{6.5}$$

Where:

LHV = Lower Heating Value

m_w = *mass of water in the calorimeter*

Cp_C = *Heat capacity of the calorimeter*

ΔT = *Temperature change of the water in the calorimeter*

The results of this experiment are shown in Table 6.3. All plastics have a comparable LHV to diesel fuel, indicating that they are similar in calorific value, with LDPE outperforming diesel. Thus, the application of fuel oil in developing countries for meeting energy demands is justified.

Table 6.3. Experimentally determined LHV of fuel types

	Fuel Type				
	LDPE	HDPE	PP	PS	Diesel
LHV ($x10^3$ kJ/kg)	44.94	40.98	40.03	39.14	41.5
Standard Deviation	0.78	0.94	1.31	0.88	1.30

6.3.3.2 HHV

To estimate the total energy requirement presented in Equation 6.1, determination of HHV of the energy sources used to drive the pyrolysis process is necessary. HHV of the selected pyrolysis energy sources - wood and propane gas - was obtained from reported literature values. These values are 17.48 mmBTU/short ton for wood and wood residuals, and $2.52x10^{-3}$ mmBTU/scf for propane gas (U.S. Environmental Protection Agency [USEPA], 2018). These values were converted to MJ/kg basis using conversion factors. For propane gas, the ideal gas law and molecular weight (44.1 g/mol) were employed using standard temperature and pressure (0°C and 1 ATM) to determine the total number of moles for converting scf to mol basis and then to mass basis. The resulting HHV values were 20.32 MJ/kg and 47.52 MJ/kg for wood and propane gas, respectively.

Recycled fuel oil was the final energy source option considered for providing the required pyrolysis energy. The HHV of plastic fuel oils was calculated from experimental LHV utilizing Equation 6.6. The number of moles of water (H_2O) for Equation 6.6 were determined by assuming complete stoichiometric combustion of each plastic polymer repeat unit to CO_2 and H_2O, according to Equation 6.7. Because the composition of the pyrolysis fuel oil is a function of plastic type, process temperature, pressure, and duration of time spent in the reactor, the key assumption that the researchers followed here is that the polymer decomposes to shorter polymer chains, represented by a collection of monomers. Subsequently, the monomer units were identical for LDPE and HDPE. The calculated HHV (MJ/kg fuel oil) for the LDPE, HDPE, PP and PS are 49.82, 45.87, 47.35 and 48.91, respectively.

$$HHV_{Fuel\ Oil} = LHV_{Fuel\ Oil} + n_{H_2O} \cdot \Delta H_{vap-H_2O} \tag{6.6}$$

$$Polymer\ Repeat\ Unit + bO_2 \rightarrow cCO_2 + dH_2O \tag{6.7}$$

Where:

$HHV_{Fuel\ Oil}$ = *HHV of plastic fuel oil*

$LHV_{Fuel\ Oil}$ = *Experimentally determined LHV of plastic fuel oil*

n_{H_2O} = *number of moles of H_2O present from stoichiometry balance*

ΔH_{vap-H_2O} = *Enthalpy of vaporization of H_2O at ambient conditions, 2.4417 MJ/kg [56]*

Polymer Repeat Unit = Plastic monomer unit: C_2H_4 (LDPE, HDPE); C_3H_6 (PP); C_8H_8 (PS)

b, c, d = Stoichiometry coefficients

The results of this analysis are presented in Table 6.4 and compared with averaged literature reported measurements [39, 57-59]. Except PS, the reported data corresponds closely to the method utilized in this study.

Table 6.4. Calculated and literature reported HHV comparison

HHV (MJ/kg Fuel)				
Method	LDPE	HDPE	PP	PS
Calculated	49.8	45.9	47.4	48.9
Literature Analysis	47.0	46.4	47.0	41.9
% Difference	5.67	1.23	0.79	14.32

6.4 CO_2 Emissions

6.4.1 CO_2 Combustion Factors

The CO_2 emissions from the energy needed to drive the pyrolysis reaction using traditional sources were determined from literature values for reported CO_2 combustion factors (USEPA, 2018). For wood and propane gas, the respective values obtained were 1,640 kg CO_2/short ton and 0.1546 kg CO_2/scf (USEPA, 2018). As described previously in the HHV calculations, these values were converted to kg CO_2/kg energy source using conversion factors and ideal gas law. The resulting values were 1.81 kg CO_2/kg wood and 2.77 kg CO_2/kg propane gas. CO_2 combustion factors for recycled fuel oil were experimentally determined as discussed in the following section. Since the fuel oil is combusted to serve as a pyrolysis energy source and combusted for additional applications, experimentally measured CO_2 emissions are utilized in 3T generation and combustion emissions.

6.4.2 CO_2 Emissions Experiments

Experiments to measure CO_2 emissions from the combustion of the fuel oil samples and diesel were conducted in the same a Parr Model 1108 Oxygen Combustion Bomb fitted with analog pressure and digital temperature measurement, as shown in Figure 6.4. After combustion, the gases were slowly vented to a Bacharach 10-5000 Fyrite Gas Analyzer to measure the percent CO_2 in the gas.

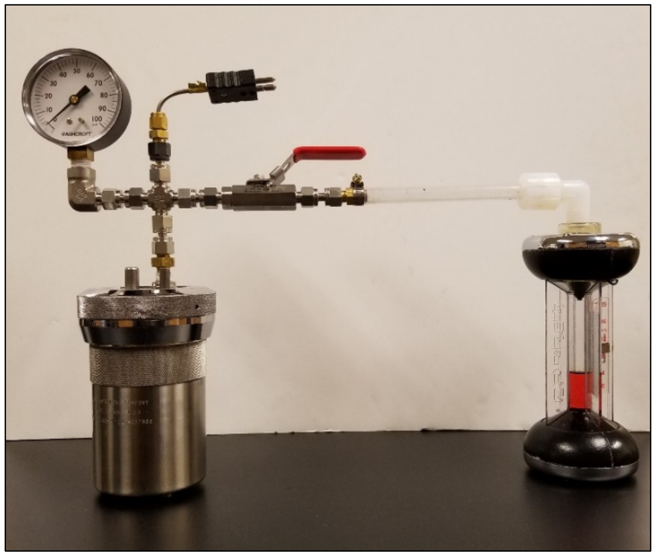

Figure 6.4. Modified oxygen bomb calorimeter and Fyrite device

Assuming the resulting combustion products can be modeled as ideal gases, the total moles in the bomb were calculated using Equation 6.8. From these results, the total mass of CO_2 released from the combustion was calculated using Equation 6.9. Results were corrected for the measured 75% thermal efficiency of the oxygen combustion bomb.

$$n_T = \frac{PV}{RT} \tag{6.8}$$

$$m_{CO_2} = y n_T MW \tag{6.9}$$

Where:

n_T = *Total moles of gas*

P = Final pressure after combustion

V = Volume of the oxygen combustion bomb

R = Ideal gas constant

T = Final temperature after combustion

m_{CO_2} = *Mass of* CO_2

y = Mole fraction of CO_2

MW = molecular weight of CO_2

The total mass of CO_2 released from combustion was further divided by the mass of fuel utilized in the sample to yield emissions in terms of mass basis, kg CO_2/kg fuel. Additionally, this result was divided by the LHV of the fuel to obtain energy basis emissions, g CO_2/MJ fuel. The results of this analysis are presented in Table 6.5. From the table, it can be observed that all plastic fuel oils, except PS have lower CO_2 emissions than diesel fuel. This indicates a positive reduction in CO_2 emissions compared with existent petro-fuels utilized in developing countries, improving environmental sustainability.

Table 6.5.Experimentally determined CO2 emissions of fuel types

Fuel Type	CO_2 Emissions			
	Mass Basis (kg CO_2/kg Fuel)	Standard Deviation	Energy Basis ($x10^{-3}$ kg CO_2/MJ Fuel)	Standard Deviation ($x10^{-3}$)
LDPE	3.12	0.05	69.33	1.15
HDPE	2.98	0.05	72.65	1.17
PP	2.98	0.04	74.65	1.32
PS	3.48	0.01	89.01	0.21
Diesel	3.16	0.10	76.01	2.48

6.5 Results & Discussion

6.5.1 Process Energy Required

The process energy requirement utilizing the total reaction energy and HHV of pyrolysis energy sources is reported in Table 6.6. As anticipated, wood requires the highest amount of energy input as it is lower in calorific value in comparison with propane gas and recycled fuel oil. The latter two fuels have similar calorific content, and therefore, have similar energy requirements.

Table 6.6. Process energy requirement for pyrolysis of waste plastic to fuel oil using mean reaction energy and various pyrolysis energy sources

Energy Source	Pyrolysis Process Energy Requirement (kg Energy Source/kg Fuel Generated)			
	LDPE	HDPE	PP	PS
Wood	0.42	0.40	0.22	0.09
Propane Gas	0.18	0.17	0.09	0.04
Recycled Fuel Oil	0.17	0.18	0.09	0.04

6.5.2 3T Emissions

The calculated generation CO_2 emissions for 3T approach are reported in Table 6.7, utilizing the reaction energy mean from 95% confidence interval presented in Table 6.2. The emissions are presented in mass and energy basis. Analyzing the results, wood has the highest CO_2 emissions due to its low HHV, followed by the recycled fuel oil and propane gas. Additionally, LDPE and HDPE fuels have highest emissions followed by PP and PS. Even though the four plastics have similar HHVs, since PP and PS have lower Ea for the pyrolysis reaction, the amount of fuel required to convert 1kg of plastic to fuel oil is lower than LDPE and HDPE, leading to lower CO_2 generation emissions. In terms of LPDE and HDPE, LDPE is reported to have higher emissions in mass basis versus HDPE in energy basis. The reason for this occurrence is that LDPE has a higher CO_2 combustion factor, whereas HDPE has lower calorific content.

When comparing the 3T generation emissions with diesel WTT emissions, a reduction in CO_2 emissions results, as shown in Figure 6.5. This reduction is due to the analysis of a LMDCE for waste plastic management in developing countries. Because the plastic is collected, separated and processed to fuel directly near or at dumpsites, along with at locations of waste plastic generation via appropriate technology solutions (DeNeve, *et al.*, 2017, Joshi & Seay, 2016), the transportation of the raw feedstock to centralized recycling facilities or refineries is removed, resulting in significant decreases in CO_2 emissions for generation of fuel oil. This is opposite of crude petroleum derived diesel fuel, which is often transported long distances on ships and trucks, resulting in large contribution to the total supply chain emissions of WTT.

Table 6.7. Calculated 3T generation CO2 emissions for plastic fuels using mean reaction energy

3T Emissions								
Pyrolsysis Energy Source	Mass Basis (kg CO_2/kg Energy Source)				Energy Basis (x10^{-3} kg CO_2/MJ Energy Source)			
	LDPE	HDPE	PP	PS	LDPE	HDPE	PP	PS
Wood	0.75	0.72	0.39	0.17	16.71	17.51	9.77	4.24
Propane Gas	0.49	0.47	0.26	0.11	10.94	11.47	6.40	2.78
Recycled Fuel Oil	0.53	0.52	0.28	0.13	11.75	12.78	6.91	3.40

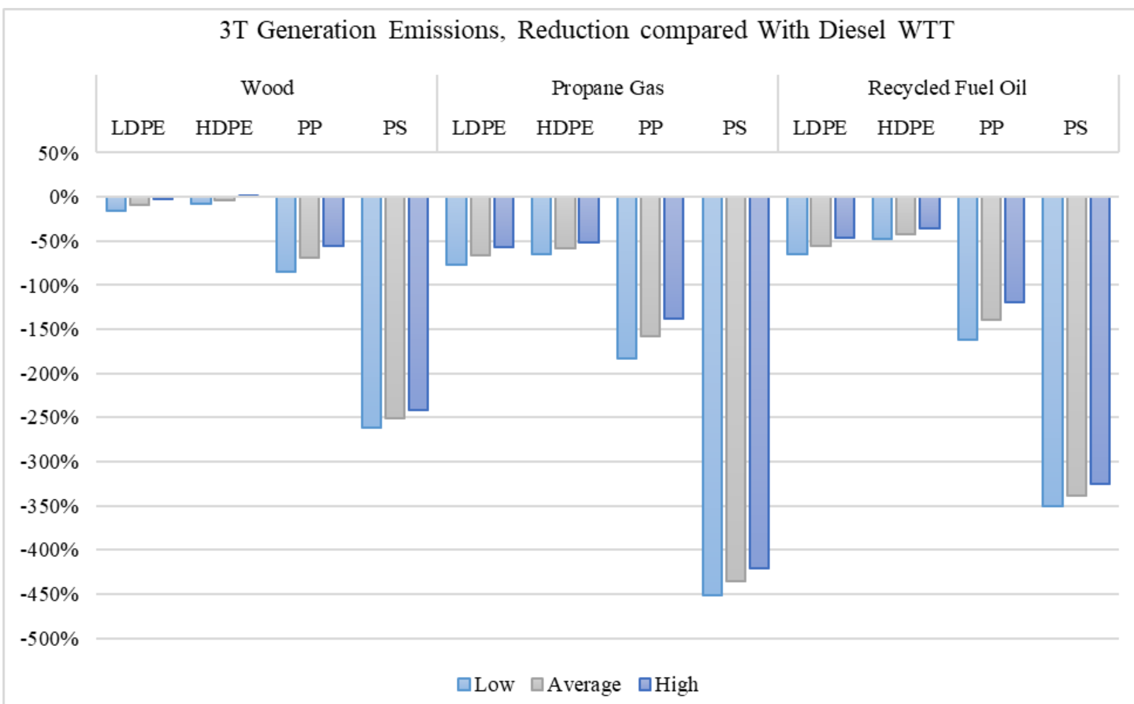

Figure 6.5. Percent reduction in 3T generation emissions, compared with diesel WTT emissions (20.43×10^{-3} kg/MJ fuel) (Churkunti, 2015).

Previously obtained 95% confidence interval range for reaction energy is utilized to depict that for all values of reaction energy (low, average, and high), including various pyrolysis fuel sources, a positive reduction in CO2 emissions is noticed.

Hence, the 3T emissions are only a function of the energy required for conversion of plastic to fuel via pyrolysis and the energy utilized for thermal decomposition. Energy efficient, high calorific energy sources with reduced CO_2 combustion factors are preferred, leading to greatest percent reduction in CO_2 emissions. Plastics such as PP and PS are also preferred for conversion but are likely to be present in slightly lower quantities than LDPE or HDPE (Geyer, *et al.*, 2017). As a result, mixed plastics (LDPE, HDPE, PP and PS) are normally likely to be used for conversion to fuel oil in developing communities, which serve as an ideal source of reliable energy for regions lacking capital and waste management infrastructure while being an environmentally sustainable solution.

6.5.3 Total Generation & Combustion Emissions

Since the total generation emissions are lower than WTT for 3T, and combustion emissions are comparable to diesel, the total generation and combustion emissions are also lower for plastic derived fuels, as shown in Figure 6.6. Since this analysis is based on a function of combustion emissions and energy content of the plastic fuels, PP outperforms the remaining fuel oil types. Regardless, the reduction in GHG CO_2 emissions for plastic fuels is significant, promoting its use as an alternative fuel in developing countries.

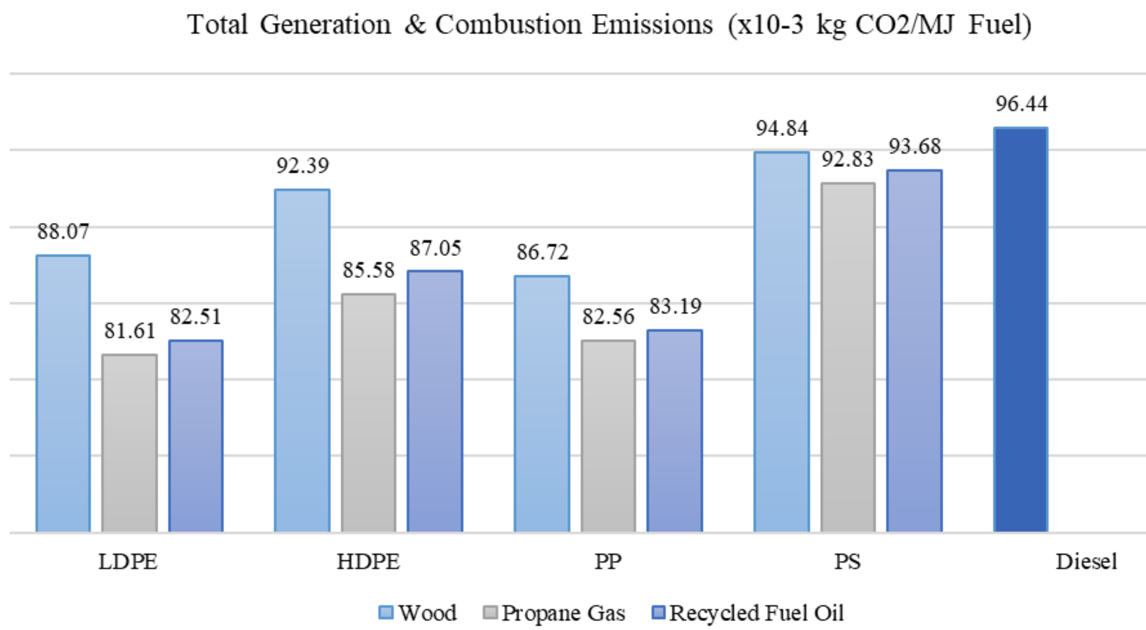

Figure 6.6. Total generation plus combustion emissions for plastic derived fuels in comparison with petroleum derived, diesel

6.6 Conclusions

The extended analysis of this article considers the addition of sensible energy alongside activation energy for determining the pyrolysis process energy requirements. The updated process energy requirements for each plastic type increased from previously reported conclusions. The reported percent increases are 12.18% for LDPE, 12.74% for HDPE, 23.54% for PP, and 37.27% for PS derived fuel oils.

Taking these updates into consideration, the percent reduction in 3T generation emissions and the total generation plus combustion emissions for plastic derived fuels were recalculated. The results of this analysis show that all plastic derived fuels except PS fuel produced via wood fired pyrolysis yields a reduction in 3T CO2 emissions. That is, the 3T emissions for wood fired PS pyrolysis are 0.7% greater than that of diesel well-to-tank emissions reported at 20.43×10-3 kg/MJ fuel (Churkunti, 2015). This outcome leads to a slightly higher generation emissions than diesel, but can be diverted using either propane gas or recycled fuel oil for meeting the pyrolysis energy requirement of producing PS fuel. In return, the total generation plus combustion CO2 emissions for all plastic derived fuels are still lower than that of diesel WTT plus combustion emissions, making the 3T process a viable option for reducing waste plastic accumulation globally.

6.7 Acknowledgements

The assistance of Dr. Todd Cowan; chemical engineering student, Shelby Browning; and mechanical engineering student, Samuel Hawthorne at the University of Kentucky, along with high school interns Ryan Chua, Reese Hutchins and Max Besaw from Paducah Tilghman High School in Paducah, Kentucky is gratefully acknowledged.

CHAPTER 7. DESIGN AND OPERATION EMISSIONS OF A LMDCE TECHNOLOGY FOR CONVERTING WASTE PLASTIC TO PLASTIC DERIVED FUEL OIL

7.1 Introduction

To combat waste plastic accumulation in developing regions, the principles of a locally managed decentralized circular economy (LMDCE) were applied to design and test a simple technology that converts waste plastic to plastic derived fuel oil (PDFO). The technology, named as the Trash to Tank (3T) electric processor, performs slow-pyrolysis of polyolefin-based plastics (high density polyethylene [HDPE], low-density polyethylene [LDPE], and polypropylene [PP]) to generate PDFO that serves as an alternative source of petroleum fuels, used for diesel generators, farming equipment, and cook stoves (Joshi & Seay, 2016).

The 3T electric processor is intended to be used in rural or highly populated, urban regions of developing countries struggling with proper waste management. Due to a lack of capital, infrastructure, education associated proper waste disposal, municipal solid waste and waste plastic generated in low-income regions and slums of developing countries are often discarded openly on undeveloped plots of land or burned in the open environment. As a result, the UKATS processor severs to alleviate waste plastic accumulation challenges in these regions by serving as an appropriate technology based, LMDCE solution for managing waste plastic locally by using local community participation and local resources.

This research contribution assesses the viability of 3T electric processor in terms of its mass and energy balance, operation costs, and PDFO generation and combustion emissions.

7.2 Fabrication of the Trash to Tank Electric Processor

As an LMDCE solution, the 3T electric processor has been conceived using appropriate technology principles. It is a simple, non-automated technology that can be operated by local individuals with minimal formal technical education. The processor can be constructed using scrap parts and non-standard materials of construction, being an affordable (~$800) yet effective solution for removing waste plastic from the ecosystem.

Depicted in Figures 7.1 and 7.2, the 3T electric processor primarily consists of a simple retort, a condenser, piping, fittings, and an electric heating element.

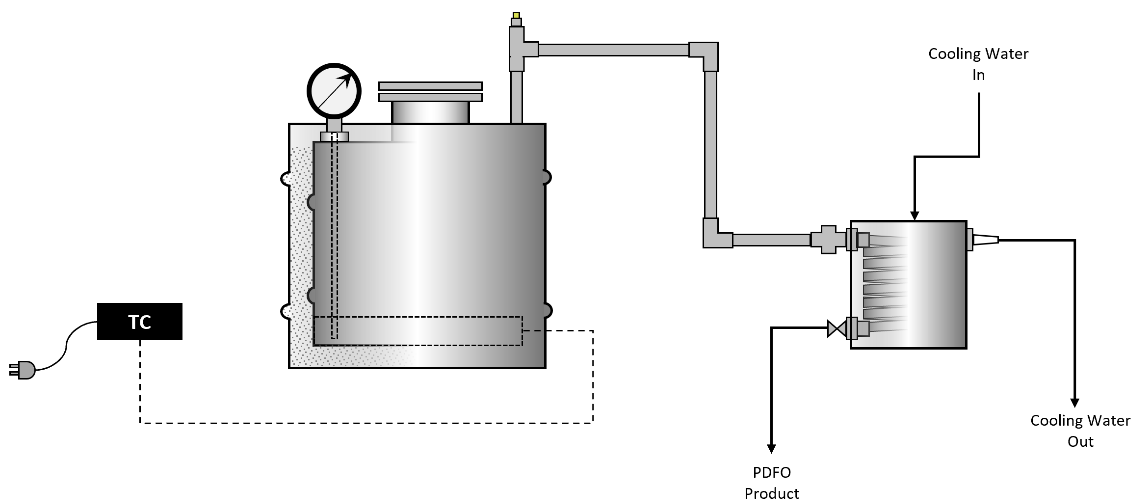

Figure 7.1. Schematic of the 3T Electric Processor

The retort is fabricated using a 10-gallon rolled low carbon steel inner drum housed in a 20-gallon low carbon steel outer drum. The inner drum's outer base is wrapped with a 240-volt, 1900-watt heating ring that is connected via high temperature electrical wiring to a temperature controller. The temperature controller monitors the temperature of the process using a thermometer fitted in the inner barrel. The inner barrel is also fitted with a pipe screw cap for adding waste plastic to the retort, and an outlet pipe for venting PDFO gases. The space between the inner and outer drums is packed with high temperature fiberglass insulation, and the outer barrel is covered with a lid (Figure 7.2) to reduce heat loss to the environment.

Figure 7.2. Photograph of the 3T Electric Processor

In general, the retort acts as a simple batch reactor that performs slow pyrolysis of waste plastic. As a result, it heats, melts and vaporizes the plastic polymers into shorter hydrocarbon chains, generating PDFO gases. The PDFO gases exit the retort through the outlet pipe, which is fitted with a pressure relief valve. The outlet pipe then connects to additional piping and fittings that carry the gases to a simple condenser. The condenser is fabricated using aluminum piping housed in a pail. The aluminum pipe is curled throughout the pail to maximize surface area for condensation. The PDFO gases are condensed using tap water in the pail, which exits at the top of the condenser via clear tubing. Meanwhile, the condensed PDFO fuel exits the bottom of the condenser through additional clear tubing that is connected to the end of the aluminum piping.

7.3 Determining the Mass and Energy Balance of the Trash to Tank Electric Processor

After fabrication, the 3T electric processor was tested in a lab setting to determine its effectiveness in terms of a mass balance and an energy balance. Three runs were performed using PP plastic pellets. The weight of the plastic input, volume of PDFO output, density of PDFO, voltage and resistance of the heating element, and the time increment for which the voltage was applied to the processor were measured to calculate the mass and energy balances.

7.3.1 Mass Balance

Table 7.1 summarizes the mass balance results for the experimental runs. The density of the PDFO was determined to be 0.754 kg/L, which is lower than the literature reported density for kerosene and diesel (Speight, 2011, Engineering ToolBox, 2003). Overall, 65.82% mass balance efficiency was achieved, yielding 0.87 L of PDFO per kg of plastic used.

Table 7.1. 3T electric processor mass balance results

Run	Type of Plastic	Weight of Plastic (kg)	Weight of Fuel (kg)	Volume of Fuel (L)	Efficiency (L of fuel/kg of plastic)	Efficiency (%, Mass Basis)
1	PP	1.70	1.00	1.33	0.78	58.99
2	PP	3.10	1.76	2.34	0.75	56.79
3	PP	3.00	2.45	3.25	1.08	81.68
				Average	**0.87**	**65.82**

These results highlight the tradeoffs encountered when applying appropriate technology to the implementation of LMDCE in developing countries. For instance, due to the use of simple batch reactor type retort and a single-tube heat exchanger, the mass balance efficiency is reduced. The addition of a reflux column, or an advanced shell and tube heat exchanger would improve the mass balance efficiency greatly, but the associated costs are not affordable in rural or low-income urban regions of developing regions.

7.3.2 Energy Balance

To ensure quality of PDFO product, the heating rate of the 3T electric processor must be maintained carefully to prevent wax generation. If heat is applied too rapidly, the slow pyrolysis of waste plastic is not sufficiently completed, resulting in wax. Therefore, the energy input to the 3T electric processor was incrementally increased during a run to ensure PDFO generation. These incremental increases in energy input were measured by increasing the voltage applied to the heating element and the time duration for which the voltage was applied. Equation 7.1 summarizes the energy balance calculation performed for each run.

$$Net\ Energy\ (kJ) = m_{PDFO}(kg) * Q_{PDFO}\left(\frac{kJ}{kg}\right) - \sum_{i=1}^{n} \frac{V_i^2}{R} * 0.06t_i\ \ (kJ) \qquad (7.1)$$

Where:

m_{PDFO} = mass of PDFO (kg)

Q_{PDFO} = lower heating value of PP fuel, as determined in Chapter 6 (40,027 kJ/kg) (Joshi & Seay, 2020)

i = increment

n = number of increments

V = voltage (v)

R = Resistance (Ω)

t = time

Note, V^2/R is power (W). Power multiplied by time yields energy consumption (kWh). In Equation 7.1, the use of a conversion factor, 0.06, represents conversion from W to kW and from kW to kJ/h.

The results of the energy balance are presented in Table 7.2. Due to the calorific value of PDFO, the energy balance is positive for converting plastic to PDFO via the 3T electric processor. Thus, a value-added product is produced from waste plastic, which can in return be used by local communities in developing regions as an alternative source of petroleum fuel for diesel generators or kerosene cookstoves.

Table 7.2. 3T electric processor energy balance results

Run	**Fuel Energy Produced (kJ)**	**Total Energy Input (kJ)**	**Net Energy (kJ)**
1	40139.88	7565.28	32574.59
2	70471.14	10676.23	59794.90
3	98086.16	17513.50	80572.66
	Average (kJ/kg of PDFO)	**6918.31**	**33108.69**
	Average (kJ/L of PDFO)	**5216.40**	**24963.95**

7.4 Cost of Operations for Trash to Tank Electric Processor

To determine the economic viability of operating the 3T electric processor, the cost of energy input was assessed against the value of the fuel produced. Specifically, the cost associated with electricity consumption was compared to the value of PDFO as an alternative to diesel or kerosene. The results, presented in Table 7.3, indicate a positive return on investment. Per liter of PDFO produced, approximately 252% profit is incurred through the sale of diesel and 339% through the sale of kerosene. As a result, the implementation of the 3T electric processor in developing regions for combating waste plastic accumulation may present business opportunities for small-scale entrepreneurs and recycling organizations.

Table 7.3. Operation costs and economic gains from production and sale of PDFO

Cost of Electricity ($/kWh) (Energy Information Association [EIA] 2021a)				0.132
Price of Diesel ($/L) (EIA, 2021b)				0.674
Price of Kerosene ($/L) (EIA, 2021c)				0.840

Run	Total Energy Input (kWh)	Cost of Energy Input ($/L)	PDFO Sold as Diesel Net Profit ($/L)	PDFO Sold as Kerosene Net Profit ($/L)
1	2.10	0.21	0.47	0.63
2	2.97	0.17	0.51	0.67
3	4.86	0.20	0.48	0.64
	Average	**0.19**	**0.48**	**0.65**

7.5 PDFO Generation and Combustion Emissions via the Trash to Tank Electric Processor

To understand the environmental benefits of deploying 3T electric processors as an LMDCE solution for waste plastic management in developing countries, the total generation, or production, and combustion emissions of PDFO were determined. Because the 3T electric processor operates using electricity, the generation emissions are likely to vary based on the source of electricity generation. In Table 7.4, results of generation emissions as a function of various energy sources such as coal (lignite and bituminous), petroleum oil, natural gas, renewables, and nuclear are presented (World Nuclear Association, 2011). Combustion emissions are then added to generation emissions to yield total emissions. Equation 7.2-7.3 detail the calculation of generation emissions. The total emissions are compared with diesel generation and combustion emissions (Air Resources Board, 2009) to understand the impact of electricity source on total emissions.

$$Generation\ Emissions\ (kg\ CO_2) = Average\ Energy\ Input\ Requirement\ of\ PDFO\ \left(\frac{kWh}{kg}\right) * Emissions\ of\ Energy\ Source\ \left(\frac{kg\ CO_2}{kWh}\right) \tag{7.2}$$

$$Total\ Emissions\ (kg\ CO_2) = Generation\ Emissions + Combustion\ Emissions \quad (7.3)$$

Where:

Combustion Emissions = emissions associated with combustion of PDFO, as determined in Chapter 6 for PP (2.98 kg CO_2/kg PDFO or 2.25 kg CO_2/L PDFO) (Joshi & Seay, 2020)

The results of this analysis indicate that electricity sourced from energy sources such as coal and petroleum to produce PDFO leads to higher total CO_2 emissions than diesel. In contrast, energy sourced from natural gas, renewables, or nuclear power have lower emissions than diesel. Hence, although the 3T electric processor is considered an economically viable LMDCE solution, the source of electricity generation in developing countries will impact its environmental benefits.

Table 7.4. Generation and combustion emissions of PDFO produced via 3T electric processor as a function of energy source

	Diesel Generation + Combustion Emissions			**4.01**	**3.40**
Electricity Source	**CO_2 Emissions of Electricity Source (kg/kWh)**	**Average PDFO Generation Emissions (kg CO_2/ kg PDFO)**	**Average PDFO Generation Emissions (kg CO_2/L PDFO)**	**Total Generation + Combustion Emissions (kg CO_2/kg PDFO)**	**Total Generation + Combustion Emissions (kg CO_2/L PDFO)**
Lignite Coal	1.05	2.03	1.53	5.01	3.77
Bituminous Coal	0.89	1.71	1.29	4.69	3.53
Petroleum Oil	0.73	1.41	1.06	4.39	3.31
Natural Gas	0.41	0.79	0.60	3.77	2.84
Renewable*	0.05	0.09	0.07	3.07	2.31
Nuclear	0.03	0.06	0.04	3.04	2.29

*Renewable energy sources include the average of solar, biomass, hydroelectric, and wind

7.6 Conclusions

In this contribution, an LMDCE solution for converting waste plastic to PDFO in developing regions was developed according to the principles of appropriate technology and tested in a lab scale operation. Termed as the 3T electric processor, the technology's mass and energy balances were determined along with its cost of operation and environmental emissions. The mass balance indicated that tradeoffs from the implementation of appropriate technology principles reduce the overall efficiency of the process due to a lack of sophisticated distillation and condensation equipment. The energy balance and economic gains were positive indicating that the technology is feasible for use by small-scale entrepreneurs in developing regions. However, the source of electricity generation will greatly impact the environmental suitability of the 3T electric processor.

CHAPTER 8. FUEL ANALYSIS OF PLASTIC DERIVED FUEL OIL AS AN ALTERNATIVE FOR DIESEL AND KEROSENE

8.1 Introduction

This research contribution's proposed solution for reducing waste plastic accumulation in developing regions focuses on conversion of waste plastic into plastic derived fuel oil (PDFO) via slow pyrolysis using the principles of a locally managed decentralized circular economy (LMDCE) and appropriate technology. In return, a viable technology was developed to achieve this goal – the Trash to Tank (3T) electric processor, as detailed in Chapter 7. However, due to the use of low-cost construction materials that are simple, sourced locally by common citizens, and that can be operated with basic technical education of citizens, the 3T electric processor was designed to be non-automated, lacking sophisticated distillation and condensation equipment for producing PDFO. Thus, the PDFO produced using the UKATS electrical processor is primarily a chemical mixture of hydrocarbon chains similar to those found in traditional diesel and kerosene (Joshi & Seay, 2016 and Budsaereechai, 2019).

Nonetheless, PDFO has beneficial applications in developing regions as an alternative source for diesel and kerosene. Particularly, it can be used in diesel generators and kerosene cookstoves, serving as a reliable source of energy for lighting and cooking (Joshi & Seay, 2016). As a result, the objective of this research is to analyze the composition of PDFO and assess how it can be optimized in LMDCE applications, especially when implementing appropriate technology solutions such as the 3T electric processor. By studying the impact of temperature and time, the two variables that can be easily employed to adjust slow pyrolysis reaction chemistry in appropriate technology settings, the composition and stability of PDFO as it relates to diesel and kerosene is measured.

8.2 Materials and Methods

8.2.1 Collecting PDFO Samples

To understand the effect of temperature on the composition and stability of PDFO, the 3T electric processor was modeled using a bench-scale autoclave Parr pressure vessel reactor with a Parr 4843 controller, Figure 8.1. This setup was used to generate PDFO from polyolefin-based waste plastics, high-density polyethylene (HDPE), low-density polyethylene (LDPE), polypropylene (PP), and mixed plastic, which was an equal mixture of HDPE, LDPE, and PP by weight. These plastics were sourced from household waste, including milk jugs (HDPE), Ziploc® bags (LDPE), and food packaging containers (PP). The plastics were cleaned and cut to small pieces for insertion in the reactor. The temperature of the slow-pyrolysis experiments was varied between 370-400°C in increments of 10°C for each plastic type. This range was chosen to reflect optimum PDFO production as a function of temperature, i.e., in general, temperatures below 370°C produced minimal amount of PDFO, whereas above 400°C produced wax for plastics such as HDPE. The experiments were conducted in sets of at least 3-5 runs per plastic type and per temperature increment. The PDFO generated through slow-pyrolysis was condensed in a single -tube, shell and tube copper heat exchanger, cooled with tap water.

To understand the effect of time on the composition and stability of PDFO, the Parr bench-scale reactor and controller setup was used to generated PDFO from HDPE and LDPE at temperatures of only 370°C and 400°C. These plastics were chosen due to time constraints and their similarity in polymer chemistry; these temperatures were chosen to bookend the impact of temperature on the time-focused experimental runs. Hence, for observing the impact of time, fuel samples were collected at increments of approximately half an hour for 2 hours after observing the first drop of fuel, or after approximately 4.5 hours of starting the experiment for HDPE and 3.5 hours for LDPE. The experiments were replicated in sets of three.

Figure 8.1. Parr reactor and Parr 4843 controller setup for slow pyrolysis experiments

8.2.2 Analyzing PDFO Samples

The collected liquid PDFO samples were then analyzed using a gas chromatograph-mass spectrometer (GC-MS) and a thermogravimetric analyzer (TGA). GC-MS studies were completed using an Agilent Technologies 7890 A gas chromatograph interfaced with an Agilent Technologies 5975 C mass spectrometer and triple-axis detector. Sample preparation involved taking 500 μL of each sample and diluting to 2.5 mL using pentanes. Injection volume for each sample was 5 μL. Analytes were separated using a capillary column (Agilent Technologies HP-5MS, 30 m 0.25 mm; i.d. 0.25 mm) and ultra-high purity (> 99.999%) helium gas as a mobile phase. The initial oven temperature was set at 60 °C, ramped to 200 °C at a rate of 10 °C/min, then ramped at 5 °C/min to 280 °C. The mass source, quadrupole, and injector were held at a constant temperature of 230 °C, 150 °C, and 300 °C, respectively. Target analytes (C_7 through C_{30} hydrocarbons) were identified based on the retention time and the most abundant signature m/z ion (also used for quantitation) for each signal. Next, to analyze the thermal degradation of PDFO, thermogravimetric analysis (TGA) studies were completed in triplicate on each sample (5-8 mg) using a TA Instruments Q500 TGA with platinum pans. A heating rate of 10°C/min from 30 to 600 °C under a constant dry nitrogen flow (40 mL/min) was utilized.

8.3 Results and Discussion

8.3.1 Effect of temperature

8.3.1.1 GC-MS Results

The GC-MS results provided the total abundance of C_7-C_{30} hydrocarbons present in each sample. As a result, the total number of hydrocarbons in the experimental runs of each plastic type at each temperature increment were averaged for the set of runs. The averages were then normalized to obtain percent relative abundance for each hydrocarbon number. The results of this analysis are present in Figure 8.2.

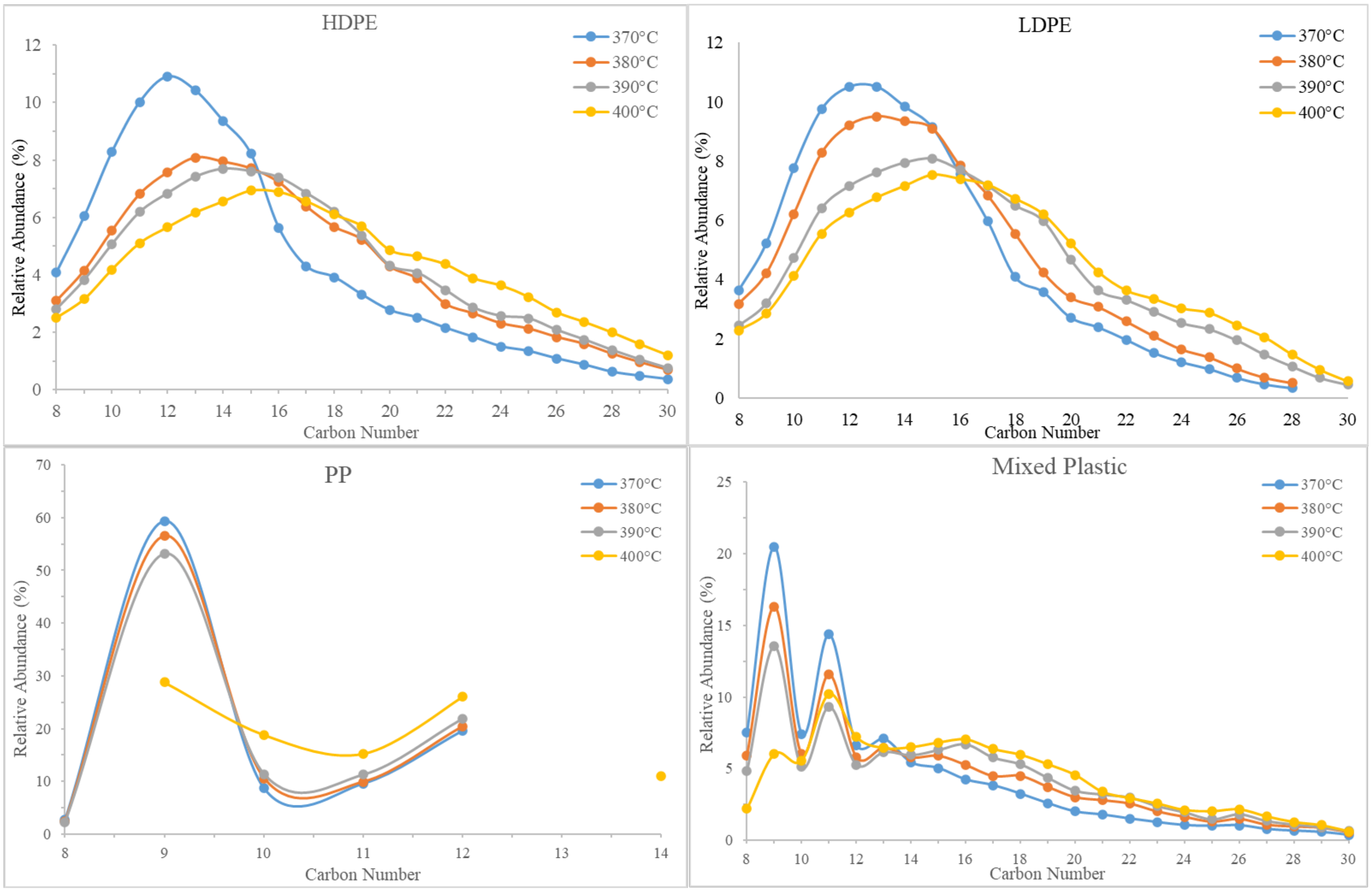

Figure 8.2. GC-MS results for PDFO as a function of temperature and plastic type

The results indicated that the hydrocarbons present in PDFO composition of all plastics analyzed are primarily aliphatic (alkanes and alkenes), or saturated and unsaturated hydrocarbons due to the depolymerization chemistry of the polyethylene (PE) and PP plastics, which undergo chain scission mechanism during pyrolysis (Achilias et al., 2007, Agboola et al., 2017, Budsaereechai et al., 2019, CROW, 2021, Demirbas, 2004, Gonzales et al., 1998, Miandad et al, 2017, and Zeus, 2005). For PE-based plastics, hydrocarbons in the range of C_7-C_{30} were observed, whereas for PP-based plastics, branched hydrocarbons were predominantly present in the range of C_8-C_{12}. As a result, the PDFO obtained from mixed plastic was a combination of both straight chain and branched hydrocarbons. In fact, the percent relative abundance of branched hydrocarbons can be directly correlated to the mixed plastic samples by observing similar trends in the C_8-C_{12} range in Figure 8.2. In comparison with petroleum derived distillates, diesel fuel (No. 2) contains approximately 75-90% aliphatic alkanes and cycloalkanes, and 10-25% aromatics and olefins/alkenes (United States Department of Health and Human Services, 1995 and Rentar, 2018). Kerosene (diesel fuel No.1) is a light distillate primarily consisting of branched chain alkanes, cycloalkanes, and mixed aromatic cycloalkanes (Gad, 2014).

In Figure 8.2, the percent relative abundance of predominantly present hydrocarbons for HDPE and LDPE shifts from left to right as temperature increases. For instance, the peak of the curves shifts from C_{12} at 370°C to C_{15} at 400°C for both plastics. In PP, an opposite effect is seen where the trough shifts slightly from C_{10} at 370°C to C_{11} at 400°C. In mixed plastic, the predominant peak shifts from C_9 at 370°C to C_{11} at 400°C. For the two inner temperatures of 380°C and 390°C, percent relative abundance shifts incrementally towards 400°C. Table 8.1 summarizes the predominant hydrocarbons present in PDFO derived from each plastic at the two outer temperatures. As temperature increases, the fraction of heavier hydrocarbons in the PDFO composition increases. This phenomenon may be attributed to the boiling point of heavier hydrocarbons, which vaporize at higher temperatures. Note, literature reported diesel and kerosene hydrocarbon ranges are also reported on Table 8.1 (United States Department of Health and Human Services, 1995). However, these ranges vary widely in literature; diesel hydrocarbon ranges have been reported from C_7-C_{24} and C_8-C_{17} for kerosene (Rentar Fuel Catalyst, 2019, International Energy Association-Advanced Motor Fuels [IEA-AMF], 2021, ALS Global, 2021, Gad, 2014, Gad, 2005).

Table 8.1. Summary of predominant hydrocarbons in PDFO as a function of temperature and plastic type

Kerosene (C_9-C_{16})			
Diesel (C_{11}-C_{20})			
PDFO Type & Temperature	**PDFO Temperature (°C)**	**Relative Abundance (%)**	**Hydrocarbon Range**
HDPE	370	81.17	C_8-C_{18}
	400	80.82	C_9-C_{23}
LDPE	370	80.45	C_9-C_{18}
	400	80.90	C_{9}-$_{22}$
PP	370	97.26	C_9-C_{12}
	400	88.99	C_9-C_{12}
Mixed Plastic	370	82.03	C_8-C_{17}
	400	81.34	C_9-C_{21}

8.3.1.2 TGA Results

Because TGA curves are a function of both temperature and weight loss, averages of TGA curves were not taken for the duplicate runs. Instead, best fit curves that summarized the trends observed at each temperature for the duplicate runs were chosen.

The TGA results of PDFO thermal degradation as a function of temperature are presented in Figure 8.3. As temperature increased for all plastics analyzed under this study, an increase in thermal stability, or a decrease in volatility, of the PDFO was observed. These results allude that as the pyrolysis temperature increases, heavier and longer hydrocarbon chains are broken during the chain scission mechanism. (Rentar Fuel Catalyst, 2021)

In addition, PP-based PDFO degraded at lower temperatures than PDFO generated from PE and mixed plastic as shown in Figure 8.4. These results can be attributed to several factors, including the PP polymer chains being comprised of tertiary carbons at every second carbon, which favors carbocation during thermal degradation; the lower activation energy of depolymerization of PP (182 kJ/mol) than PE (294 kJ/mol); and the presence of branched hydrocarbons in PP-based PDFO (Aboulkas and Nadifiyine, 2008, Budsaereechai, 2019, Cai *et al.*, 2008, Chandrasekaran *et al.*, 2015, CROW, 2021, Miandad *et al.*, 2017, Miandad *et al.*, 2019, Phetyim and Pivsa-art, 2018, and Zhou *et al.*, 2006).

Figure 8.4 also depicts the comparison of PDFO thermal degradation with that of diesel and kerosene. In general, the trend observed in terms of stability is kerosene < diesel < PDFO. However, at lower temperatures of 370°C, the rate of weight loss for PDFO is more similar to diesel and kerosene than at higher temperatures of 400°C. This further alludes to the increased presence of longer chain hydrocarbons present in PDFO at increased temperatures.

The higher stability of PDFO also leads to an increased fuel quality, or the reduction in the degradation of the fuel at ambient conditions due to polymerization, acidity, oxidation, emulsion, and microorganism infestation (Corrosonpedia, 2018). However, as with diesel combustion, the efficiency of PDFO combustion is a function of the engine technology (Rentar Fuel Catalyst, 2021). Albeit PDFOs offer an additional advantage than traditional petroleum fuels in that due to the polymer chemistry of PE and PP-based plastics, no Sulfur Oxide (SOx) is emitted during combustion.

8.3.2 Effect of Time

Using the analysis approach detailed in Section 8.3.1.1, the GC-MS results for studying the impact of sample time on composition are presented in Figure 8.5.

The results portray that sample collection time does not have a significant impact on composition. Except for HDPE at 400°C, the peak hydrocarbon chain length increases by 1-2 carbon numbers from the first sample time to the final sample time. This implies that slightly heavier hydrocarbons are exiting the reactor at increased run times. However, a clear visible shift in composition is only noticed as temperature increases, that is the peak hydrocarbon chains for all sample run times shift from approximately C_{12} to C_{16} as temperature increases from 370°C to 400°C.

As for the TGA results for the effect of sample time on the stability of PDFO, thermal degradation curves varied between duplicate runs and no significant trend was consistently observed as sample time increased. The results of all duplicate runs are provided in Appendix B. Additional analysis is required as initial results were inconclusive.

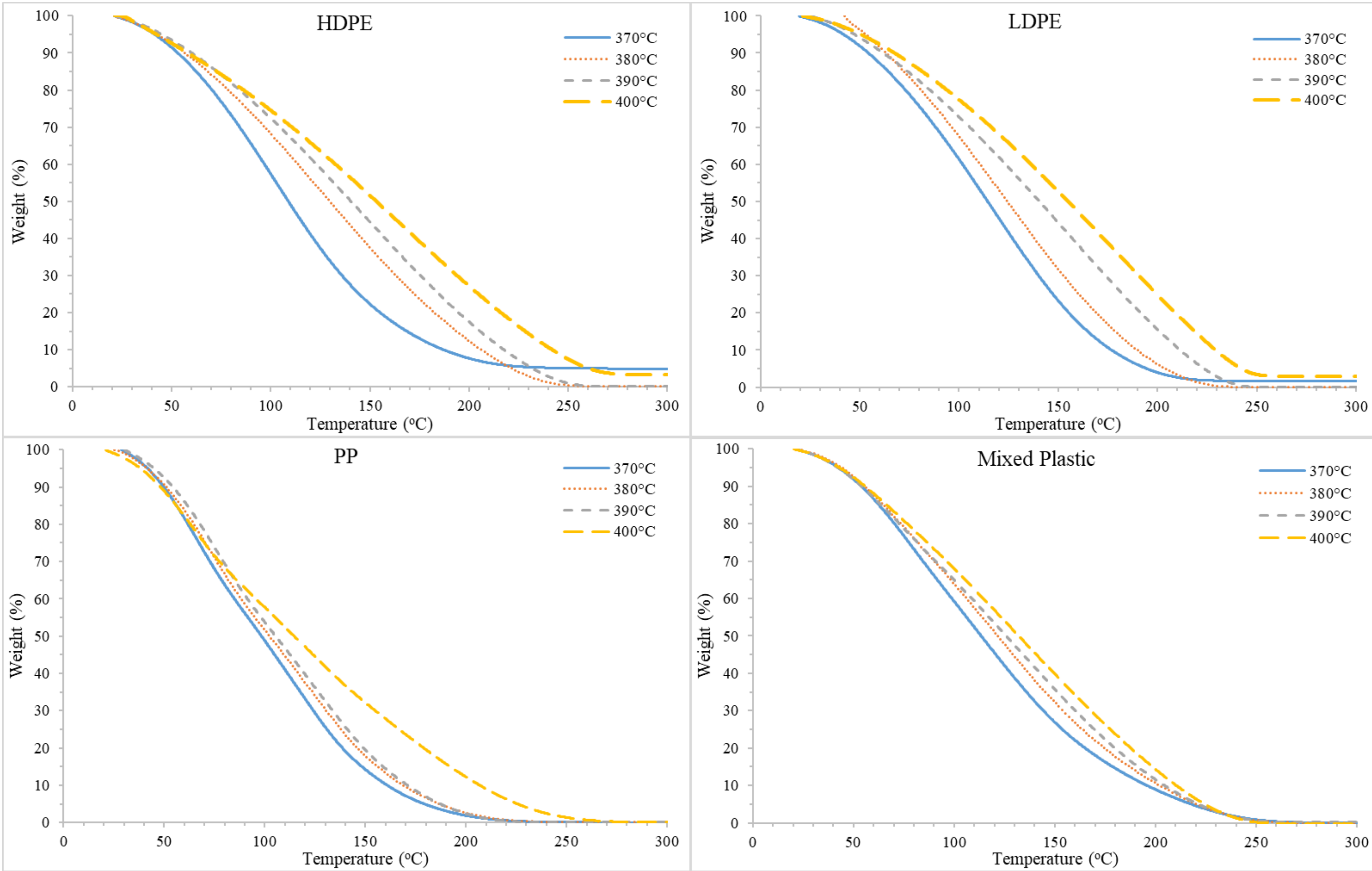

Figure 8.3. TGA results for PDFO as a function of temperature and plastic type

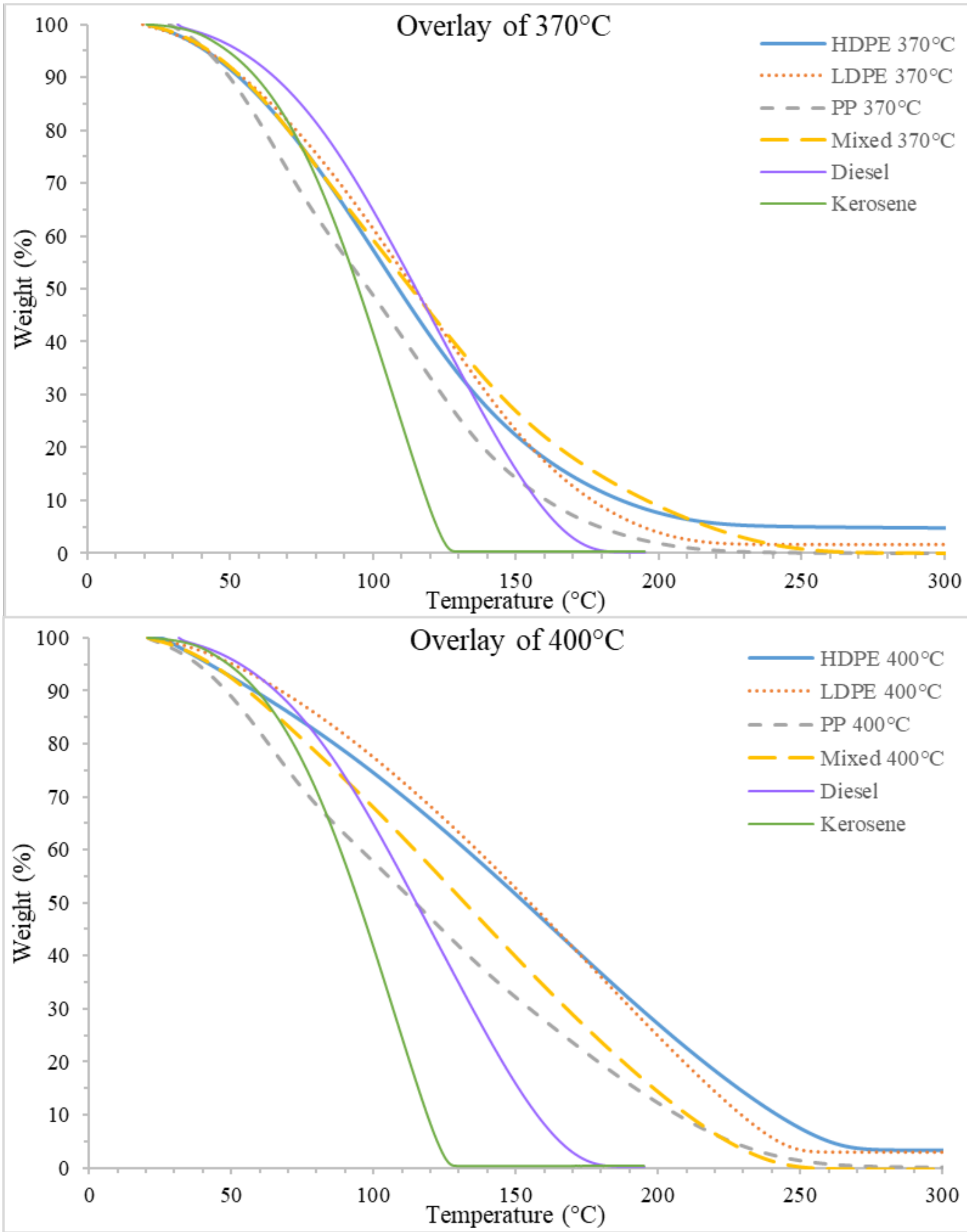

Figure 8.4. TGA results overlay of PDFO with diesel and kerosene

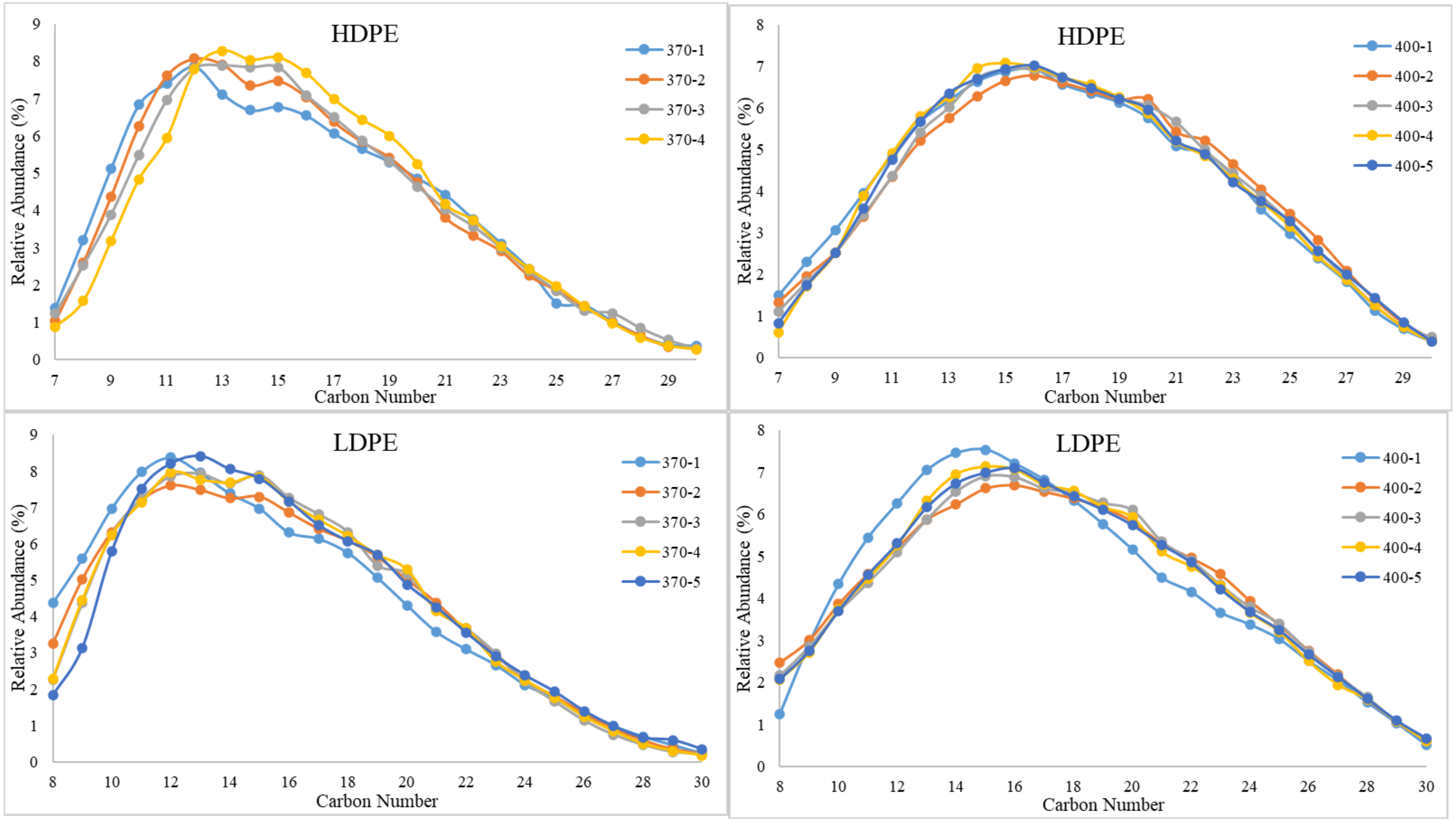

Figure 8.5. GC-MS results for PDFO as a function of sample time and plastic type

Note, sample naming convention, “Temperature-Sample Number”; i.e., “370-1” indicates the first sample collected at 370°C.

8.4 Conclusion

This research contribution considered the impact of temperature and time as two variables affecting the composition and stability of PDFO derived in appropriate technology based, LMDCE applications. The results yield that temperature has significant contribution on PDFO composition, and as temperature increases, the stability of PDFO increases with an increased production in heavier hydrocarbons. The effects of sample time on composition were determined to be minimal, and the results of thermal degradation for understanding fuel stability were determined to be inconclusive.

CHAPTER 9. SUPPLY CHAIN CONSIDERATIONS AND UNCERTAINTY ASSESSMENT OF LMDCE IMPLEMENTATION

9.1 Introduction

To assess the impact of a locally managed decentralized circular economy (LMDCE) in a developing region for combating waste plastic accumulation, it is necessary to evaluate the economic, environmental, and societal benefits of LMDCE applications. Two subset parishes of Kampala, Uganda were chosen as a case study. In this analysis, the use of the Trash to Tank (3T) electric processor for converting waste plastic to PDFO (see Chapter 7 for details) is chosen as the LMDCE solution for managing waste plastic accumulation in an urban, developing region. Hence, the supply chain considers the financial costs and profits associated with collecting and converting waste plastic to PDFO (economic sustainability); the emissions produced from the transportation and conversion of waste plastic to PDFO plus the combustion emissions from using PDFO (environmental sustainability); and the number of jobs created while removing plastic from the ecosystem, in return alleviating waste management challenges and improving health within the communities (social sustainability).

Note, in this analysis, the traditional supply chain optimization model (minimization of operating costs, transportation costs, and distribution costs) is modified to reflect LMDCE principles of local management of waste plastic on an individual and community level, especially in areas lacking proper infrastructure to manage waste (Troschinetz, 2008, Sujauddin, 2008). Therefore, a centralized plastic recycling facility that collects waste plastic from various sources and distributes the products to various customers is not evaluated. Instead, a review of the existing road infrastructure, methods of household waste disposal, household income, and the demographics of the users of 3T electric processor are used to understand how LMDCE may be implemented throughout a developing urban community by quantifying its supply chain.

Figure 9.1 depicts the two parishes studied in this analysis: Rubaga in Rubaga division and Kololo IV in Central division, which primarily represent lower-income/slum and upper/middle-income neighborhoods, respectively. In-country assessments with Kampala City Capital Authority (KCCA), the local waste management municipality, determined that Rubaga parish's waste is collected by KCCA at no cost to the citizens from skips (dumpsters) located throughout the region. In contrast, Kololo IV parish's waste is collected house-to-house by private waste collection companies that charge the citizens a small fee for waste disposal (Katusijmeh, 2012).

Because the waste management practices, transportation infrastructure, and the population demographics of these two parishes vary in income and standards of living, two types of LMDCE applications were considered – a fully decentralized LMDCE and a partially decentralized LMDCE – to determine the optimum process for waste plastic collection and management. In a fully decentralized LMDCE, small scale entrepreneurs collect and process waste plastic locally and independently, whereas in a partially decentralized LMDCE, non-government recycling organization assist in collection of waste plastic and small-scale entrepreneurs process it to PDFO. Based on these two applications, three supply chain case studies were considered as summarized in Section 9.2 to further study waste collection and transportation logistics based on the infrastructure of the parishes. An uncertainty assessment was then performed on the variables used in the supply chain case studies to understand the inherent uncertainty of the results.

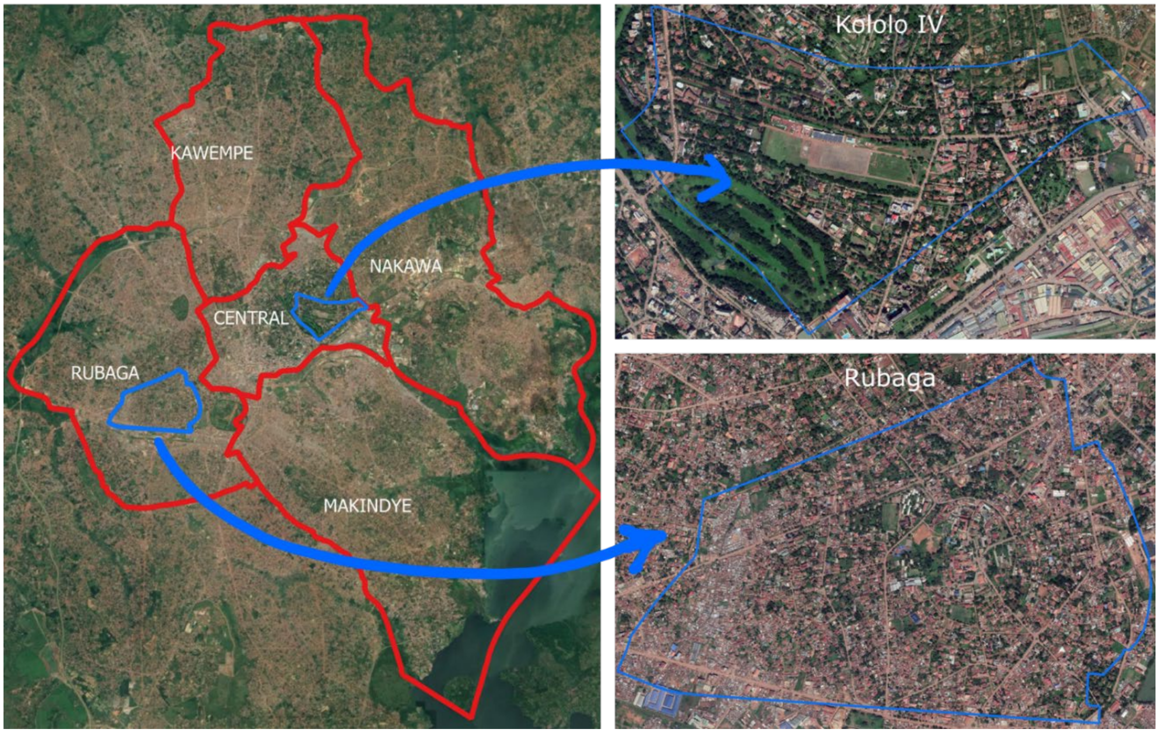

Image basemap source: Quantum Geographical Information System (QGIS) 2019.

Figure 9.1. Rubaga parish in the Rubaga division and Kololo IV parish in the Central division of Kampala, Uganda.

9.2 LMDCE Supply Chain Considerations Case Studies

9.2.1 Fully Decentralized LMDCE, Lower-Income/Slums

The first LMDCE supply chain case study considers a fully decentralized approach in lower-income/slum regions of Rubaga parish where small-scale entrepreneurs locally collect waste plastic from their neighbors and process it via the 3T electric processor. The PDFO generated is sold locally as an alternate source of diesel to local consumers. In this approach, small-scale entrepreneurs are distributed equally throughout the Rubaga parish and buy sorted waste plastic from their neighbors (Figure 9.2). This approach highlights the infrastructure challenges faced by local waste collection municipalities in heavily populated developing regions where narrow streets and unpaved roads hinder house-to-house waste collection. The approach is therefore similar to informal scrap and waste collectors in developing countries that travel through neighborhoods with minimal or nonexistent waste collection to assist in overall waste management (Alluri, 2019). Due to size of the Rubaga Parish (3.3 km^2), in this fully decentralized approach of LMDCE, it is assumed that no transportation costs are incurred by the small-scale entrepreneurs as they merely travel on foot to collect the desired amount of waste plastic.

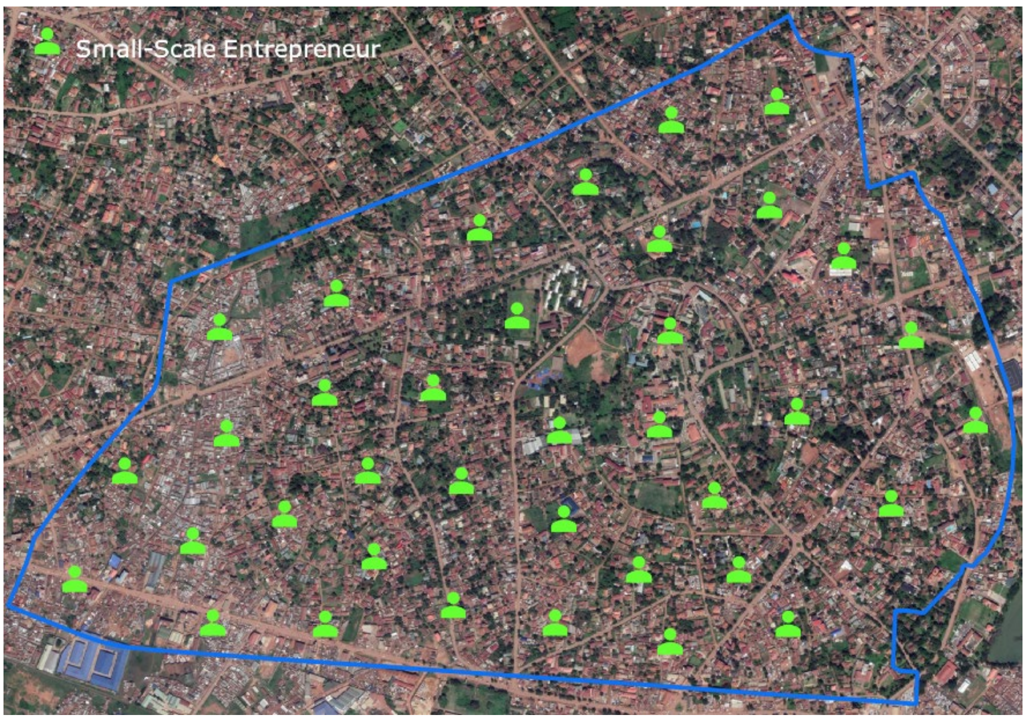

Image basemap source: QGIS 2019.

Figure 9.2. Depiction of a fully decentralized LMDCE, lower-income/slums

This supply chain case study therefore considers the annualized cost of the 3T electric processor, purchasing price of sorted waste plastic from consumers, and the selling price of the PDFO. Based on the amount of plastic available in the parish, the number of UKATS processors that can be supported, and the number of jobs that can be created are determined. The emissions associated with converting waste plastic to PDFO and the combustion emissions of the PDFO are also determined and compared with traditional well-to-tank (WTT) diesel generation and combustion emissions.

9.2.2 Partially Decentralized LMDCE, Lower-Income/Slums

The second LMDCE supply chain case study considers a partially decentralized approach in Rubaga parish where a non-profit, non-governmental organization (NGO), serving as a collection facility, assists in waste plastic collection and shredding, in return selling the waste plastic to small-scale entrepreneurs for further converting to PDFO via the 3T electric processor. Utilizing the existent skip locations provided by KCCA, the NGO collects and buys sorted waste plastic from citizens. The waste plastic is then taken to a centralized NGO facility within the Rubaga parish from where it is resold to the community's small-scale entrepreneurs (Figure 9.3). This approach reflects the current waste management practices followed in Rubaga parish by KCCA, where citizens travel to the skips to discard municipal solid waste. It relies on the existent road network and skip locations to collect the sorted waste plastic from citizens. This approach also models local NGOs that support waste management municipalities by collecting recyclables and selling them to downstream processing facilities for reentry into the plastic manufacturing supply chains (Plastics for Change, 2021, Varier, 2017).

In this case study, the transportation costs associated with collecting the waste plastic from skip locations in Rubaga parish are optimized using a travelling salesman approach. The NGO's operating costs for buying sorted waste plastic, shredding it, operator salaries, and overhead costs are further accounted. These costs are balanced with the amount of plastic that needs to be collected from the community and its selling price to the small-scale entrepreneurs to breakeven. In return, the number of 3T electric processors supported and the number of jobs created are determined. Finally, the emissions associated with the pickup and transport of waste plastic to the NGO's facility, conversion of waste plastic to PDFO by entrepreneurs, and the combustion of PDFO are compiled to determine the total generation and combustion emissions. These emissions are compared with diesel WTT generation and combustion emissions. As with the fully decentralized approach, entrepreneurs are assumed to travel on foot to the NGO's facility located within the Rubaga parish to purchase the shredded waste plastic. As a result, transportation emissions at the entrepreneurial level in a partially decentralized LMDCE model are assumed to be nonexistent.

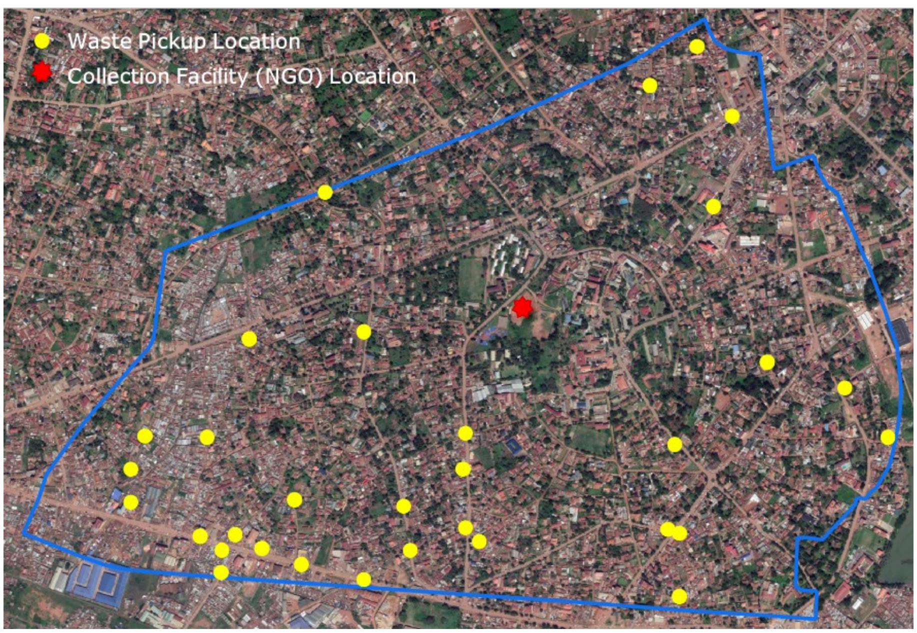

Image basemap source: QGIS 2019.

Figure 9.3. Depiction of a partially decentralized LMDCE, lower-income/slums

9.2.3 Partially Decentralized LMDCE, Upper/Middle-Income

The third LMDCE supply chain case study considers house-to-house waste plastic collection from affluent neighborhoods in Kololo IV parish by an NGO, followed by shredding and reselling of the waste plastic to small-scale entrepreneurs from the NGO's facility located within the Kololo IV parish (Figure 9.4).

Image basemap source: QGIS 2019.

Figure 9.4. Depiction of a partially decentralized LMDCE, upper/middle-income

This approach reflects developed and sufficient road infrastructure to allow waste management municipalities to travel house-to-house for waste pickup. It is also similar to house-to-house waste recycling in developed regions, where consumers sort recyclable materials and pay a small fee for having their recycling picked up by local municipalities or recycling organizations within the region. However, in this case study, three sub-factors were considered, where either the NGO buys the sorted waste plastic from the consumers, receives it for free, or charges for picking it up. These subfactors were considered to understand the NGO's breakeven costs (as described in Sections 9.2.2 and 9.3) as a function of the sorted waste plastic purchasing costs, including the downstream effects of these costs when the waste plastic is resold to the small-scale entrepreneurs. In addition, the jobs created, and the generation and combustion emissions of the approach are determined (as described in Section 9.2.2).

9.3 Methodology

The above-mentioned supply chain considerations case studies were developed using the equations provided in Sections 9.3.1 to assess the economic, environmental, and societal sustainability of LMDCE implementation in an urban, developing region. The amount of municipal solid waste (MSW) and waste plastic generated in each parish were determined using the geographical information system (GIS) model detailed in Chapter 5. Since the total waste plastic generation reflects all seven types of plastics (#1: polyethylene terephthalate [PET], #2: high-density polyethylene [HDPE], #3: polyvinyl chloride [PVC], #4: low-density polyethylene [LDPE] #5: polypropylene [PP], #6: polystyrene [PS], and #7: other), only polyolefin-based plastics (HDPE, LDPE, and PP) were considered for conversion to PDFO via slow pyrolysis (DeNeve, *et al.*, 2017, Joshi & Seay, 2016, Wong, *et al.*, 2015, Kumar and Singh, 2011, Singh and Ruj, 2016). The amount of polyolefin-based plastic in the global waste stream is reported to be approximately 57% (Geyer, 2017). Table 9.1 reports the results of the GIS model and the respective amounts of polyolefin-based plastics generated in Rubaga and Kololo IV parishes.

Table 9.1. Parish overview: number of buildings, population, and waste generation

Parish	Rubaga	Kololo IV
Total Number of Building	8,778	410
Total Population	29,218	3,530
Municipal Solid Waste Generation (kg/day)	42,564.41	8,663.17
Waste Plastic Generation (kg/day)	3,406.24	526.65
Polyolefin Based Waste Plastic Generation (kg/day)	1,892.41	385.16

As mentioned previously, the 3T electric processor was used as the LMDCE solution for converting waste plastic to PDFO. Table 9.2 summarizes the daily feedstock capacity and PDFO production rate for the UKATS processor, as determined in Chapter 7. Table 9.3 provides the average cost of construction and equipment life of the 3T electric processor. In this preliminary analysis, it is assumed that a ready demand exists for PDFO in the parishes of interest, due to the ready application of PDFO as an alternative for diesel and kerosene, especially in diesel generators and kerosene cookstove. It is anticipated that a relatively low amount of PDFO will be generated in comparison with traditional diesel and kerosene, and the use of PDFO is not expected to replace these fuels. As a result, all PDFO generated is sold to the community.

Table 9.2. 3T electric processor operations

Waste Plastic Processed	10 kg/day
PDFO Produced	7.78 L/day (0.78 L/kg of Waste Plastic)
Energy Required	1.45 kWh/L of PDFO

The following factors were considered in the fully and partially decentralized LMDCE supply chain case studies for small-scale entrepreneurs. To determine the number of entrepreneurs that can be supported in a region, it is assumed that all polyolefin-based waste plastic generated may be converted to PDFO.

- Operation costs
    - Purchase price of sorted waste plastic from consumers
    - Cost of 3T electric processor
    - Electricity costs associated with operating the 3T electric processor
- Selling price of PDFO
- Income, or profit earned

The following factors were considered in the partially decentralized LMDCE supply chain case studies for sorted waste plastic collection organizations, or NGOs. In the partially decentralized, lower-income/slums case study, transportation costs are minimized using travelling salesman approach. In the partially decentralized, upper/middle-income, house-to-house collection case study, waste pickup from each street within the region is multiplied by a route planning factor to reflect the roads that are revisited for entrance/exist to and from neighborhoods. In both cases, the minimum amount of sorted waste plastic collection required by the NGO to breakeven is determined.

- Operation costs
    - Purchase price of sorted waste plastic from consumers
    - Cost of industrial shredder
    - Electricity costs associated with operating the industrial shredder
    - Salaries for vehicle driver and industrial shredder operator
    - Overhead costs
- Transportation costs
    - Distance travelled (travelling salesman or total distance of roads times route planning factor)
    - Vehicle type, year, weight, and volume
    - Vehicle fuel economy
    - Diesel fuel costs
    - Number of trips required based on the amount and bulk density of waste plastic collected
    - Vehicle maintenance and repair cost

- Selling price of shredded plastic
- Income earned to breakeven (it is assumed that the NGO operates to generate only sufficient funds required to balance total incurred costs)

The following factors were considered in the fully and partially decentralized LMDCE supply chain case studies for determining emissions (CO_2) associated with conversion of waste plastic to PDFO and consumption of PDFO:

- Generation emissions
  - Emissions from use of electricity
    - Source of electricity generation
  - Emissions from transportation (partially decentralized LMDCE cases only)
    - Vehicle emissions factor based on type and year of model
- Combustion emissions
  - Emissions from combustion of PDFO

9.3.1 Equations for Supply Chain Considerations

<u>Total Costs:</u>

$$Total\ Cost_{Entrepreneur}(\$) = Plastic\ Purchase + Equipment\ Purchase + Equipment\ Operation \tag{9.1}$$

$$Total\ Cost_{Collection\ Facility\ (NGO)}(\$) = Plastic\ Purchase + Equipment\ Purchase + Equipment\ Operation + Transportation + Vehicle\ Maintenance\ \&\ Repair + Employee\ Salary + Overhead \tag{9.2}$$

$$Earnings_{\ Entrepreneur}(\$) = PDFO\ Sale(\$)\ - Total\ Cost_{Entrepreneur}(\$) \tag{9.3}$$

$$Earnings_{\ Collection\ Facility\ (NGo)}(\$) = Plastic\ Sale\ (\$)\ - Total\ Cost_{Collection\ Facility\ (NGO)}(\$) \tag{9.4}$$

Operating Costs:

$$Plastic\ Purchase\ (\$) = Plastic\ Collected\left(\frac{kg}{day}\right) * Plastic\ Purchase\ Price\ \left(\frac{\$}{kg}\right) \tag{9.5}$$

$$Plastic\ Collected\ (kg) = Total\ Plastic\ Generated(kg) * Plastic\ Collection\ Efficiency \tag{9.6}$$

$$Equipment\ Purchase_{\ UKATS\ Electric\ Processor,\ \ Shredder}\left(\frac{\$}{day}\right) = \frac{Annual\ Interest\ Rate\ * Purchasing\ Price\ of\ Equipment}{1 - \frac{1}{(1 + Annual\ Interest\ Rate)^n}} * \frac{1\ year}{365\ days} \tag{9.7}$$

$$Equipment\ Operation_{\ UKATS\ Electric\ Processor}\ (\$) = PDFO\ Conversion\ Energy\ Requirement\ \left(\frac{kWh}{L\ of\ PDFO}\right) * PDFO\ Produced\ (L) * Electricity\ Cost\ \left(\frac{\$}{kWh}\right) \tag{9.8}$$

$$Equipment\ Operation_{\ Shredder}\ (\$) = Shredder\ Power\ Required\ (kW) * Electricity\ Cost\ \left(\frac{\$}{kWh}\right) * \frac{Plastic\ Collected\ (kg)}{Plastic\ Shredded\ \left(\frac{kg}{h}\right)} \tag{9.9}$$

Transportation Costs:

$$Transportation\ (\$) = \frac{Distance\ Travelled(km) * Route\ Planning\ Factor * Fuel\left(\frac{\$}{L}\right)}{Fuel\ Economy\left(\frac{MT - km}{L}\right) * \left(Weight\ of\ Empty\ Vehicle + \frac{Plastic\ Collected}{Trip}\right)(MT)} * Trips\ Required \tag{9.10}$$

$$\frac{Plastic\ Collected}{Trip} = \frac{Plastic\ Collected}{Trips\ Required} \tag{9.11}$$

$$Trips\ Required = \frac{Plastic\ Collected\ (kg)}{Vehicle\ Bed\ Volume\ (m^3) * Waste\ Plastic\ Bulk\ Density\ (\frac{kg}{m^3})} \tag{9.12}$$

$$Maintenance\ \&\ Repair\ (\$) = Distance\ Travelled(km) * Route\ Planning\ Factor * Maintenance\ \&\ Repair\ Factor\ \left(\frac{\$}{km}\right) * Trips\ Required \tag{9.13}$$

Total Emissions:

$$Total\ Emissions(kg\ CO_2) = Generation\ Emissions(kg\ CO_2) + Combustion\ Emissions(kg\ CO_2) \tag{9.14}$$

$$Generation\ Emissions(kg\ CO_2) = Transportation\ Emissions(kg\ CO_2) + Electricity\ Emissions\left(\frac{kg\ CO_2}{kWh}\right) * Total\ Electricity\ Usage_{UKATS\ Electric\ Processor+Shredder}\ (kWh) \tag{9.15}$$

$$Total\ Electiricty\ Usage_{UKATS\ Electric\ Processor+Shredder}\ (kWh) = PDFO\ Conversion\ Energy\ Requirement\ \left(\frac{kWh}{L\ of\ PDFO}\right) * PDFO\ Produced\ (L) + Shredder\ Power\ Required\ (kW) * \frac{Plastic\ Collected\ (kg)}{Plastic\ Shredded\ \left(\frac{kg}{h}\right)} \tag{9.16}$$

$$Transportation\ Emissions(kg\ CO_2) = Distance\ Travelled(km) * Route\ Planning\ Factor * [Weight\ of\ Empty\ Vehicle + Plastic\ Collected](MT) * Vehicle\ Emissions\ Factor\left(\frac{kg\ CO_2}{MT - km}\right) \tag{9.17}$$

The descriptions of the above-mentioned equation variables are detailed in Tables 9.3 and 9.4.

Table 9.3 defines the dependent variables; Table 9.4 details the independent variables, including stochastic and deterministic independent variables, their assumptions, sources, and range of values bookending uncertainty for supply chain considerations.

Table 9.3. List of dependent variables

Dependent Variable	**Description**
Total Cost $_{\text{Entrepreneur}}$	The total operating costs of the entrepreneur
Plastic Purchase	Costs associated with purchasing sorted waste plastic from local consumers
Equipment Purchase	Purchasing price of either the 3T electric processor or an industrial shredder
Equipment Operation	Costs associated with operating either the 3T electric processor or an industrial shredder
Total Cost $_{\text{Collection Facility (NGO)}}$	The total operating and transportation costs of the collection facility, or NGO
Transportation	Transportation costs associated with operating a Class 6-7 medium heavy duty waste pickup vehicle for collecting waste plastic from the community
Vehicle Maintenance & Repair	Costs associated with maintenance and repair of a Class 6-7 medium heavy duty waste pickup vehicle used for collecting waste plastic from the community
Earnings $_{\text{Entrepreneur}}$	The total income earned by the entrepreneur as profits
Earnings $_{\text{Collection Facility (NGO)}}$	The total income earned by the collection facility, or NGO
Plastic Collected	The total amount of plastic collected from the community
Equipment Purchase $_{\text{3T electric processor, Shredder}}$	The annualized equipment costs associated with the purchase of either the 3T electric processor or an industrial shredder, averaged per day
Equipment Operation $_{\text{3T electric processor}}$	Costs associated with operating the 3T electric processor
Equipment Operation $_{\text{Shredder}}$	Costs associated with operating the industrial shredder

Transportation	Costs associated with collecting waste plastic from the community and transporting it to collection facility (NGO) location
Plastic Collected/Trip	Maximum amount of plastic that can be carried in the bed of Class 6-7 medium heavy duty waste pickup vehicle
Trips Required	Number of trips required by the Class 6-7 medium heavy duty waste pickup vehicle to fully collect amount of waste plastic generated within the region
Total Emissions	CO_2 emissions produced from generation and combustion of fuels
Generation Emissions	CO_2 emissions produced from transportation of waste plastic and equipment used to convert waste plastic to PDFO
Total Electricity Usage 3T electric processor + Shredder	Total amount of electricity used for operating the 3T electric processor and industrial shredder
Transportation Emissions	CO_2 emissions associated with use of Class 6-7 medium heavy duty vehicle for collecting and transporting waste plastic

Table 9.4. List of independent variables

Stochastic Independent Variables				
Variable	**Description**	**Source**	**Assumption(s)**	**Range of Uncertainty**
Employee Salary	Salaries of vehicle driver and industrial shredder operator	Data Africa (2021), Paylab (2021)	Average salary for population working as general laborers. It is assumed that the NGO employs 2 people for collecting waste plastic and 1 person for shredding it.	3.10 – 5.56 ($/day)
PDFO Sale	Selling price of PDFO generated from 3T electric processor	GlobalPetrolPrices.com (2021a)	PDFO sold at a discounted price of diesel fuel. Fluctuation in diesel prices is assumed to be 20%.	0.7 – 1.12 ($/L)
Plastic Sale	Selling price of shredded plastic to entrepreneurs as determined by NGO		Value of shredded plastic is higher than that collected from local consumers. Linearly increased according to plastic purchase price.	0.18 – 0.24 ($/kg)
Plastic Purchase Price	Local plastic purchase price, which serves as an incentive for consumers to sort household waste plastic	KCCA (Chapter 3, Section 3.6.)	Based on price per kg of plastic collected by waste pickers at Kiteezi landfill in Kampala, Uganda.	0.11 – 0.17 ($/kg)

Plastic Collection Efficiency	Percentage of plastic collected from the total amount of plastic generated by the community.		Reflects the amount of education provided by the NGO to the general population for sorting and recycling waste plastic, and the participation rate of the community.	Minimized to determine the percentage of plastic collection required by NGO to breakeven.
Annual Interest Rate	Annual interest rate to account for inflation within country	Trading Economics (2021)		2.4 – 3.4 (%)
Purchasing Price of Equipment	Total purchase price of either the 3T electric processor or the industrial shredder	Chapter 7, Section 7.2 INTBUYING (2021)	3T electric processor costs are determined based on quality of fabrication materials.	3T electric processor: 700 – 900 ($) Shredder: 1,459 – 1,659 ($)
"n"	Number of years		Lifespan expectancy of 3T electric processor and industrial shredder	3T electric processor: 3 – 5 (years) Shredder: 5 – 7 (years)
Electricity Cost	Cost of electricity per hour	GlobalPetrolPrices.com (2021b)	Electricity use for small-scale entrepreneur is charged according to household rate (0.19 $/kWh); whereas the NGO is charged according to business rate (0.16 $/kWh). Fluctuation in	Household: 0.15 – 0.22 ($/kWh) Business: 0.13 – 0.19 ($/kWh)

			electricity price is assumed to be 20%	
Fuel	Price of diesel fuel for operating waste pickup vehicle	GlobalPetrolPrices.com (2021)	Fluctuation in diesel prices is assumed to be 20%.	0.82 – 1.23 ($/L)
Fuel Economy	Fuel economy of a Class 6-7 medium heavy duty waste pickup vehicle	Haven, P. and Gutin, O. (2015)	Varied between 2016-2021 vehicle models	18.47 – 23 (gallons/1,000 ton-mile)
"MT"	Metric tons	N/A	N/A	N/A
Weight of Empty Vehicle	Weight of empty Class 6-7 medium heavy duty waste pickup vehicle	Energy Efficiency & Renewable Energy (2010).		11,500 – 14,500 (lb)
Vehicle Bed Volume	Volume of a Class 6-7 medium heavy duty waste pickup vehicle	Hawley (2021)		10 – 16 (cubic yards)
Waste Plastic Bulk Density	Bulk density of waste plastic collected from household wastes	WRAP (2009)	Field work data for mixed plastic with film measured in a 7.5-15 MT caged stillage with no compaction and measured as 28 kg/m^3.	20 – 40 (kg/m^3)
Maintenance & Repair Factor	Average maintenance and repair costs associated with driving a heavy duty vehicle	McClusky, B. (2012)	Heavy duty vehicle assumed to be 0.05 $/mile for a new vehicle, or 0.15 $/mile for a 5+ years old or 750,000+ miles driven vehicle	0.05 – 0.15 ($/mile)

Combustion Emissions	Emissions generated from use of PDFO.		PDFO derived from polyolefin plastics (HDPE, LDPE, and PP) as reported in Chapter 7.	2.24 – 2.34 (kg CO_2/L of PDFO)
Vehicle Emissions Factor	Amount of CO_2 emitted from a Class 6-7 medium heavy duty waste pickup vehicle	Haven, P. and Gutin, O. (2015)	The vehicles in operation in Uganda are likely to be older, used models. Hence, emissions are based on 2014 vehicle models.	210 – 250 CO_2 g/short ton-mile
Deterministic Independent Variables				
Variable	**Description**	**Source**	**Assumption(s)**	**Value**
Overhead	Overhead costs associated with NGO's operation		10% of plastic sale	10 (%)
Total Plastic Generated	Amount of plastic generated per parish as determined in Table 9.1.	Chapter 5	Chapter 5	Rubaga parish: 1,941.55 (kg) Kololo IV parish: 300.19 (kg)
PDFO Conversion Energy Requirement	The amount of energy required to produce a liter of PDFO from waste plastic	Chapter 7	Chapter 7	1.45 (kWh/L of PDFO)
PDFO Produced	Total amount of PDFO produced from waste plastic collected	Chapter 7	Chapter 7	0.87 (L PDFO/kg plastic)

Shredder Power Required	Amount of power required to operate industrial shredder	INTBUYING (2021)		2.2 (kW)
Plastic Shredded	Plastic shredding capacity of industrial shredder	INTBUYING (2021)		125 (kg/h)
Distance Travelled	Total distance travelled by waste pickup vehicle	Section 9.3.3 and 9.4.1	Section 9.3.3 and 9.4.1	Rubaga parish, Travelling Salesman: 12.85 (km) Kolol IV parish, House-to-House: 14.01 (km)
Route Planning Factor	A multiplication factor that accounts for the distance repeated by waste pickup vehicle when entering/existing roads to collect waste plastic	Section 9.3.3	Section 9.3.3	Rubaga parish, Travelling Salesman: 1 Kololo IV parish, House-to-House: 1.5
Electricity Emissions	CO_2 emissions produced from electricity generation	World Nuclear Association, 2011	Electricity in Kampala, Uganda is sourced from a hydroelectric plant.	0.026 (kg CO_2/kWh)

9.3.2 Minimizing Transportation Costs via Travelling Salesman for Partially Decentralized LMDCE, Lower-Income/Slums

For the purposes of this research, KCCA assisted in determining the waste data collection points in Rubaga parish by georeferencing the location of existing skips. Epicollect5 version 2.0, a web, and mobile data collection application (epicollect5, 2019) was used to collect georeferenced data regarding the municipal solid waste collection points. KCCA sourced and employed individuals from Rubaga division to travel with KCCA waste pickup vehicle drivers to mark the skips' locations using Epicollect5 in smartphones featuring a global positioning system (GPS). The data collectors were recruited based on the individuals' knowledge of the geographical boundaries of the Rubaga division, interpersonal relationships, and smartphone literacy, and were trained on how to use the Epicollect5 mobile application to collect the data.

After data collection, the georeferenced KCCA skip locations were then imported to a QGIS software (QGIS 2019) with OpenStreetMap (OpenStreetMap, 2021) to begin conducting a travelling salesman analysis for the NGO collecting waste plastic in the partially decentralized LMDCE, lower-income/slums case study. In the initial supply chain considerations, the NGO is assumed to be located within the parish. Therefore, an empty plot of land was surveyed using QGIS and OpenStreetMap and used as the assumed location for the NGO. An inbuilt, free, QGIS transportation logistics and mapping tool, known as ORS Tools, was utilized to determine the optimum transportation route for the NGO by performing the travelling salesman calculations. ORS Tools is a crowdsourced application programing interface (API) from openrouteservice (openrouteservices, 2021). By relying on the existing global geographical data coverage present in OpenStreetMap, ORS Tools has the functionality to compute directions, time-distance matrices, isochrones, and route optimizations (openrouteservice, 2021).

The georeferenced skip locations and the chosen NGO facility location were added within the ORS Tools interface and its inbuilt travelling salesman calculation was performed (present in Advanced Configurations menu in ORS Tools). The optimum route and total distance travelled for gathering waste plastic from collection points within Rubaga parish were determined.

9.3.3 Transportation Costs for Partially Decentralized LMDCE, Upper/Middle-Income

In the house-to-house waste collection case study for partially decentralized LMDCE, upper/middle-income, the waste pickup vehicle was assumed to travel all the main roads of the Kololo IV parish. QGIS and OpenStreetMap were also employed in this scenario to determine the total distance of road infrastructure present in the parish. By using in-built OSM Downloader tool, multiline strings were downloaded as a map layer from OpenStreetMap. These multiline strings converted the existing road infrastructure into simple polylines that could be measured (by applying QGIS Add Geometry Attributes tool) to determine the distance of each string. The summation of distance provided the total distance travelled by the waste pickup vehicle for collecting waste plastic from each house or business within the parish.

To account for the roads that are travelled in both directions for waste pickup, or that must be revisited for entering/exiting the region, the total road infrastructure distance was multiplied by a route planning factor. In this analysis, this factor was assumed to be 1.5, indicating that half of the roads within the parish were travelled twice for waste plastic collection.

9.3.4 Uncertainty Assessment

To understand and quantify the inherent uncertainty present in the variables of the LMDCE supply chain factors, a lower and upper range was determined for the stochastic variables to bookend their approximate values in reality. This procedure was followed for all stochastic variable using the ranges of uncertainty presented in Table 9.3. By allowing Microsoft Excel to randomly select each stochastic variable's value between the specified range and by performing 1000 iterations for the calculations in Equations 9.1-9.17, resulted the following average outputs and their respective standard deviations:

- Fully decentralized LMDCE, lower-income/slums
    - Number of processors supported by the region = number of jobs created for small-scale entrepreneurs
    - Small-scale entrepreneur earnings
    - PDFO generation and combustion emissions
- Partially decentralized LMDCE, lower-income/slums
    - NGO earnings (minimized to breakeven)
    - Number of processors supported
    - Number of jobs created (small scale entrepreneurs and NGO employees)
    - Small-scale entrepreneur earnings
    - PDFO generation and combustion emissions
- Partially decentralized LMDCE, upper/middle-income
    - NGO earnings (minimized to breakeven)
    - Number of processors supported
    - Number of jobs created (small scale entrepreneurs and NGO employees)

- Small-scale entrepreneur earnings
- PDFO generation and combustion emissions

Initially, the plastic collection efficiency was randomly varied with the other stochastic variables. This led to the earning of the NGO being higher than the breakeven point, or a profit was generated. For this reason, the plastic collection efficiency was minimized to determine the breakeven point for the NGO. In return, the amount of educational training required in the community for promoting waste plastic recycling is determined. The results of this analysis are presented in Section 9.4.

9.4 Results and Discussion

9.4.1 Travelling Salesman Results

The optimized route for collecting waste plastic from skip locations in Rubaga parish for the partially decentralized LMDCE, lower-income/slums case study is presented in Figure 9.5. The total distance travelled by the waste pickup vehicle was 12.85 km.

9.4.2 House-to-House Transportation Distance Results

The total distance travelled by the waste pickup vehicle for collecting waste plastic from house-to-house for the partially decentralized LMDCE, upper/middle-income case study was determined to be 14.01 km, represented in Figure 9.6 for Kololo IV parish.

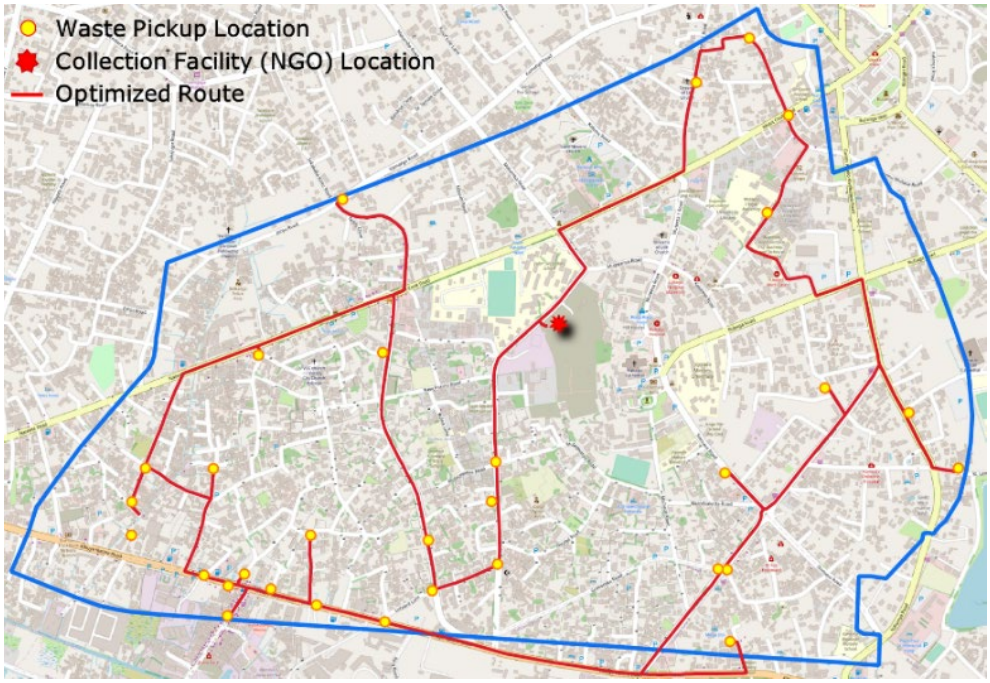

Figure 9.5. GIS results of travelling salesman approach for collecting waste plastic from Rubaga parish

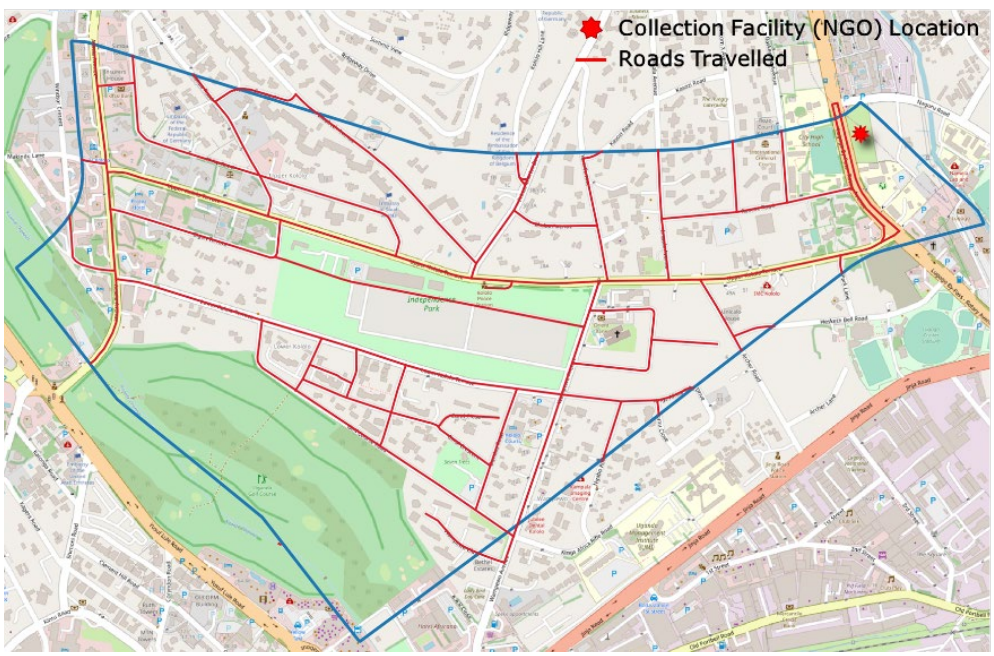

Figure 9.6.GIS results of house-to-house waste plastic collection for Kololo IV parish

9.4.3 Supply Chain Considerations and Uncertainty Assessment Results

Table 9.5 reports the results of the fully and partially decentralized LMDCE case studies. In the fully decentralized LMDCE, lower-income/slums case study, the increased population density resulted in a greater amount of waste plastic being displaced from the ecosystem. Since this approach aims to identify the total LMDCE implementation potential by assuming 100% waste plastic conversion to PDFO, approximately 189 small-scale entrepreneur jobs were created with an average daily earning of $3.57. This is slightly higher than the average general labor rate of $3.10/day (Data Africa 2021). In this case study, the entrepreneur incentivizes community sorting of waste plastic by paying the local consumer $0.14/kg for the sorted waste plastic.

Next, in the partially decentralized LMDCE case studies, both for the lower-income/slums and upper/middle-income regions, the amount of waste plastic collection from the community was minimized to determine the participation rate and waste management education requirements of consumers for breaking even. In the lower-income/slums region of Rubaga parish, a 20% participation rate was required for the NGO to purchase sorted waste plastic from consumers, collect it from the skip locations via travelling salesman approach, shred it, and sell it for an increased price to entrepreneurs. In doing so, the NGO earned approximately $1.56/day after all costs, and the entrepreneur earned $2.82/day. The NGO's earnings are minimal since they reflect breakeven gains; however, as the entrepreneur pays a premium price for shredded waste plastic ($0.21/kg), the entrepreneur makes lower than the general labor rate (Data Africa 2021).

A similar result is produced in the partially decentralized LMDCE for upper/middle-income parish of Kololo IV, where house-to-house waste collection by the

NGO and purchase of waste plastic from affluent consumers leads to significant upstream costs for the NGO. For instance, even if the NGO collects 100% of all waste plastic generated within the region, it experiences an average loss of $0.74/day without significantly increasing the selling price of plastic for the entrepreneurs. In return, the entrepreneur earns approximately $2.86/day for purchasing the shredded plastic at the premium price of $0.21/kg.

As a result, two additional scenarios were tested for the partially decentralized LMDCE for upper/middle-income regions: 1) receiving the sorted waste plastic for free from consumers and 2) providing a plastic recycling service to the consumers by charging a fee for waste plastic pickup at $0.10/day per household (Table 9.5). Since the NGO doesn't encounter any upstream plastic purchasing costs in these two scenarios, the NGO begins to breakeven in these two scenarios and the plastic collection efficiency decreases to 35% for free plastic pickup, and 20% for charged waste plastic pickup. The shredded plastic purchase price for the entrepreneurs is also reduced to $0.14/kg in these two scenarios. In return, the entrepreneurs' earnings reflect those of the fully decentralized LMDCE case study.

In general, as plastic collection efficiency decreases, the number of jobs created in the community decrease due to a decrease in demand for sorted waste plastic. A decrease in plastic collection efficiency further leads to an increase in CO_2 generation emissions for implementing LMDCE in a partially decentralized case study. This is due to the waste pickup vehicle being primarily empty when collecting waste plastic from skips or from households at lower waste plastic collection efficiencies. Nonetheless, in all cases presented in Table 9.5, a net reduction in CO_2 emissions is observed for generation and combustion of PDFO via LMDCE, varying between 12.92-31.27%, with a standard deviation of 0.88-1.65% when compared with diesel WTT emissions.

Lastly, the uncertainty assessment determined that by varying the independent stochastic variables considered in the supply chain case studies, the standard deviation for NGO earnings and small-scale entrepreneur earnings varied between 107.05-352.86% and 31.93-39.51%, respectively. The high standard of deviation for the NGO's earnings can be associated with the uncertainty of the community's participation in waste plastic recycling and the NGO's staffing approach, which contribute to approximately 95% of total operating costs. For instance, verifying if an incentive is needed for low-income/slums and upper/middle-income communities to sort the waste plastic and the price at which consumers are willing to sell the waste plastic to the NGO, will reduce upstream waste plastic collection costs and stabilize the size of the NGO's outreach. Additionally, by stabilizing the average daily waste plastic collection and shredding operations, the staffing costs of the NGO may be reduced. For example, a set of individuals may be able to both collect the waste plastic from participating consumers and shred it in the same day, instead of hiring both vehicle drivers and operators for shredding the waste plastic.

Table 9.5. Results of supply chain consideration and uncertainty assessment for fully and partially decentralized LMDCE case studies

Case Study	**Fully Decentralized LMDCE, Lower-Income/Slums, Plastic Purchased from Consumer**		**Partially Decentralized LMDCE, Lower-Income/Slums, Plastic Purchased from Consumer**		**Partially Decentralized LMDCE, Upper/ Middle-Income, Plastic Purchased from Consumer**		**Partially Decentralized LMDCE, Upper/ Middle-Income, Free Plastic Collection**		**Partially Decentralized LMDCE, Upper/ Middle-Income, Plastic Collection Fee Paid by Consumer**	
Uncertainty	Results	Standard Deviation	Results	Standard Deviation	Results	Standard Deviation	Results	Standard Deviation	Results	Standard Deviation
Plastic Collection Efficiency (%)	100	-	20	-	100	-	35	-	20	-
Waste Plastic Displaced (kg)	1,892.41	-	378.48	-	385.16	-	134.81	-	77.03	-
NGO Plastic Purchase Price ($/kg)	-	-	0.14	-	0.14	-	0.00	-	$0.10/day per household	-
Entrepreneur Plastic Purchase Price ($/kg)	0.14	-	0.21	-	0.21	-	0.14	-	0.14	-
3T electric processors Supported	189	-	37	-	38	-	13	-	7	-
Jobs Created	189	-	40	-	41	-	16	-	10	-
NGO Earnings ($/day)	-	-	1.56	1.67	0.74	1.79	0.70	2.47	1.07	1.92
Small-Scale Entrepreneur Earnings ($/day)	3.57	1.14	2.82	1.10	2.86	1.13	3.47	1.12	3.52	1.14
PDFO 3T Emissions (% reduction from Diesel WTT Emissions)	31.37	0.88	28.03	0.91	26.60	0.91	20.33	1.18	12.92	1.65

9.5 Application to Sustainability

The economic sustainability of the LMDCE model is directly correlated to the amount of waste plastic present in a region, as depicted in Table 9.5. In the fully decentralized LMDCE for lower-income/slums region of Rubaga Parish, a total potential for 194 small-scale entrepreneur jobs existed. In the partially decentralized LMDCE for upper/middle-income region of Kololo IV, approximately 10-13 jobs could be supported based on the plastic collection efficiency. The profit earned by the entrepreneurs is primarily a function of the plastic purchasing price and the price of electricity, contributing to approximately 90% of the total operating costs. In like terms, breakeven costs for the NGO are impacted by the purchasing price of plastic and staffing requirements. However, as long as a demand exists for sorting and collecting waste plastic, and converting it into a meaningful recycled product locally, positive economic gains are anticipated from the sale of PDFO.

The environmental sustainability of LMDCE is positive in all scenarios of fully and partially decentralized case studies. A net reduction in CO_2 generation and combustion emissions is experienced when compared with WTT emissions for diesel. The CO_2 emissions are reduced from 12.92-31.27% for implementing LMDCE. This is because the waste plastic is sourced locally, transported locally, and converted to PDFO locally via a renewable form of electricity (hydroelectric power for Kampala, Uganda). In general, the fully decentralized model yields the highest emissions benefits as transportation emissions are eliminated.

Defined as the measure of humanity's welfare, in literature, social sustainability is indicated by protection of human health, participation and education of communities, promotion of sustainable living, environmental justice, and resource security (Mohamed and Paleologos, 2021, USEPA, 2015). By considering these aspects, the societal sustainability of LMDCE implementation can be attributed to increasing rural and developing communities' participation in recycling of valuable materials via a cradle-to-grave approach that eliminates waste plastic from the environment. In return, the community benefits from improved health due to the reduction of waste plastic accumulation, and small-scale entrepreneurs experience increased standard of living that may further promote increased societal fairness. Specifically, the 3T electric processor can be operated by individuals with minimal technical education, including homemakers and single parents to either increase or supplement their daily income.

9.6 Conclusion

This research contribution analyzed the supply chain considerations of implementing LMDCE in a developing region for combating waste plastic accumulation via the 3T electric processor. Three LMDCE case studies were evaluated: 1) fully decentralized LMDCE in lower-income/slums with small-scale entrepreneurs individually collecting and processing waste plastic to PDFO, 2) partially decentralized LMDCE in lower-income/slum with NGOs serving as plastic collection facilities, collecting sorted waste plastic from skip locations, shredding and selling it to entrepreneurs for processing, and 3) partially decentralized LMDCE in upper/middle-income regions with NGOs collecting waste plastic from house-to-house, followed by the steps identified in part 2. Additionally, the impact of waste plastic collection efficiency, plastic purchase price, and range of uncertainty associated with stochastic variables were studied. Conclusively, the supply chain considerations and uncertainty assessment of LMDCE implementation in developing regions yielded positive overall economic, environmental, and societal benefits.

CHAPTER 10. FUTURE WORKS

The future works of this research contribution can be categorized into the following areas of further study, development, and analysis.

10.1 Estimating Waste Plastic Generation Globally via Geographical Analysis

This research utilized geographical analysis and availability of waste management data from Kampala, Uganda to estimate waste plastic generation for Sub-Saharan African regions at a community level. However, the Geographical Information System (GIS) and OpenStreetMap tools can be combined in a similar approach to estimate waste plastic generation for other developing regions globally, and will be especially beneficial in Norther Africa, South Asia, Middle East, South America, and Central America. By identifying data for a subset of these continents, waste plastic generation behavior can be predicted by the model to provide an estimated total waste plastic generation and the potential impacts of appropriate waste management solutions.

10.2 PDFO Composition

In this analysis, the effects of temperature and time on PDFO composition and stability were studied via gas chromatography-mass spectrometry (GC-MS) and thermogravimetric analyzer (TGA), respectively. However, PDFO composition can also be characterized using Fourier-transformed infrared spectrometry (FTIR), boiling point, and density. The results of these analysis can be similarly compared with diesel and kerosene to further assist in identifying optimum operating condition for generating a PDFO more similar to diesel or kerosene in appropriate technology applications.

The PDFO 3T processor also has the potential to serve as a simple, reflux column. Once PDFO has been generated by pyrolysis of waste plastic, it can be fed back in the 3T electric processor retort on a batch-scale to boil out distillates in the kerosene and diesel ranges according to the densities of traditional diesel and kerosene. This is an appropriate technology solution for fractioning PDFO, and its composition should be further verified using the analysis techniques mentioned above.

10.3 Use of PDFO as an Alternative to Diesel and Kerosene

Subsequently, the PDFO generated should be tested in a diesel engine or kerosene cookstove (based on PDFO composition) to determine its performance and emissions in comparison to traditional diesel and kerosene. The use of PDFO in diesel engines can ben modeled similar to previously published literature (Kalagaris, 2017a, Kalagaris 2017b, Kalagaris 2018, Kumar & Sankaranarayanan, 2016) to determine how PDFO produced in a locally managed decentralized circular economy (LMDCE) based appropriate technology setting differs from lab scale settings.

To test the performance of PDFO in a kerosene cookstove as an alternative for cooking oil, the combustion emissions of PDFO should be assessed via U.S. Environmental Protection Agency (USEPA) methods 8260D (USEPA 2006) and 8270E (USEPA 2014), along with testing for particulates. USEPA method 8260D is industry standard for analyzing volatile organic compounds by gas chromatography-mass spectrometry (GC-MS) (USEPA 2006), while USEPA method 8270E analyzes semi-volatile organic compounds by GC-MS (USEPA 2014). Due to simple hydrocarbon chemistry of polyolefin-based plastics, PDFO does not generate sulfur oxide (SOx) emissions when combusted. This advantage over traditional petroleum derived kerosene may lead to improved health for communities using kerosene as a source of cooking fuel.

APPENDIX A. SUPPLEMENTARY INFORMATION – METRIC GENERATION

Methods

In this study, we have established a metric based on the principles of sustainability to determine critical locations suitable for implementing locally managed decentralized solutions (LMDCE) for waste management, mainly targeting unsound disposal of waste plastic on land. A list of 200 countries were analyzed using 9 indicators, representing the three pillars of sustainability – economic, social and environmental. These indicators include, gross domestic product (GDP) (Billion USD), GDP per capita (USD), population, population below poverty line (%), population density (capita/km^2), estimated MSW generation (MT/day), environmental stress (MT MSW/km^2), estimated waste plastic in MSW (MT/day), and estimated unsound waste plastic disposal (MT/day). For a given nation, our goal was to understand how factors beyond environmental contributors, such as economic status and population growth impacted waste plastic generation and accumulation.

To develop the metric, year 2016 was chosen as the basis for analysis since it is the latest available reported data. Country specific statistics for economic and social indicators were obtained from the U.S. Department of State and the U.S. Central Intelligence Agency (Central Intelligence Agency [CIA] 2017a, CIA 2017d, CIA 2017e, CIA, 2017f, U.S. Department of State, 2017). Environmental indicators, including of MSW generation per capita and % plastic in MSW were obtained from the World Bank (Hoornweg & Bhada-Tata, 2012), while unsound MSW disposal information was obtained from Waste Atlas, an online crowdsourced MSW management database (Waste Atlas, 2017). Unsound MSW disposal refers to open dumping or burning of waste in controlled or uncontrolled dumpsites. Hence, unsound waste plastic disposal was calculated based on percent of plastic present in MSW and percent of MSW unsoundly disposed. Additionally, total land area – excluding area occupied by major bodies of water – was used to calculate the population density and environmental stress, based on total population and MT of MSW generated per km^2, respectively (CIA, 2017b).

To address the problem of missing data for certain indicator categories for some countries, the World Bank income level (dependent on gross national income) and region classifications were used to group the countries and average the available reported data (Hoornweg & Bhada-Tata, 2012, Waste Atlas, 2017, World Bank, 2017). These averages were then substituted for the missing data. Grouping the countries based on these classifications simultaneously provided close approximations of current situations as countries in the same region with similar financial outlooks are likely to experience similar waste management challenges.

These classifications were also used to determine the estimated percentage of waste plastic in MSW in 2016. To estimate this value, we linearly interpolated reported data on percent plastic in MSW for 2005 and 2025. The 2025 projections were based on income level; as a result, the nations with reported data for 2005 were assigned 2025 projection values. As mentioned previously, the countries with unreported percent plastic in MSW data for 2005, and hence, 2025, were estimated based on the grouping technique. This generated a complete list of percent plastic in MSW for 2005 and 2025, which was linearly interpolated for 2016. This final percent value was then multiplied by estimated MSW generation (MT/day) to obtain estimated waste plastic in MSW (MT/day).

Country Data

The list of countries and regions was obtained from the U.S. Department of State (U.S. Department of State, 2017). This list accounted for a total of 202 established nations. This list does not include territories or islands occupied by several countries. From the list, Holy See, or Vatican City, and North Korea were removed due to lack of data in several of the economic, environmental, and social indicators, yielding a list of 200 nations. Palestinian territories were included, comprising of West Bank and Gaza Strip.

Calculation Basis

Three indicators were chosen as reference tools for estimating missing country-specific data in each indicator type or as precursor data for calculating other indicators. All together they are:Income Level 2015, Region, and Land Area 2016 (km^2). For each indicator, several countries, marked with an asterisk (*) were found to have insufficient data. Reported data in each indicator type was obtained from the same source for consistency. As a result, if the source did not report data for a given country, that country was marked with an (*).

Income Level 2015 refers to income level thresholds as generated by The World Bank based on Gross National Income 2015 (World Bank, 2017), and includes Low Income (LI), Low Middle Income (LMI), Upper Middle Income (UMI) and High Income Countries (HIC). Region classifications include East Asia and Pacific (EAP), Europe and Central Asia (ECA), Latin America and the Caribbean (LCR), Middle East and North Africa (MENA), South Asia (SAR), Sub-Saharan Africa (AFR), and Organization for Economic Cooperation and Development (OECD) countries. However, the World Bank

(World Bank, 2017) reported Curacao, Nauru, Sint Maarten and Tuvalu as “other” in region-based classification. Consequently, for coherency, Income Level and geography of these regions were used to classify them. Curacao and Sint Maarten were classified as OECD, while Nauru and Tuvalu were identified as EAP.

Data for (*) countries was estimated using Income Level and Region classifications. Again, based on the assumption that countries in the same region, with similar economic status are likely to face similar challenges and benefits, generated comparable data. Hence, in each group, an average of referenced available data was taken, which in return was used as a replacement for missing data. In some groups, referenced data was only available for one country, or only one country (with missing data) existed. In this case, an average of available countries in the overall Income Level category was taken as replacement for missing data. These methods were followed for all indicators, generating a complete set of data for the 200 countries evaluated in this study.

The Land Area 2016 (km^2) data was obtained from U.S. Central Intelligence Agency (CIA, 2017b). This category excluded area occupied by bodies of water in a country. However, for countries of Sudan and South Sudan, total area (land and water) was used, as this was the only information reported by the source. This calculation basis indicator was used to calculate Population Density (capita/km^2) and Environmental Stress (tonnes of municipal solid waste/km^2) indicators.

Economic Indicators

Gross Domestic Product (GDP) 2016 (Billion USD) and GDP per Capita 2016 (USD) were used as economic indicators for this study. Data was obtained from U.S. Central Intelligence Agency (CIA, 2017d, CIA, 2017e, CIA, 2017f). Latest available data was used as reported by the source. Countries with data prior to 2016 are footnoted. These economic indicators were used to identify developing, poverty-stricken countries where distributed solutions for waste plastic management can be used as entrepreneurial opportunities.

Social Indicators

The social indicators chosen for this study were based on population statistics. These include Population 2016, Population Below Poverty Line 2016 (%) and Population Density (capita/km^2). The first two indicators were sourced from U.S. Central Intelligence Agency (CIA, 2017a, CIA, 2017e, CIA, 2017f). Population Density was calculated by diving Population 2016 by Land Area 2016 (km^2). Countries with data prior to 2016 are footnoted. For Palestinian Territories, Population Below Poverty Line 2016 (%) was reported separately for West Bank and Gaza Strip. As a result, to obtain an average value of the overall region, the reported percentages for each region were multiplied by the respective population present to obtain total individuals living below poverty line in each region. These numbers were summed and divided by the total population of both regions, multiplied by 100 to obtain an average percentage value of Population Below Poverty Line 2016 for Palestinian Territories. These social indicators were used to understand the impact of population on a country's waste generation, how developed the population is, and the result of population density on determining the most feasible targeted solution to waste plastic management.

Environmental Indicators

The Environmental indicators were specifically focused on waste accumulation. The indicators observed in this study include Estimated MSW Generation 2016 (tonnes/day), Environmental Stress (tonnes MSW/km^2), Estimated Waste Plastic in MSW 2016 (tones/day) and Estimated Unsound Waste Plastic Disposal (tonnes/day). A publication by The World Bank, *What a Waste, A Global Review of Solid Waste Management* (Hoornweg & Bhada-Tata, 2012), reported the amount of MSW generated in kg/capita/day during 2005 and projected generation for 2025 for 161 countries (Hoornweg & Bhada-Tata, 2012). These two sets of data were linearly interpolated to estimate MSW generation in kg/capita/day for 2016. See Equation A.1. In addition, the missing data for the remaining 39 countries was obtained via average grouping as described in Calculation Basis. Lastly, this estimated MSW generation 2016 (kg/capita/day) was multiplied by Population 2016 and conversion factor of 1,000 from kg to tonnes to obtain Estimated MSW Generation 2016 (MT/day). Note, the total amount in tonnes/day for year 2016 is greater than that reported in What a Waste, Estimated Generation 2025 (MT/day) as the latter number only reports the amount of waste generated by the urban population of 2025.

$$Y_2 = \frac{(X_2 - X_1)(Y_3 - Y_1)}{(X_3 - X_1)} + Y_1, where\ Y_2\ is\ the\ desired\ middle\ point \tag{A.1}$$

Environmental Stress (MT MSW/km^2) is Estimated MSW Generation 2016 (MT/day) divided by Land Area 2016 (km^2), times 365 days. Furthermore, Estimated Waste Plastic in MSW 2016 (MT/day) was determined by using The World Bank data for 145 countries, which reported % of MSW comprised of waste plastic for 2005 (Hoornweg & Bhada-Tata, 2012). The report moreover predicted the % increase in waste plastic generation based on Income Level for year 2025. Hence, this data and Equation A.1 were used to generate % waste plastic for 2016, and remaining missing data was averaged based on available data, according to the method described previously. In conclusion, this % based result was multiplied by Estimated MSW Generation 2016 (MT/day) to obtain Estimated Waste Plastic in MSW 2016 (MT/day). Note, Turkey's plastic composition % varied from 5-14% for year 2005; as a result, this data was treated as missing. The grouped average result for Turkey was 8.38%, which was concluded to be accurate in this case, and used for further calculations.

Finally, an unsound disposal of MSW (%) category was added to estimate the amount of mismanaged waste. Waste Atlas, an online crowdsourced MSW management database was used as the source of this data (Waste Atlas, 2017). This data was reported in percentage and was directly correlated to the percent of unsound waste plastic disposal—the target category, with the missing data being averaged according to grouping technique. This yielded Estimated Unsound Waste Plastic Disposal in (tonnes/day) after multiplying the percent unsound waste plastic disposed by Estimated Waste Plastic in MSW 2016 (MT/day). This method of averaging data based on nearby regions was particularly helpful for this indicator. The reason being most of the missing data accounted for countries in the low or low-middle income level. In these regions, waste is disposed where convenient, and municipalities do not have resources to collect all the waste, let alone collect waste composition data, requiring for the data to be approximated based on similarity with nearby countries. Therefore, these are the countries in most need of and appropriate for a LMDCE as solutions to waste accumulation are managed by individuals, communities and waste pickers rather than relying on governmental municipalities and established waste management infrastructure.

Generation of Heat Map

First, all countries in each economic, social and environmental indicator were given a value, or ranked, from 1 to 200. Countries that performed the poorest, were highly populated and generated the highest amount of waste were assigned low values, while the opposite were assigned top values. As a result, the lowest scoring country in each indicator type received a value of 1, while the best received the highest value. If in an indicator category, two or more countries had the same data value, they were given the same score. For instance, several OECD countries in the unsound disposal category reported 0% mismanagement of MSW. As a result, they were all assigned the same score. Therefore, in some indicator categories, the score did not reach up to 200.

Furthermore, weighting factors were applied to each indicator type. Users can adjust global or indicator specific weighting factors according to a region's unique challenges or to highlight a specific category that contributes to waste plastic mismanagement. Weighting factors were then multiplied by the country score, or rank. Both global weighting factors and indicator-specific weighting factors were considered. The purpose of the global weighting factors was to weigh the three pillars of sustainability (economic, social and environmental) equally. Likewise, the purpose of the indicator specific weighting factors was to weigh all indicators in each of the three pillars equally. Hence, initially, the global indicators were assigned values of 33.33%, while the 8 individual indicators were given values of 50% (economic), 33.33% (social), and 25% (environmental). Lastly, the summation of each country's indicator ranking multiplied by its weighting factor, multiplied by the global weighting factor generated the data required for producing the heat map, as shown in Equation A.1 in the main body of the text. As a result, the country with the lowest total sum was noted to be the region where a LMDCE is likely to be successful. These regions are highlighted in the heat map with dark colors. In contrast, countries with highest total sum are likely to be economically developed, where waste management is currently occurring efficiently, and recycling practices are performed with a centralized circular economy, requiring minimal change, and were shaded with light colors on the heat map. The map was generated using mapchart.net online software (mapchart.net, 2018).

APPENDIX B. TGA RESULTS OF PDFO AS A FUNCTION OF TIME

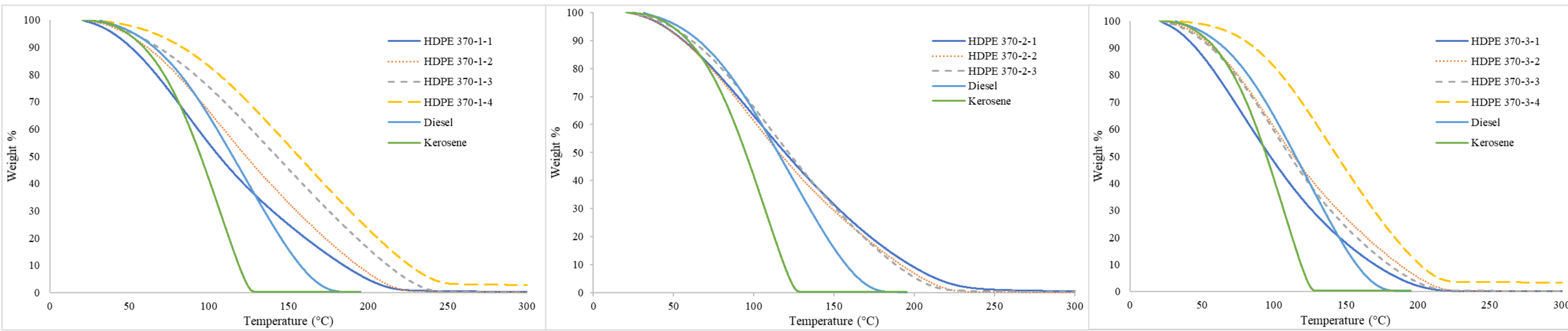

Figure B.1 TGA Results for HDPE (370°C) as a function of time

Note, sampling name convention is "PLASTIC Temperature-Run#-Sample#", i.e., "HDPE 370-1-1" indicates the first sample for the first run of HDPE at 370°C.

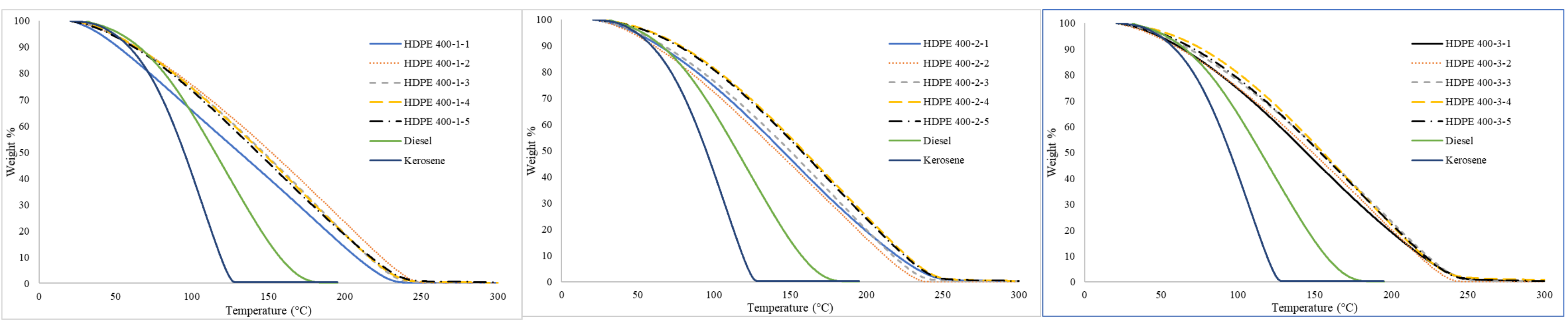

Figure B.2 TGA Results for HDPE (400°C) as a function of time

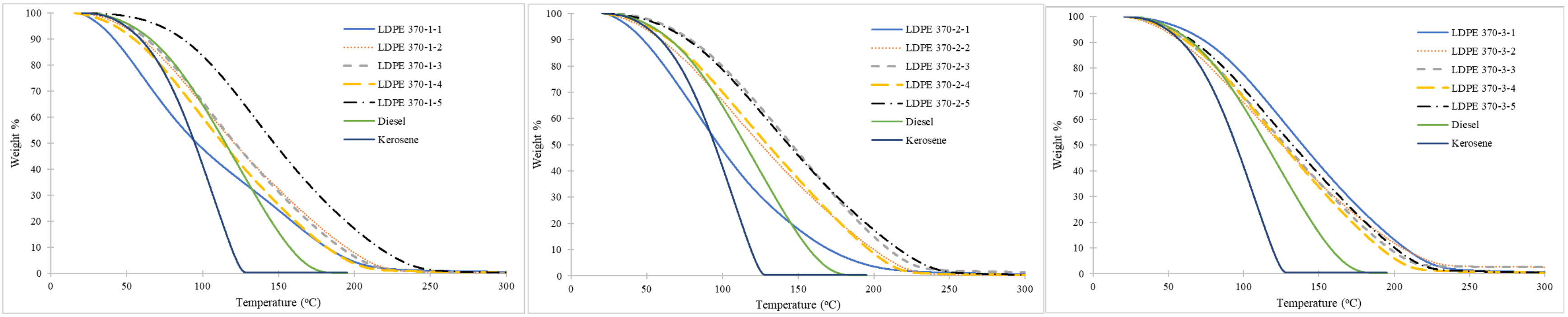

Figure B.3 TGA Results for LDPE (370°C) as a function of time

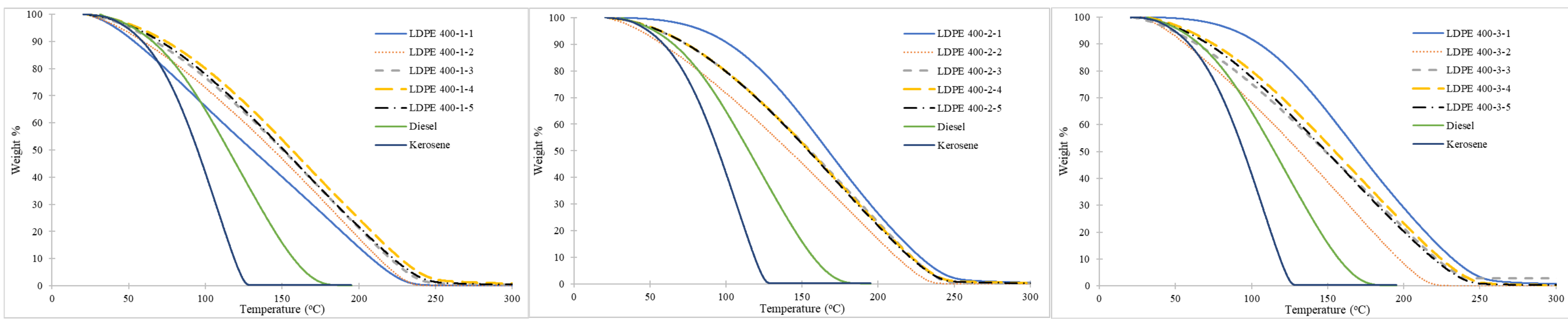

Figure B.4 TGA Results for LDPE (400°C) as a function of time

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Professional Publications:

Joshi, C., Browning, S. & Seay, J. (2020). Combating plastic waste via Trash to Tank. Nature Reviews Earth & Environment 1, 142. https://doi.org/10.1038/s43017-020-0032-3

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Joshi, C., Seay, J. (2020). Optimization of Fuel Composition for Plastic Derived Fuel Oil Produced via Trash to Tank. American Institute of Chemical Engineers Annual Meeting. Virtual Presentation.

Joshi, C., Rana, T. Seay, J. (2019). Determining Waste Plastic Generation in Developing Cities via Geographical Analysis. American Institute of Chemical Engineers Annual Meeting. Presented by Co-Author.

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Joshi, C., Seay, J. (2016). Developing a Sustainable, Appropriate Technology Based Solution to Convert Municipal Solid Waste Derived Plastics into Fuel Oil. International Congress on Sustainable Chemistry Product and Process Engineering.

Joshi, C., Higgins, J. (2016). An Appropriate Technology Based Solution for Assisting Developing Countries in Meeting Their Advancement Challenges. Makerere University.

Scholastic and Professional Honors:

1st Place International Rapid Fire People's Choice Award, International Congress on Sustainability, Science and Engineering, August 2018. Rapid Fire research presentation titled, "Novel Approaches to Waste Plastic Management in Developing Countries."

1st Place International Student Research Poster Competition Award, International Congress on Sustainability, Science and Engineering, August 2018. Research poster titled, "Novel Approaches to Waste Plastic Management in Developing Countries."

2017 Sustainable Engineering Forum Student Paper Award, American Institute of Chemical Engineers, June 2017. Research paper: Joshi, C., and J. Seay (2016) "An Appropriate Technology Based Solution to Convert Waste Plastic into Fuel Oil in Underdeveloped Regions," Journal of Sustainable Development, Vol. 9, No. 4.

Best Presentation, Undergraduate Research Forum Session, American Institute of Chemical Engineers, November 2016. Research presentation titled, "A Green Chemistry Approach for Producing Non-Synthetic Pesticide in Under-Developed Regions."

2nd Place National Student Research Poster Competition Award, Sustainable Engineering Forum, November 2016. Research presentation titled, "Process Design, Modification, and Sustainability Assessment of Coal and Biomass Co-Fired Plants for Generation of Transportation Fuel: A Case Study in Kentucky."

National Undergraduate Research Forum Award, Young Professionals Committee, American Institute of Chemical Engineers, November 2016. Awarded to team: Chandni Joshi, Sarah Willett, Shelby Browning and Shelby Doucet for research work titled, "A Green Chemistry Approach for Producing Non-Synthetic Pesticide in Under-Developed Regions."

1st Place International Student Research Poster Competition Award, International Congress on Sustainability, Science and Engineering, October 2016. Research poster titled, "Coal and Biomass Based Transportation Fuel Manufacturing and Sustainability Assessment: A Case Study in Kentucky."

International Rapid Fire People's Choice Award, International Congress on Sustainability, Science and Engineering, October 2016. Research presentation titled, "An Appropriate Technology Solution for Addressing the Problem of Global Municipal Solid Waste Plastic Accumulation."

Best Student Oral Presentation Award, International Congress on Sustainable Chemistry, Product and Process Engineering, June 2016. Research presentation titled, "Developing a Sustainable, Appropriate Technology Based Solution to Convert Municipal Solid Waste Derived Plastics into Fuel Oil."

1st Place National Student Research Poster Competition Award, Sustainable Engineering Forum, November 2015. Research poster titled, "An Appropriate Technology Based Multifunctional Processor for Sustainable Production of Green Chemistry Based Products."

1st Place National Student Research Poster Competition Award, AICHE Annual Undergraduate Poster Competition, November 2015. Research poster titled, "An Appropriate Technology Based, Sustainable Solution for Converting Waste Plastic to Fuel Oil in Rural India."

1st Place International Student Research Poster Competition Award, International Forum on Sustainable Manufacturing, September 2015. Research poster titled, "An Appropriate

Technology Based, Sustainable Process for Converting Waste Plastic to Fuel Oil in Rural India."

2nd Place International Student Research Poster Competition Award, International Congress on Sustainability, Science, and Engineering, May 2015. Research poster titled, "An Appropriate Technology Based Processor for Sustainable Production of Biodiesel and Non-Synthetic Pesticide in Underdeveloped Regions."

Outstanding Freshmen Recognition Award, University of Kentucky College of Engineering Paducah Campus, November 2014. Awarded through American Institute of Chemical Engineers, Annual Conference

Student of the Year 2013-2014, West Kentucky Community and Technical College, August 2013-May 2014.

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