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ASSESSING THE INTERDEPENDENCY OF WASTE BY-PRODUCTS AMONG SELECTED ENTERPRISES IN THE AGRO-FOOD VALUE CHAIN IN GHANA

BY

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DECLARATION

I hereby declare that with the exception of references made to other people's work, which I have duly acknowledged, this work is produced from my own research under supervision and that it has neither been partially nor wholly presented elsewhere for the award of a degree.

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ABSTRACT

Industrial food waste is detrimental to the environment, people, and livelihoods. The adverse impacts are projected to worsen amid concerns over waste generation forecasts for 2050. To mitigate this, studies recommend enhancing the practice of Industrial Ecology (IE) where material and energy flows are circulated within and among industries to minimise waste. However, IE studies and adoption in Africa are low, and in Ghana, largely undocumented with few studies focusing on a single firm. Also, policies such as Planting for Food and Jobs aimed at enhancing the production of food crops are yet to address post-harvest challenges, suggesting that food waste would increase should the status quo remain. This research employs the mixed method approach, applying input-output and material flow analyses to investigate by-product reuse and interdependency within and among enterprises and model an Eco-Industrial Network (EIN) for enterprises along the agro-food value chain in Ghana using Stan2web (Stan), a material flow analysis tool. It determined that, although 88% of enterprises sampled have knowledge of interdependencies, only 78.86% practised it at the firm level, while 53.89% practised forms of industrial ecology across enterprises, although in fairly low volumes. The noticeable synergy was between some food, and non-alcoholic and alcoholic beverages industries, and waste management companies for the production of compost. Overall, only 7.7% of respondents have identified new useful by-products from other industries, partly attributable to concerns of consumers on by-product reuse, especially in the manufacture or production of food and beverages. However, 25% and 78.8% indicated their willingness to pay for useful by-products and participate in an environmental management system, respectively, as part of efforts to deepen by-product reuse and recycling, underscoring opportunities to deepen by-product exchanges. The mapped synergies revealed that establishing wastewater treatment and steam and/or biogas plants and incentives from regulators would be essential to transitioning toward circularity. This study contributes to literature by documenting IE within and among enterprises in the agro-food value chain in Ghana. Based on the findings the study recommends further investigations into the techno-economic potential for IE, the feasibilities of building and operating wastewater treatment, and steam and/or biogas plants, and the roles of regulatory agencies in deepening IE in Ghana.

DEDICATION

This work is dedicated to my parents, Rev. Yaw and Mrs. Comfort Owusu Agyei.

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1 INTRODUCTION

1.1 Background

Activities of humans, domestic or industrial, generate large volumes of waste, threatening the environment, lives, and profits (Laohalidanond *et al.*, 2015). It has, therefore, become imperative to efficiently manage the critical environmental problems, including solid waste, water scarcity, pollution, and resource depletion, arising from these activities to safeguard future generations (Marconi *et al.*, 2018). Already, global solid waste generation is inching toward 2 billion tons per year and is projected to increase by 70 percent, to 3.4 billion tons by 2050, with generation volumes in sub-Saharan Africa tripling, according to a 2021 report by the Hazardous Waste Haulers Environmental (HWHE). HWHE stressed that middle- or high-income countries are expected to generate the highest of the estimated waste yet, sustainably manage the least, only 10 percent. This would likely expose its population to grievous environmental and human health risks.

Agricultural-based industries, generating over 1.3 billion tons of food waste annually (Arun *et al.*, 2020), are expected to contribute significantly to the projected increase in waste generation, highlighting risks of raw material shortages for industries, especially in developing and underdeveloped countries, and the need for effective waste management techniques for the sector (Neves *et al.*,2019). Widespread ineffective processing, storage, and drying techniques, and poor infrastructure networks would exacerbate food insecurity concerns in Africa, as sub-Saharan Africa may struggle to raise an estimated US $ 4 billion per year to mitigate food insecurity (UNEP, 2021). Kim *et al.* (2018) stated that population growth, estimated to reach 8.5 billion in 2030, profit-driven industrial practices, and global development approaches would be the drivers of this food wastage.

To avert these, researchers are studying new approaches to sustaining the current human population without compromising the future (Omer, 2008; Chertow, 2014). These approaches focus on enhancing efficiencies of industrial processes, and interdependencies of waste by-products and materials in transition among enterprises while reducing adverse environmental impacts thereof. One such approach is deepening the practice of Industrial Ecology (IE) among multiple firms. That is, and between multiple firms (Chertow, 2000). In essence, IE occurs at three levels: within a firm where internal processes are aimed at improving the circular movement of resources between various departments of the same firm. This ensures minimal waste generation as waste from one part of the industry is processed and/or reused by another. IE also occurs between firms where exchanges of materials and energy involve more than one firm either co-located (often referred to as Eco-Industrial Parks (EIP) or dispersed; and at regional level where exchanges transcend regional and/or national borders among a network of industries known as Eco-Industrial Network (Chertow, 2000; Fraccascia *et al.*, 2016). Chertow (2000) described interdependencies among firms as Industrial Symbiosis (IS).

Industrial Symbiosis (IS) is a concept under industrial ecology (White, 1994). IS broadly describes how one industry can use or reuse by-products, residues, energy, or waste from another industry, essentially to prolong the life and usefulness of that material (CEN-CENELEC, 2018; FISSAC 2020). IS promotes circularity or exchanges of materials and energy as it compels participating industries to depend on one another, and is inspired by the biological symbiosis or interdependencies in the environment. In the natural environment, resource use is circular, where waste by-products from one organism are recycled by another and energy cascaded (Chertow, 2014). For instance, wood waste is decomposed to enrich the soil and in turn support the growth of food and fodder. Importantly, IS facilitates the triple benefit: economic, environmental, and social gains (Mirata, 2004; OECD, 2012) and manifests in seven ways, namely: self-organising, organisation boundary change, facilitation-brokerage, pilot facilitation and dissemination, government planning and eco-cluster development. While some are spearheaded by governments, others are private-developer-led (Fraccascia *et al.*, 2016).

IE is critical to agri-businesses due to the nature of waste, mostly biodegradable, generated in the sector (Alfaro & Miller, 2013; Kliopova *et al.*, 2016). This makes the concept important to Africa and in particular, Ghana, where the agriculture sector is a major employer (33 percent of the workforce), according to Ghana Statistical Service (2021). With IE, the sector could benefit by improving value creation and addition, and synergies within the sector. For instance, the processes leading to the production of fertilizers, animal feed, and biofuels could be closed, creating avenues for waste to be reused. Biodegradable waste from agro-based industries could be converted, through economically, environmentally, and socially inclined processes into organic fertilizers to replace the popular inorganic ones or into animal feed, creating a cyclical life for the by-product. This approach also called '*closed system manufacturing*', typically requires little-to-no retrofitting of existing systems, and could enhance the profitability of the sector (Niutanen & Korhonen, 2003; Chertow, 2014).

1.2 Problem Statement

The adoption of IE and related concepts in Africa remains low. Oni *et al.* (2022) determined that although legal frameworks have been established in most African countries to facilitate the adoption of interdependency initiatives, the laws are inadequate and implementation is lacklustre. This signifies the countries on the continent, including Ghana, are yet to fully harness inherent opportunities of industrial synergy for sustainable development. This underscores the need for comprehensive research, assessing current penetration levels, and exploring opportunities to enhance adoption.

In Ghana, studies on industrial performances have focused mostly on firm-level IE or prioritised one of the foundations of triple benefits: economic, social, or environmental benefits, and/or how to optimise operations to improve performance. For example, Nukpezah *et al. (*2019) assessed the application of industrial ecology principles in the management of industrial by-products in Ghana. While this study is foundational to IE deployment in Ghana, it was limited, in that, it assessed by-products from only one industry. This exposes the need for cross-industrial or inter-industrial research, a gap this study seeks to contribute to bridge.

The aforementioned a signifies data paucity challenge, especially on interdependencies among multiple industries. Data aggregation has become the fulcrum of IS. Critical questions on economic, social, and environmental viability could only be answered with data (Fernandez-Mena *et al*., 2016). An assessment of raw material inputs, processes, products, by-products, and waste management strategies must be conducted across industries, particularly, agro-based industries. This is important in identifying available technologies and related gaps, risks, and drivers of IS, and formalising existing symbiosis. For instance, studies have shown that poor persons living in communities around dumpsites collect waste and sell it (Adama, 2012; Oduro-Kwarteng and Van Dijk, 2013). The collectors are responsible for about 95 percent of all waste recycled in Ghana, yet their activities are largely undocumented (Grant and Oteng-Ababio, 2021). Their activities promote IS by facilitating the transport of waste by-products from one industry or consumer to another. It is therefore crucial to understand the role of such persons in the agro-processing value chain to inform policies and programmes toward achieving sustainable development.

Government policies such as; District Centre for Agriculture Commerce and Technology, Planting for Food and Jobs, Planting for Export and Rural Development, and One District One Factory are flagship policies geared toward increasing the production and processing levels of agro-input for industries (New Patriotic Party, 2016). Importantly, they are geared toward the attainment of Sustainable Development Goal 1 – ending poverty; Goal 2 – ending hunger; Goal 3 – ensuring good health, Goal 8 – promoting decent work; Goal 9 – promoting innovation and industrial development; and Goal 17 – partnership for the goal. In addition to other policies announced in respect of the other goals, these are likely to increase waste generation in the country, undermining the aforesaid goals and prompting sustainable approaches to managing industrial inputs, jobs, outputs, and by-products to safeguard investments, people, and the environment. For instance, despite these government interventions, Sugri *et al. (*2021) determined that post-harvest losses remained high in the Upper West Region of Ghana, between 15.6 percent and 36.5 percent for fresh produce and 6.9 percent to 34.9 percent for dry produce.

Equally important, there is the need to adequately increase the human resource capital in this area. The government's industrialisation targets give credence to the need to develop local capacities for innovative solutions. This study would contribute to the knowledge base on the subject in Ghana and seek to highlight critical considerations to govern and induce rapid deployment of the interdependence among industrial systems for sustainable growth.

1.3 **Justification**

Due to the low level of IS study conducted within Ghana, this study is relevant. There is a need to assess existing and potential symbiosis that can exist and how these relationships can be created. As Ghana climbs the industrial ladder from being a developing country to an industrialised country, innovative approaches to managing by-products and waste, particularly in the agricultural sector would be required to improve material efficiency and safeguard the environment.

It is also important to investigate the best approach to deploying IS in the country, given the models available. Certainly, a strategic plan is required to manage the development of new industrial zones. However, an approach for roping in existing industries and industrial complexes to harness the advantages of IS is necessary. This research would seek to highlight critical considerations for overcoming existing barriers. It will also evaluate how or where inputs are sourced, processed, and delivered to customers. It will study the industries' sustainability practices, environmental initiatives, and opportunities for synergies.

1.4 Aim of the Study

The aim of this study is to assess the interdependency of waste by-products and materials in transition among selected industries in the agro-food value chain in Ghana. The study will focus on assessing existing interdependencies within an industry and among industries, and model potential exchanges that could be adopted.

1.5 Specific Research Objectives

In determining the aim of the study, the following specific objectives will be assessed:

i. Profile selected enterprises within Greater Accra and parts of the Eastern Regions;

ii. Determine interdependency within the enterprises in the agro-food value chain in Ghana;

iii. Assess interdependencies or Industrial Symbiosis (IS) among enterprises; and

iv. Model an eco-industrial network of potential exchanges among agro-food enterprises.

1.6 Research Questions

The research questions that guided the collection of relevant data include:

i. What are the inputs, outputs, and by-products of the involved enterprises?

ii. What are the levels of internal and external exchanges?

iii. What are the IE practices adopted by enterprises?

iv. Is there a potential to deepen interdependencies or exchanges among the enterprises?

v. What challenges or incentives could undermine or deepen any such relationship?

1.7 Conceptual Framework

Industrial ecology, inspired by the intricate web of relationships found in natural ecosystems, presents a conceptual framework that aims to transform industrial systems into sustainable, closed-loop networks. Frosch (1992) explored the principles, components, and implementation strategies of industrial ecology, emphasising the importance of waste minimisation, recycling, and a holistic approach to resource management.

1.7.1 Foundational Principles

At the core of industrial ecology is the analogy with natural ecosystems. In nature, ecological systems operate through a web of connections, where organisms live, consume each other, and efficiently use available resources. This analogy is the foundation upon which industrial ecology is built. It recognises that industrial systems consist of interconnected processes, just like organisms in a natural ecosystem. Industrial processes interact with one another, exchanging materials and energy, much like the organisms in a food web.

Industrial ecology also challenges the conventional view of waste as a product's end-of-life burden. Instead, it encourages the integration of waste materials into the industrial food web, recognising them as potential inputs for other processes. This integration extends to product design and it highlights the importance of creating products that can be easily disassembled and their materials reused.

1.7.2 Key Components

Waste management and recycling form a pivotal component of industrial ecology. This involves efficient collection, transportation, and separation of waste materials within industrial systems. Moreover, industrial processes must be designed or adapted to accommodate waste materials as inputs. Recycling and reuse are central to this concept, with the goal of minimising waste generation and promoting resource efficiency.

Regulation and liability are essential considerations to encourage responsible waste management and recycling. However, these regulations should not create unnecessary restrictions or liability issues. Instead, they should facilitate the safe transfer and use of regulated waste materials.

Additionally, cost internalisation plays a critical role in industrial ecology. Traditional accounting systems often do not reflect the true costs of waste disposal and environmental impacts. Therefore, new accounting methods are needed to internalise these costs, encouraging businesses to consider external factors when making decisions.

1.7.3 Implementation Strategies

Implementing industrial ecology requires collaboration across various domains. Engineers and product designers play a vital role in designing products and processes that align with the principles of waste minimisation and reuse. They must consider the end-of-life scenarios for products and materials.

Education and training are equally important. Business schools, engineering programs, and educational institutions should incorporate environmental and systems thinking into their curricula. Moreover, professionals need the training to raise awareness about industrial ecology concepts and foster a culture of sustainability within organisations.

1.7.4 Policy and Incentives

Policy and incentive developments are crucial aspects of industrial ecology. Policies and incentives can drive or stifle the adoption of industrial ecology principles. As such, experimentation is essential to understand the real-world effects of policies and incentives, against the backdrop that policymakers must approach policy changes with caution due to the complex and nonlinear nature of industrial systems. Relatedly, differential economic incentives can encourage businesses to differentiate between virgin materials and waste or recycled materials. Furthermore, facilitating waste brokerage and information sharing can help industries efficiently utilise waste materials.

1.7.5 Stakeholder Collaboration

Industrial ecology is a collaborative endeavour that involves various stakeholders, including engineers, product designers, businesses, policymakers, educators, and environmental activists. Each group has a unique role in promoting and implementing industrial ecology practices.

Alfaro and Miller (2013) developed a model for businesses to integrate industrial ecology principles and practices. In this model, adapted for the study, there is interdependency among the actors in the industrial complex in Figure 1.1. The Animal farm supplied meat to the guest house and biowaste to the digester to power the guest house. The sludge from the digester is used as fertilizer on farms to produce food crops to feed the guests. The fish pond and rice mill depend on the farm and the waste generated is used for animal feed and organic manure. These exchanges mimic natural ecosystem practices where waste from one ecosystem cycle serves as an input for another.

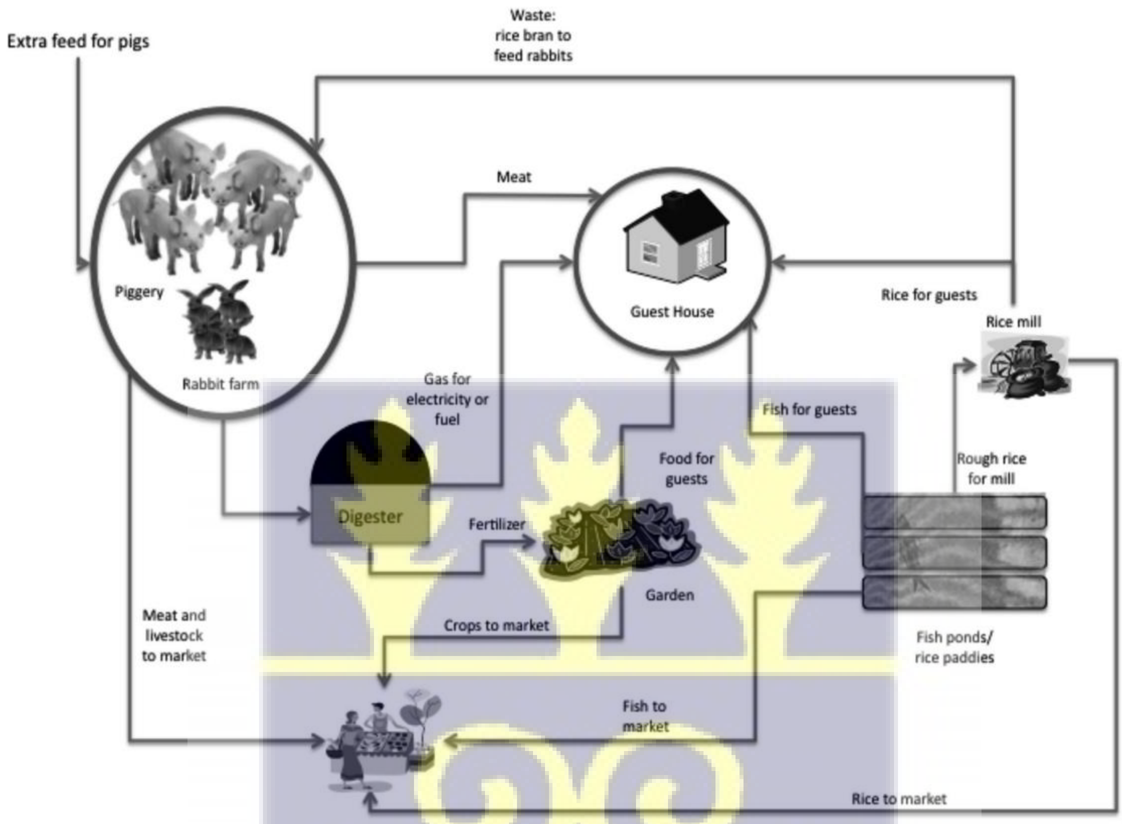

Figure 1.1: Industrial Ecology Model developed by Alfaro and Miller (2013)

1.8 Research Process

The study utilises the conceptual framework (Figure 1.2) to mitigate the challenges of low adoption of IE in Ghana, undocumented synergies, and the expected increase in food waste arising from the projected increase in food production. Based on literature, factors for determining the profile of industries for EIN development include determining the latitudes and longitudes of the involved enterprises and identifying the input, output, and by-products of each firm (Aviso *et al.*, 2010; Gu *et al.*, 2013). For expediency, this study grouped the enterprises under the food industry, non-alcoholic industry, alcoholic industry, packaging industry, and waste management industry based on similarities in input, output, and by-products churned out by each industry. At the firm level, factors of IE were assessed. Identified factors include initiatives to reduce, reuse or recycle by-products and water, and reduce energy consumption and pollution (Chertow 2000). The study determined firm-level policies that contributed to achieving the aforesaid. The study employed Material Flow Analysis (MFA) to trace the flow of material, water, and energy within an enterprise to determine the aforesaid parameters. Across firms, the study assessed interdependencies or synergies among the enterprises (Chertow, 2007). The synergies among firms are also referred to as Industrial Symbiosis (IS) and it involves the application of multiple techniques to determine how waste by-products from one industry are useful to others (Moodie *et al.*, 2019). In this study, following an assessment of firm-level initiatives to promote IE, input-output analysis is used to identify synergies among industries (Dias *et al.*, 2020). It identified material, water, and energy exchanges, and inter-firm pollution prevention strategies. Importantly, it determined opportunities to deepen these exchanges by identifying firms that could utilise waste by-products from other enterprises. The results are used to model potential interdependencies for the industries (Côté and Hall 1995; Côté and Cohen-Rosenthal 1998; Chertow 2000; Veiga and Magrini 2009). The modelled interdependencies or Eco-Industrial Network is to reduce waste, and document existing and potential synergies, and the roles of some principal actors.

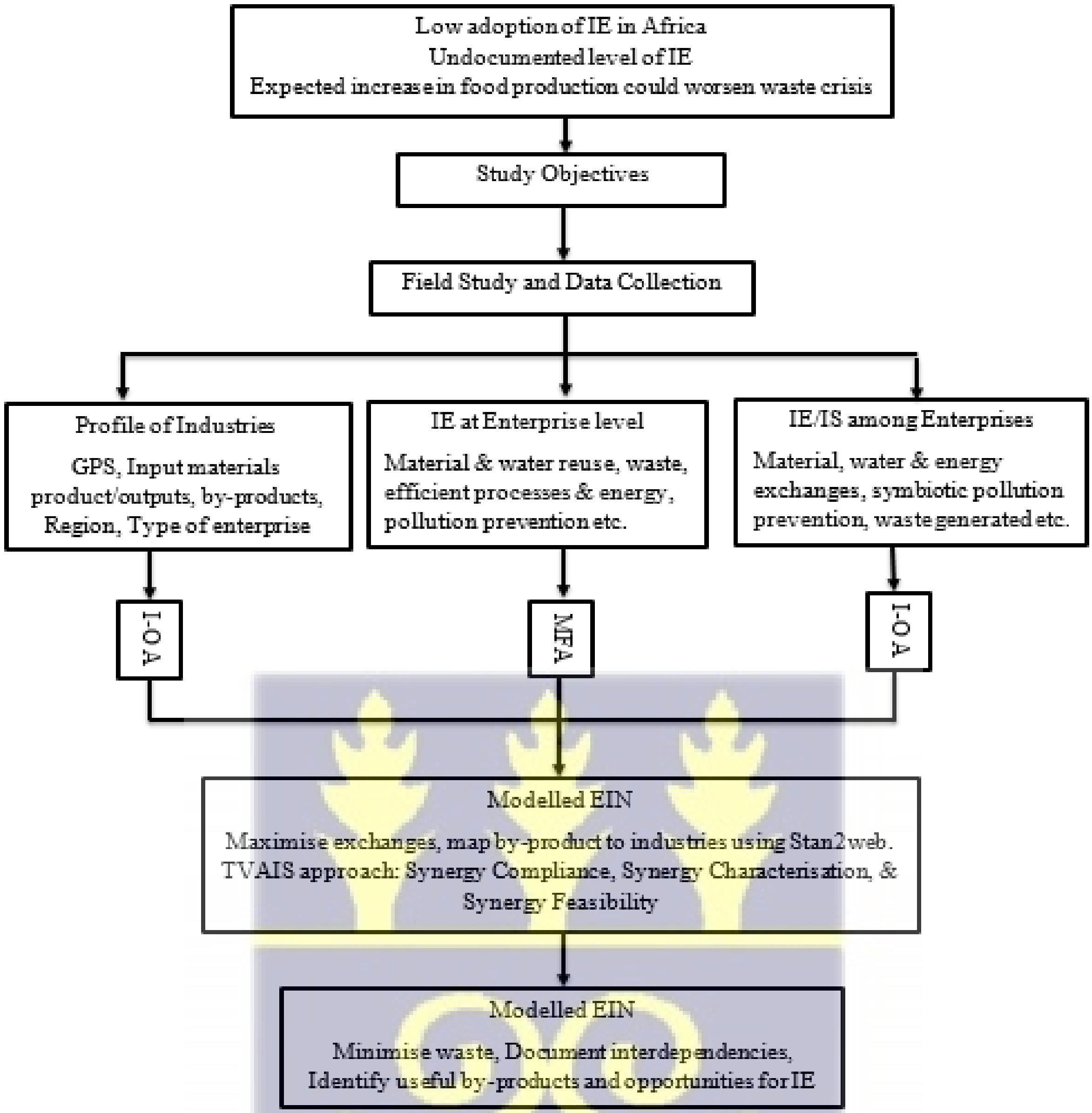

Figure 1.2: Overview of the Research Process

Abbreviation
IE = Industrial Ecology; IS = Industrial Symbiosis; I-O A = Input-Output Analysis; MFA = Material Flow Analysis; EIN = Eco-Industrial Network

2 LITERATURE REVIEW

2.1 Sustainability Initiatives: Circular Economy

Sustainable initiatives are measures to propel global economies toward sustainable development (Geng *et al.*, 2019). Waste has detrimental social, economic, and environmental impacts, requiring sustainable measures to safeguard the environment for future generations. Circular economy is a sustainable initiative to optimise societal production and consumption by reducing waste arising from resource extraction, manufacturing, and consumption (Mhatre *et al.*, 2021). It focuses on mimicking natural systems where waste from one organism is utilised by another; that is, ensuring a cyclical flow of materials and energy within and/or among industries, consumers, and extractors in the economy, with each actor along the chain classifying the received waste as a resource (Ogunmakinde *et al.*, 2021). Approaches to achieving CE at the industrial level as highlighted by foundational studies include industrial ecology (Frosch and Gallopoulos, 1989; Graedel, 1996; Lifset and Graedel, 2002), industrial ecosystem (Jelinski *et al.*, 1992), and industrial symbiosis (Chertow and Ehrenfeld, 2012).

2.2 Circular Economy, Industrial Ecology, and Industrial Symbiosis

Circular Economy (CE) is an economic concept to reduce waste and the consumption of resources (Prieto-Sandoval *et al.*, 2018). It is a multidiscipline approach to reducing adverse environmental, social, and economic impacts by transitioning from a linear ‘take-make-dispose’ model of consuming resources toward a circular model, in which waste, as a resource is valorised through recycling and reuse (Gregson *et al.*, 2015). The appeal of CE is that it promises to reconcile environmental and economic goals by simultaneously, reducing resource use and stimulating economic growth. Against this backdrop, although concepts related to sustainable development ‘come and go’, CE has been very successful in gaining policy, business, and civic traction (Hobson, 2019).

Industrial Ecology (IE) seeks to gain insight and promote the flow of material and energy in and among industries. While CE focuses on all actors in the environment including consumers, manufacturers, and extractors, IE is geared toward promoting CE among industries, making IE a subset of CE (Geissdoerfer *et al.*, 2017; Lüdeke-Freund *et.al.*, 2018). This indicates that IE seeks to harness economic, social, and environmental opportunities in reusing, reducing, and recycling waste or by-products from other industries, and how industries are regulated to determine how production ecosystems can be modelled to reduce waste (Taddeo *et al.*, 2017). In sum, IE is CE adherence among industries.

Industrial Symbiosis (IS), a concept of IE, is a novel approach to creating industrial networks for economic, environmental, and social benefits (Isenmann and Chernykh, 2009). It seeks to improve resource efficiency by commercialising materials in transition, energy, and water sharing; logistics, and assets management among industries (Bogle and Fairweather, 2012). Chertow (2000 and 2007) defined industrial symbiosis (IS) as a collective approach to competitive advantage in which separate industries exchange materials, energy, water, and/or by-products, to advance sustainable development. This symbiotic approach is to address critical sustainable bulwarks, including resource depletion, waste management, and pollution, by using waste streams to generate value across networks of industrial actors (Chertow, 2007; Massard *et al.*, 2014). IS has been viewed as a process of interaction among firms, which over time produces efficient outcomes (Boons *et al.*, 2014). More recently, IS has also been studied as an example of a business model for Circular Economy (Bocken *et al.*, 2014; Short *et al.*, 2014). In essence, IS encompasses all interdependencies, sustainable environmental initiatives, and pollution prevention strategies. The definitions of CE, IE, and IS establish a relationship among them- IS is a means to achieve IE, while IE feeds into the bigger global goals of CE.

2.3 Conceptual Framework: Industrial Ecology and Principles

White (1994) described industrial ecology as the study of material and energy flows in industrial and consumer processes, the effects of such flows on the environment, and the influences of economic, political, regulatory, and social factors on the flow, use, and transformation of resources. IE shifts from linear industrial systems (throughput) to an ecosystem that nears complete circularity (round-put) of material and energy flow (Niutanen & Korhonen, 2003). Also, IE can be defined as an approach to designing products and processes that evaluates product optimisation and environmental interactions (Graedel & Allenby, 2010).

In outlining key principles underpinning IE, Morseletto (2019) emphasised the sustainable use of resources is due to the finite nature of resources on and below land, on and below water, and in the atmosphere. This dictates that to be classified as implementing IE, industries must apply technologies that utilises nature's renewable resources while minimising the depletion of non-renewable sources. The report also stated the IE must preserve ecological and human health, promote environmental equity, analyse systems as a whole, assess material and energy flows and transformations, be multidisciplinary, analogies to natural systems, and be cyclical (closed). These principles are important parameters and have contributed to assessments of the impacts of industrial processes on societies, economies, and the environment (Chertow and Ehrenfeld, 2012; Murray *et al.*, 2017, Morseletto, 2019).

2.4 Relationship between Ecology and Industry

Frosch (1992) argued the view that industrial ecology highlights the complex connections between organisms and their environment, and how organisms interact with and consume each other and their waste. The study explored the avenues for industries to transition toward the natural ecosystem by fully appreciating the natural system, its benefits, and challenges. Garner and Keoleian (1995) confirmed this relationship between industry and ecology. They added that such relationships include physiological responses of individuals, structures, and dynamics of populations, interactions among species, organisation of biological communities, and processing of energy and matter in ecosystems. Similarly, the industrial system behaves like the natural system or could, although not very efficient. This is due to the fact that just like natural ecological processes, industrial processes are a set of processes that lead to a product and associated material and energy waste. However, while some industries have created technologies that reuse the waste generated by others as feedstock for production, an evolution that is mimicking the natural system (van Noordwijk *et al*., 2022), others discard the industrial by-products associated with their production.

In his seminal work, Korhoenen (2001) simplified the relationship between ecology and industry by establishing principles of the natural environment that could be emulated by industries. The principles are roundput, locality, diversity, and gradual change.

2.4.1 Roundput

The study reinforced the concept of transitioning from a linear consumption of resources that is, extract-consume-discard (throughput) toward recycling and reusing. The roundput principle encourages industries to depend on one another by developing new products for the waste generated by other industries or reusing waste from other industries for production, creating a cyclical use of resources and by-products. The principle is inspired by natural cycles such as the carbon-oxygen cycle, where plants utilise carbon dioxide and give out oxygen as a product of their food manufacturing process. In turn, animals respire the released oxygen and produce carbon dioxide as a by-product of their metabolic process, ensuring a cyclical use of and retention of energy and resources (Mao, 2021) Similarly, the natural food chain is another roundput system. In this system, plants use sunlight for photosynthesis, following which their green leaves are eaten by herbivores, including sheep, goats, and cattle, and subsequently carnivores such as lions, tigers, and wolves, and omnivores organisms, including dogs, pigs, chicken, cockroaches, and humans, feed on the herbivores and each other. Excreta and carcasses of these organisms decompose or naturally recycle into the soil, enriching the soil for plant use. The recycling of materials and energy through the cascading of resources presents an approach for industries to be sustainable. Sunlight and fossil fuels play a similar role the former plays for plants in the natural environment. Except that, in the case of industries, the cyclical use of resources is minimal and the resources are being consumed faster than they are being replaced or replenished (Daly, 1996). This indicates that emulating the principle of roundput requires industries to deepen collaboration, creating industrial processes and products that utilise or recycle waste or by-products from other industries while increasing industrial reliance on renewable resources.

2.4.2 Locality

Korhoenen (2001) argues that actors in the natural ecosystem understand the limitations of the environment and therefore adapt to prevailing environmental conditions, while cooperating with the environment through a complex web of interdependencies and relationships, including migration. However, industrial systems do not respect environmental limitations, rather, employ supply chain management approaches to circumvent such limitations. For example, industrial systems and economies import fossil fuels to augment local shortfalls. This thrives on the proposition that natural limitations or barriers could be overcome through the application of technology to enhance the extractive and manufacturing capacities of industries. The application of technology to overcome environmental limitations has impeded advancement in efforts to ensure sustainable use of local resources. Therefore, to mimic the natural ecosystem principle of locality, industries would have to restrict the importation of non-critical resources to stimulate research into locally available materials for manufacturing, avenues to replenish the resources, cooperate among regional and local industrial actors, and reduce transportation and supply chain costs.

2.4.3 Diversity

The study also acknowledged the diversity of the ecosystem as an important principle. It underscored that the ecosystem consists of different species, organisms, and relationships. That, the natural system allows different organisms and species to play specific roles at particular times. It emphasises that the failure of organisms to undertake their roles could adversely impact ecosystem services. Therefore, by allowing the varied activities and interdependencies in the environment, the environment shields itself against permanent change. For example, the earthworm plays a specific and important role in improving soil aeration even in mountainous and rocky areas. This prevents permanent hardening of the soil or land degradation. Additionally, under prolonged and harsh environmental conditions, coral reefs or forest belts optimise their ecosystem functions through diversity to safeguard the environment (Ring, 1997). In like manner, economies and industrial processes are also diverse or were diverse until profiteering became the bottom line for industries. This indicates that one of the greatest threats to the diversity principle of industrial ecology and other sustainable techniques is profit maximisation. This is due to the fact that focus on monetary gains compels industries to undermine industrial collaborations and intelligence sharing, and instead, increases the devotion of resources from different industries to outcompete others for the same output and homogenise industrial products. Achieving the principle of diversity requires industries to cooperate and interdepend on one another. Such relationships could be between and among heavy industries, large-scale manufacturers, small- to medium-scale enterprises, waste management industries, consumers, and policymakers or governments. For example, a large-scale power generation industry may declare that its fuel could include wood waste, bio-waste, peat, forestry wastes, and recycled fuel from residential households and light industries, manufacturers, and households churning out such by-products could supply such heavy industry and vice versa.

2.4.4 Gradual Change

The ecosystem understands environmental resource limitations and regenerative capacities, hence the flow of resources in the natural environment is in accordance with these critical considerations. In the ecosystem, the sun, a renewable resource, is the principal driver of the natural ecosystem and essentially regulates all other activities in the environment. Korhoenen (2001) further explained that the concept of gradual change in an industrial environment means increasing dependence on renewable resources, such as the sun, to avoid exceeding the restoration rate of non-renewable resources such as fossil fuel. Certainly, this contradicts the industrial environment where market forces drive production strategies, raising questions over how the ever-increasing demand for goods and services would shape production and drive some resources to extinction (Norton *et al.*, 1998). However, there are opportunities for market forces to also refocus industries toward gradual change as has happened in some countries. For example, the forestry sector in Finland has ensured that the annual harvesting of timber is lower than the annual growth and additions to the forest due to consumer concerns over the forestry sector's contribution to climate change (Kauppi *et al.*, 1992). Therefore, it surmises to say that the principle of gradual change is to nudge industries toward systematic, yet, gradual incremental gains, by transitioning from non-renewable resource use to renewable ones, or increasing regeneration capacities of non-renewable resources in the environment.

It is worth noting that some recent studies have corroborated the findings of Korhoenen (2001). For instance, Chertow (2007) underscored the need for an industrial system to mimic the natural ecosystem; roundput, due to its efficiency, ensures no waste in energy and material. The study proposed approaches such as replacing inefficient input materials with highly efficient ones, deepening stakeholder engagement in industrial performances, and reducing the environmental performance of industries among others, to improve industrial efficiencies Nevertheless, there have been criticisms over the ecological inspiration in managing industrial waste. Critics have maintained that the natural internal recycling and input mechanisms are primarily driven by renewable sources, inherently making the system more efficient and sustainable than the linear resource movement in an industrial system (Jensen *et al.*, 2011). While the divergence in the two systems is undeniable, harnessing the potential of industries to improve resource use and waste management would portend that the evident differences are temporal and misconceived. Markedly, Behne (2016) established that the application of social ecology would present a holistic worldview that human ingenuity can establish a future that mimics the natural ecosystem by re-designing its relationship with the environment and with one another. The finding of Behne (2016) underscores the need for IS in promoting IE.

2.5 Industrial Symbiosis and the Triple Bottom Line

The concept of industrial symbiosis hinges on different industries realising that there is a collective approach toward attaining competitive advantage (Chertow, 2007). Ordinarily, these industries in close proximity to each other achieve material flow and other exchanges like water, energy, and by-products. To achieve IS, industries collaborate through a common network of delivery systems, infrastructure, and services to create these synergies. However, industries not close to one another could also benefit from IS through special interdependencies through a specialised network anchored on a facilitator (Yeo *et al.*, 2019). The benefit from the IS interactions is grounded in the accounting framework known as the Triple Bottom Line (TBL) (Khan *et al.*, 2021; Elkington 2013 and 1994). This framework is to achieve economic prosperity, environmental quality, and social justice. In the last decade, there have been growing demands from stakeholders for industries to declare their financial, operational, and other issues relating to sustainable development, (Jackson, *et al.*, 2011), giving rise to reporting indicators that promote sustainability. One such indicator that has been widely adopted is the Global Reporting Initiative (GRI) indicators (Global Reporting Initiative, 2012). GRI seeks to provide parameters for industries to meet the TBL approach of sustainability (see Table 2.1)

Table 2.1: GRI Reporting Indicators

Category	**Aspect**
	Environmental Quality
Environmental	Material, Energy, Water and Effluents, Biodiversity, Emissions, Waste and Effluents, Suppliers Assessment, Products and Services, Compliance, Transport.
	Social Justice
Labour practices and decent work	Employment, Training and education, Diversity and opportunity, Labour management relation, Health and safety
Human rights	Strategy and management, Non-discrimination, Freedom of association and collective bargaining, Security practices, Human rights assessment, Child labour, Forced and compulsory labour, Disciplinary practices, and Indigenous rights.
Society	Community, Political Contribution, Competition and Pricing, Bribery and Corruption
Product responsibility	Community health and safety, Products and services, Advertising, Respect for privacy, Supplier social assessment
	Economic Prosperity
Direct economic impact	Customers, Providers of capital, Public Sector, Market presence, Anti-competitive behaviour, Suppliers, Employees, Anti-corruption

According to Stewart *et al.* (2021), other dimensions used are community improvement, organisational integrity, environment, entrepreneurship, education, stakeholder engagement, and stakeholder activism. Overall, the sustainability performance of industries is determined based on their impact on society now and tomorrow (Stewart *et al.* 2021; Jackson *et al.*, 2011). Elkington (1994) summarises it as TBL does not only focus on the economic importance industrial performance gives to society, but also on the environmental and social impact, they add and/or destroy.

In recent times, retrofitting dispersed industries to conform to TBL is gaining ground. The practice is to ensure that, all industries sustain the environment benefit economically and socially, irrespective of geographical differences. This underscores the relevance of this study as it seeks to evaluate existing interdependencies among industries across multiple locations and recommend initiatives toward achieving sustainability.

2.6 Phases, Tools, and Approaches for IS

Van Capelleveen *et al.* (2018) asserted that all IS projects undergo the identification, assessment, and implementation phases. This was based on the works of Ghali *et al.* (2016), which developed a framework of the phases of IS, and the five phases of IS developed by Grant *et al.* (2010). Informed by the findings and the dynamics of IS (Boons *et al*., 2016), Yeo *et al.* (2019) developed a six-step phase for IS creation – preliminary assessment, engagement of businesses, identification of synergies, feasibility assessment, implementation, and documentation for reviews.

Under preliminary assessment, studies are undertaken to understand prevailing conditions and sustainability practices. Such studies collect and characterise existing attributes of industries, streams of inputs, outputs, and by-products, and opportunities for establishing IS. Following a positive outcome in the preliminary phase, business entities are engaged to build and grow an interdependency network. This phase also involves encouraging other relevant industries to join the created network and build trust through the standardisation of by-products. During the identification of synergies stage, industries and/or facilitation agencies determine available synergies and continue to assess the economic viability of such synergies at the feasibility assessment phase. If synergies are found to be viable, the project is implemented while evaluating synergies to identify additional opportunities for enhancement. Finally, a performance review is undertaken to streamline the project, and findings are shared with involved industries and others to elicit interest. A critical study of the six phases of IS revealed that the first 2 phases: preliminary assessment and engagement of businesses, can be classified under the identification stage; the identification of synergies and feasibility assessment phases explain the assessment stage, while the implementation and documentation stages support the implementation stage identified by van Capelleveen *et al. (*2018).

The tools required for IS are with respect to these phases. Yeo *et al. (*2019) proposed tools, such as GPS gadgets, for identifying the latitudes and longitudes, addresses, and descriptions, in addition to other relevant attributes of industries to develop graphic and/or heat maps (Jensen *et al.*, 2012; Song *et al.*, 2017). Another useful tool is the process input-output and stream-based matching tools. Some useful input-output and stream-based matching tools are the Bechtel Computer Model, the United States Environmental Protection Agency's FaST (Facility Synergy Tool), and DIET (Designing Industrial Ecosystems Tool). These tools are used to assess industrial input-output data, estimate the flows of resources and match by-products of industries to another that could convert such products (Hein *et al.*, 2016; Song *et al.*, 2017). Life Cycle Inventory, plant meta-model and correlations, and publicly available technical references are important approaches to determining the input-output data of industries (Song *et al.*, 2017). Lastly, network design and optimisation tools are used to simulate exchanges among the industries and predict or model synergies that could exist (Aid *et al.*, 2015).

Computer-based useful tools include the Stan2web Software (Lombardi *et al.*, 2021; Ronoh, 2020) and MatchMaker Tool (Brown *et at.*, 1997). This indicates that in assessing exchanges and potential exchanges among industries, it is important to determine the locations of the industries, input-output, and appropriate tools for modelling potential exchanges.

2.7 Models of IS

Industrial symbiosis has a relationship with industrial ecology (IE), particularly in the exchange of materials and energy exchanges. This indicates that IS exists or operates at the levels of IE- at a firm or facility level, Inter-firm, and regional or global levels (Chertow 2000). It also establishes a relationship between IS and Eco-Industrial Parks (EIPs), a park of co-located industries implementing ecologically friendly practices. Chertow (2000) classified IS in EIPs under Type 1: through waste exchanges; Type 2: within a facility, firm, or organisation; Type 3: among firms co-located in a defined eco-industrial park; Type 4: among local firms that are not collocated; and Type 5: among firms organised “virtually” across a broader region.

Type 1 reflects IS through third-party brokers and dealers such as waste management industries and scrap dealers (van Capelleveen *et al.*, 2018; Walls and Paquin, 2015). Type 2 occurs in the confines of an industry. In this type, waste or by-products from one department of an industry is utilised by another department of the same industry. Under Type 3, by-products and waste are exchanged between industries that are co-located. The Monfort Boys Town, Integrated Biosystem, Suva in Fiji, and Burnside Industrial Park in Dartmouth, Nova Scotia are examples of EIPs under Type 3. Type 4 is similar to Type 3 except that, industries under Type 4 are not co-located. The EIP in Guayama, Puerto Rico managed by AES Corporation, and Kalundborg, Denmark are examples of Type 4 EIP. Under Type 5, cooperation among industries creates virtual interlinkages to facilitate the exchange of by-products instead of co-locating. In some instances, such networks are facilitated by local or regional government agencies. The Nordic

Industrial Symbiosis Network (NISN) for Nordic countries (Moodie *et al.*, 2019), National Industrial Symbiosis Programme (NISP) in the UK (Mirata, 2004), and By-Product Synergy, Tampico, Mexico (Morales *et al.*, 2019) are examples of virtual by-product exchange schemes to facilitate IS. This assessment provides the basis for evaluating IS among co-located or dispersed industries.

2.8 Assessing IS among Industries

Several authors have assessed IS and environmental initiatives among sustainably conscious and co-located industries also referred to as Eco-Industrial Parks (EIP), while other seminal studies have evaluated the same principles in an ecological network also referred to as Eco-Industrial Networks (EIN) (Côté and Hall 1995; Côté and Cohen-Rosenthal 1998; Chertow 2000; Lowe 2001; Deppe and Schlarb 2001; Veiga and Magrini 2009; and Gu *et al.*,2013). According to Lowe (2001), an eco-industrial park (EIP) is a group of manufacturing and service industries co-located on a common property. Ehrenfeld and Chertow (2002), however, defined an eco-industrial network, as a group of industries dependent on one another yet are not co-located. Roberts (2004) maintained that given that EIN is independent of geographical proximity, the network coverage is usually at the national or global levels. Nevertheless, the cardinal objective of EIN is similar to EIP as both seek to reduce material and energy consumption while improving industrial efficiency (Domenech and Davies 2011).

An assessment by Sodhi *et al. (*2020) on modelling methods and optimisation techniques applied in EINs and EIPs revealed the techniques, as indicated in Table 2.2. The study opined that the models are clustered and interlinked. For instance, cluster bi-level fuzzy optimisation requires mixed-integer non-linear programming (MINLP) or mixed-integer linear programming (MILP) and fuzzy optimisation even though they are themselves clusters. This also provides an approach for assessing IS and environmental initiatives among industries, hence the aim of this study--to use input-output and material flow analyses to assess existing and model potential interdependencies among selected industries in Ghana.

Table 2.2: Modelling Methods and Optimisation Approaches

Cluster	**Main Publication**
Input-Output analysis	Ayres and Ayres (2002), Duchin (1992)
Material Flow analysis	Bringezu *et al.* (1997), Moriguchi (2007), Bringezu and Moriguchi (2018), Park *et al.* (2011)
Mixed-Integer Linear programming	Boix *et al.* (2015), Gonela and Zhang (2014), Karlsson and Wolf (2008)
Lagrange relaxation and penalty functions	Walther *et al.* (2008), Pishvaee *et al.* (2009)
Multi-objective optimisation	Azapagic and Clift (1999), Erol and Thöming (2005)
Fuzzy optimisation	Taskhiri *et al.* (2011)
Bi-level optimisation	Geng *et al.* (2016), Kastner *et al.* (2015)
Evolutionary optimisation	Theo *et al.* (2016)
System dynamics and complex network theory	Kuznetsova *et al.* (2017), Mantese and Amaral (2017)

Agent-Based modelling	Romero and Ruiz (2014), Romero and Ruiz (2013)

2.9 Assessing the Technical Viability of Interdependencies

Due to complexities in assessing interdependencies of waste by-products and materials in transition and energy, a number of tools and technologies to enable industries identify possible avenues to manage waste have been proposed. One such tool is the Technical Viability Analysis for Industrial Synergies (TVAIS) framework (Dias *et al.*, 2020). TVAIS provides a standardised aggregated approach to evaluating interdependencies (Dias *et al.*, 2020). The TVAIS framework harnesses technological databases of industrial synergies through a three-phase process: synergy compliance, synergy characterisation, and synergy feasibility when assessing the viability of a synergy (Stéphane *et al.*, 2019).

2.9.1 Synergy Compliance

Dias *et al. (*2020) articulated that at the synergy compliance phase, synergies and synergistic opportunities are assessed technically to gain insight into their relevance. This assessment is undertaken through stakeholders' interaction, analysis of IS databases, technical documents, and/or industrial partnerships. Essentially, this stage focuses on analysing the reports of previous synergies to determine if the interdependencies are suitable and have the potential to be implemented. Conversely, if there are no previous reports, the potential synergy is classified as innovative, requiring further assessment.

2.9.2 Synergy Characterisation

After the compliance stage, the identified synergy's inherent technical aspects are assessed. This stage involves the evaluation of intermediary steps, including prerequisite treatment operations, technologies, and transportation systems that may be needed. Based on the outcome, synergies could be classified as direct or indirect. Synergies are classified as direct when by-products or waste can be processed by a dependent industry without subjecting the said by-product to a major or complex intermediary process. This indicates that the conversion of food waste to compost could be classified as direct since no major intermediary process is required. Contrarily, when a major intermediary process is required, the synergy is classified as indirect and it focuses on the element recovery. For instance, recovering gold from mobile phones or the separation of hydrogen from the Coke Oven Gas (COG) by-products. Detailed technical variables to be determined at this phase include, the efficiency of the synergistic technology, how the by-products would be transported, inputs such as energy and water, outputs of the treatment process, required specifications, and costs of treatment.

2.9.3 Synergy Feasibility

This is the final technical assessment. The objective of this phase is to determine whether the synergy can be implemented at a large scale and to determine the complexity or otherwise of the synergistic procedure and potential for implementation. That is, the important variables to determine are whether the technology to deepen circularity is available, has the potential to be scaled-up, and is commercially viable for the involved industries. The variables under each phase indicate that data is key to the TVAIS framework and by extension IS deployment. To this, Dias *et al.* (2020) identified technical databases and documents, scientific literature including articles, patents, industrial case studies, and documented technical briefs as sources of data.

2.10 **Prospects of IS**

Henriques *et al.* (2022) assessed the legislative context of circular economy and industrial symbiosis in Portugal, focusing on incentives and policies that could enhance the adoption of

IS. The study determined that government must provide appropriate fiscal, social, and data incentives to industries. It is also important to simplify national strategies and policies especially, if laws and policies on IS are fragmented or embedded in other policies. Lastly, the government must remove bureaucratic barriers impeding the adoption of IS (Pedersen *et al.*, 2021; Domenech *et al.*, 2019a). Dias *et al. (*2020) also assessed the technical viability of industrial synergies and determined that there must exist technologies for processing by-products. Also, it must be economically viable to incorporate by-products of other industries in the processing processes, highlighting the existence of transportation systems and by-products. This suggests that assessing the availability of by-products, existing interdependencies, and potential interdependencies is cardinal in the adoption of IS. Importantly, the availability of relevant technology and governance framework could scale up or undermine the deployment.

The success of IS models around the world bodes well for the future. For instance, in Kalundborg, an IS model among co-located industries has resulted in an annual savings of €24 million, 14 million in socio-economic savings including, 635,000 tons of CO_2, 3.6 million m^3 of water, 100GWh of energy, and 87,000 tons of materials (Stahel and MacArthur, 2019). In Texas, Chaparral Steel and TXI cement, two Midlothian Texas manufacturing plants with the same parent company, initiated the zero-emission park by forming a partnership to use the steel slag in the cement kiln to create a high-quality Portland cement (Mangan, and Young, 2000), reducing the CO_2 footprint and input material bill (Armstrong, 2013). Similarly, industries located in Burnside Park, Dartmouth, Nova Scotia, Canada, including AB Volvo, Nova Scotia Power, Pepsi Cola, Siemens, Sharp, Toyota, and Burger King, have deepened interdependencies resulting in the reduction of input materials and carbon emission. In Korea, IS among industries in the Ulsan Mipo and Onsan Industrial Park, has resulted in about $554 million in savings and about $91.5 billion in revenues for participating industries. Companies have also reduced their carbon footprint by about 665,712 tons, water by 79,357 tons, and energy use by 279,761 tons of oil equivalent (Kim *et al*., 2018).

There have been some successes for industries involved in EINs around the world. For instance, the National Industrial Symbiosis Program (NISP) is a UK IS program replicated in about 20 countries. The program is a business offering for the improvement of cooperation-shared benefits between hitherto separate industries from various sectors, of varied sizes and interests. It has the goal of transforming unused and discarded resources in water, energy and/or materials from one industry for use in other industries through the 3-R process (recover, reprocess and reuse) (Laybourn and Morrissey, 2009). Between 2005 and 2010, the program diverted through 3-R, about 7 million tonnes of industrial waste from landfills, reducing carbon footprint by over 6 million tonnes, water usage by 9.6 million tonnes, hazardous waste by over 363,000 tonnes and virgin materials by 9.7 million tonnes. The program also generated £176 million in added sales, and cut operational costs by £156 million by improving technologies in storage, transportation, waste disposal, etc. (Laybourn and Morrissey, 2009). In the Baltic Sea region, the National Industrial Symbiosis Network (NISM) is a virtual network among Nordic countries, including Norway, Finland, and Sweden, etc., to reduce and/or optimise material use, promote processing and business innovations, and reduce the CO_2 footprint. It has successfully linked national IS programs such as the Symbiosis Network Denmark, Agder Symbiosis, Swedish Network for Industrial and Urban Symbiosis, and IS in Kalundborg (Nordregio, 2015; Domenech, 2019b).

The opportunities provide the basis for advanced research to identify shortfalls and areas to improve. This supports the need for this study–to determine the intra- and inter-dependencies among industries along the agro-value chain in Ghana.

2.11 Agriculture Initiative and Agro-food Waste

The agricultural sector's contribution to Ghana's Gross Domestic Product (GDP) has declined from 21.48 percent in 2016 to 17.61 percent in 2019. Similarly, its workforce has declined from 33.89 percent of the total labour force in 2016 to 33 percent in 2021. Although in 2020, the sector's contribution to GDP increased marginally to 18.24 percent due to the devastating impact of the COVID-19 pandemic, it is expected to decline again following a recovery of the services and industry sectors (Statista, 2022).

In the last decade, governments through the Ministry of Food and Agriculture (MoFA), have implemented a myriad of programmes, including Planting for Food and Jobs (PFJ), One District One Factory, One Village One Dam, and the Commodities Exchange Commission to induce growth in the ailing sector. The interventions have resulted in the establishment of some industries to reduce the increasing post-harvest losses and create jobs (Ministry of Food and Agriculture, 2021). In spite of the nominal growth in the sector, environmental challenges such as illegal mining, forest degradation, sand winning, chemical-induced farming, and post-harvest losses continue to threaten the sector. The projections and programmes in the sector indicate that food waste among industries along the value chain would increase, along with related emissions, prompting initiatives to resolve challenges. The initiatives are important in mitigating the socio-economic and environmental impacts of food waste.

2.12 Environmental and Industrial Policies in Ghana

2.12.1 Industrial Policies

According to Wade (2015), industrial policies are concerted efforts to shift the production structure to spur economic development. He adds that macroeconomic conditions, underlying political settlements, market forces, and limits to growth imposed by the natural environment are some notable factors that influence industrial policies. Ghana's manufacturing sector has faced myriad challenges due to its susceptibility to exchange rate volatility, impacts of economic policies of development partners, and its own industrial policies implementation challenges.

Between 2014 and 2017, the Government of Ghana implemented the Ghana Shared Growth and Development Agenda II (GSGDA II) (National Development Planning Commission, 2015). The overarching objective of GSGDA II is to improve private sector productivity and competitiveness domestically and globally (MoFEP, 2018). Until the end of 2021, Ghana was implementing 'The Ghana National Medium Term Development Plan (NMTDP 2018-2021)'. It focuses on deepening the aforesaid efforts under the GSGDA II to create jobs and revitalise industrial development.

From 2022 to 2025, the Government of Ghana seeks to among others, formulate national policies and enhance sectoral coordination among stakeholders; design programmes and allocate resources to achieve sector targets; and enhance entrepreneurial development, technology adoption, and access to markets and credits. To this, the government would, through Public-Private Partnership (PPP), implement its One District, One Factory initiative and create industrial parks and economic zones, according to the Ministry of Trade and Industry (2022).

Agencies that are facilitating this growth agenda include Ghana Exports Promotion Authority, GRATIS Foundation, Business Advisory Centres, and National Board for Small Scale Industries, etc. It is important to state that achieving this objective requires collaboration among existing industries and the development of products for the volumes of waste generated.

2.12.2 Environmental Policies

Environmental policies are measures by which governments monitor, evaluate, and control hazards that could impact humans, the environment, and the economy (Zhang, 2022). The

Environmental Protection Agency, established by Act 490, is the lead agency regulating activities with environmental consequences and implementing the government's environmental policies (Adjarko *et al*., 2016). The Act empowers the agency to formulate procedures and policies by which the environment would be protected. The Ministry of Environment, Science, Technology, and Innovation (MESTI) is the supervising authority of the agency.

According to MoFEP (2018), MESTI's Medium Term Expenditure Framework (MTEF) 2018 – 2021 focuses on enhancing the application of science, technology, and innovation, protecting existing forest reserves, reducing environmental pollution, combating deforestation, desertification, and soil erosion, enhancing climate change resilience, reducing greenhouse gases, mainstreaming science, technology, and innovation in all socio-economic activities, promoting a sustainable, spatially integrated, balanced and orderly development of human settlements, and enhancing capacity for policy formulation and coordination.

In addition, other ministries and agencies have specific environmental policies that feed into the holistic national policy. The Ministry of Lands and Natural Resources oversees mineral exploration, mining, and sustainable resource management (MoTI, 2010). The Minerals Commission, Water Resources Commission, Lands Commission, Energy Commission, Petroleum Commission, and Forestry Commission are some agencies regulating various aspects of the environment. This study would contribute to achieving the objectives of Ghana's industrial and environmental policies by identifying opportunities to enhance synergies among industries, reduce industrial waste, and promote sustainability.

3 METHODOLOGY

3.1 Study Area

The study was conducted in Greater Accra and Eastern regions of Ghana. According to the Ghana Statistical Service (2018), the Greater Accra region accounted for the highest (48.1 percent) value stock of agricultural raw materials in the country, hence its selection. However, the Eastern region was selected because it hosts some critical agro-based industries in the country, according to the Business Advisory Centre in Accra. In this study, enterprises refer to independent firms while industry describes a cluster of enterprises that produce similar products.

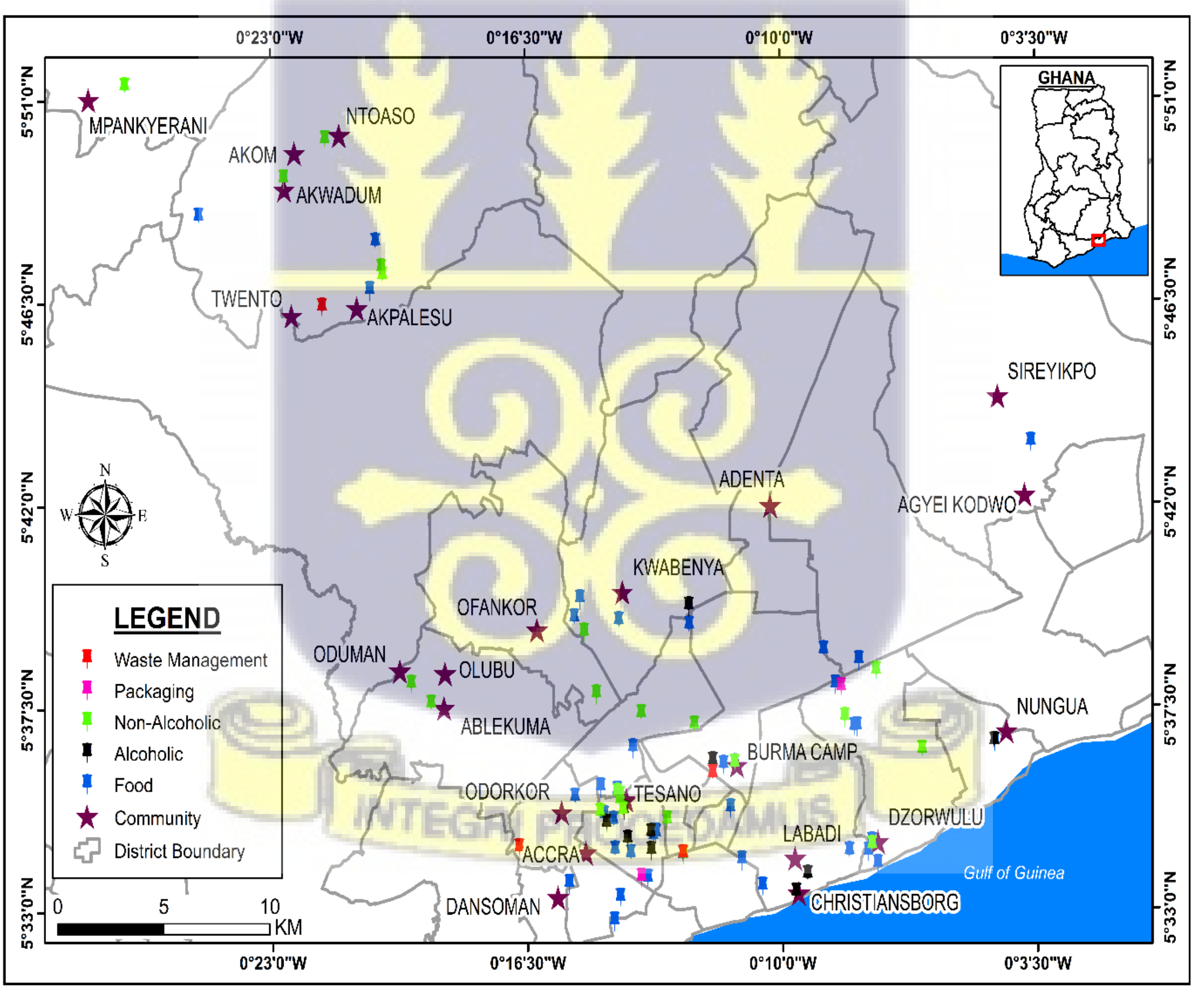

Figure 3.1: Map of Study Area

Greater Accra and Eastern Regions are important regions in Ghana. According to the Ghana Statistical Service (2021), the former hosts the capital, boasting 5,455,692 people (17.7 percent of Ghana's population) and an inter-censal growth rate of 3.7 percent while the latter boasts 2,925,653 people (9.5 percent of the population) and in inter-censal growth rate of 1.0 percent. The proportion of the population that is urban is highest in the Greater Accra Region (91.7 percent) and 7th in the Eastern Region (51.5 percent).

3.2 Sampling

A list of 103 agro-based enterprises in Greater Accra and Eastern regions, was obtained from the Business Advisory Centres (BAC) and the Association of Ghana Industries (AGI), nine (9) of which were defunct. The sample size (n) for the 94 active agro-based enterprises was calculated in accordance with a formula developed by Yamane (1967). According to Yamane, at a 95 percent confidence level and 0.5 precision level,

$$n = \frac{N}{1 + N(e)^2}$$

Where n = sample size, N = Population size, and e = level of precision.

Therefore, $$n = \frac{94}{1+94(0.05)^2} = 76 \text{ enterprises}$$

In total, 78 enterprises were surveyed, 2.6 percent above the sample size.

3.3 Research Framework

A research framework designed by Behne (2016) was adapted (see Figure 3.2) for this purpose. The new framework, as shown in Figure 3.3, highlights the main points of the study process i.e., the major processes the study underwent to generate the desired results. After study objectives were determined, field study and data collection were undertaken, collecting qualitative and quantitative data. Material use in enterprises were traced to reveal by-products from the different stages of an enterprise. The data was analysed and the results were reviewed accordingly.

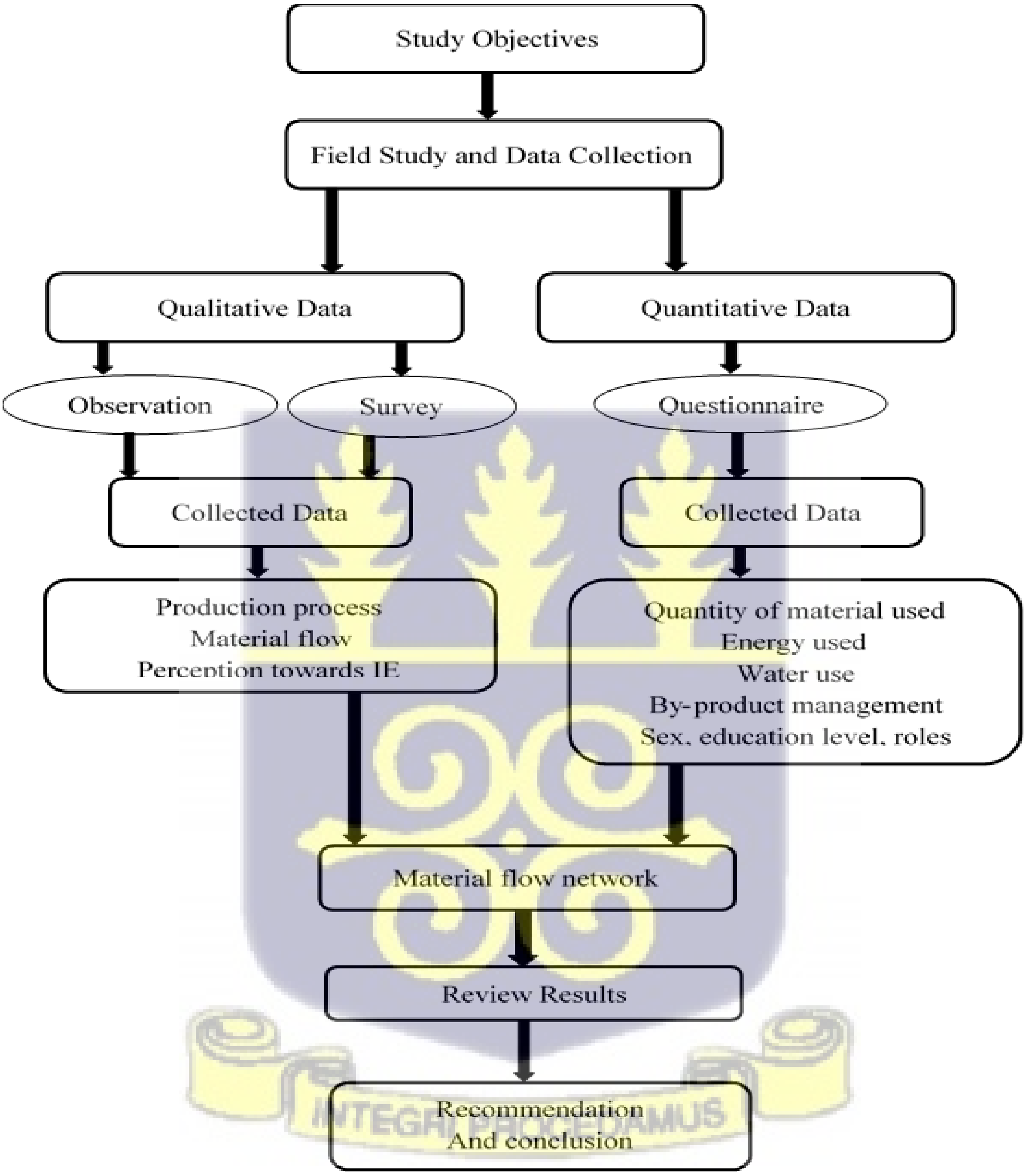

Figure 3.2: Research Framework

3.4 Instrument of Study

A questionnaire was the instrument of the study. The questionnaire was in five parts and contained open- and close-ended questions, and a Likert scale (Likert 1932). While the close-ended questions restricted respondents to pre-determined choices, the open-ended questions offered respondents the opportunity to answer questions in their own words. The open-ended questions were important sources of insight. In addition, the questionnaire involved 7-point Likert scale-type questions. The scale ranged from strongly agree (7) to strongly disagree (1). The five parts of the questionnaire included the demography section where respondents provided some personal data and profiles of involved enterprises; the general perception of interdependency section; materials exchanges at the firm level and between firms; energy and water use; and pollution prevention strategies.

3.5 Data Collection and Analysis

All questionnaires were administered by the researcher. While some respondents filled out the questionnaires on their own, the researcher read out and filled out the questionnaires for others due to literacy challenges. In some cases, respondents filled out the questionnaire at a later date. Data was analysed in line with the stated objectives. First, the GPS coordinates of enterprises were obtained and used to develop the study area map. The completed questionnaires were examined and coded to increase consistency and validity. Qualitative responses were triangulated to support the quantitative data and vice versa to mitigate the weaknesses of each method (Bryman, 2006).

3.5.1 Quantitative Data

Quantitative data was examined to appreciate the magnitude and scale of the interdependencies that exist or can exist. This evaluated the demographics of respondents and the profiles of involved enterprises. The profiles included the different types of inputs, outputs, products, and by-products generated by the participating enterprises (Aviso *et al.*, 2010; Gu *et al.*, 2013). Statistical tools such as Statistical Package for Social Sciences (SPSS) software version 27.0.1.0 and Microsoft Excel 2016 were used to analyse the data. Descriptive statistics including tables and charts were generated based on responses and inferential statistics–standard deviation and standard error were calculated. The scope of the work was limited to the data provided by the participating enterprises, proprietary concerns, and non-disclosure agreements.

3.5.2 Qualitative Data

The study used a qualitative approach of information collection to gather and analyse qualitative data. A qualitative method was used to evaluate the underlying reasons, motivations and opinions of the enterprises. It provided revelations into the nature and type of IE existing in participating enterprises (Merriam, 2009) relative to foundational metrics of IE-environmental, economic, and social (Trokanas *et al.*, 2015; Zhang *et al.*, 2017). Essentially, the study assessed the understanding of IS among respondents, IE and sustainable environmental initiatives, related practices currently being employed in their enterprises, social responsibilities to communities they operate in, and pollution prevention strategies, among others. The study also analysed models of the IE practiced and identified an approach to improving the practice among enterprises.

3.5.3 Likert Scale Analysis

A 7-point Likert scale questions were analysed using means, standard deviation and standard error. The scale ranged from 1 – strongly disagree, 2 – somewhat disagree, 3 – slightly disagree, 4 – neutral, 5 – slightly agree, 6 – somewhat agree, and 7 – strongly agree. Literature indicates that there is no significant difference between the scale ratings of a 7-point Likert scale and adjusted means of 1.1, 1.2, 2.1, and 4.1 (Dawes, 2008). Therefore, such a scale could be treated as having an equal interval (Mondiana *et al*., 2018), and averages and parametric analysis calculated (Mircioiu and Atkinson, 2017). Microsoft excel was used to compute the Standard Deviation (SD) and Standard Error (ER) for the question asked. Low SD indicates that responses did not deviate significantly from the determined mean, while low SE indicates that the sampled responses are reflective of the population (Lee *et al.*, 2015).

3.6 **Modelling Potential Exchanges**

Stan2web (Stan), a material flow analysis (MFA) software, was used to model a potential Eco-Industrial Network (EIN); exchanges or interlinkages that could exist among participating enterprises to optimise material flow (Gerber *et al.*, 2013). Modelling was done based on the three (3) phases of TVAIS: synergy compliance, synergy characterisation, and synergy feasibility (Dias *et al.*, 2020). To illustrate, existing industrial partnerships or interdependencies were assessed, indicating that if a synergy exists for a particular by-product, then a similar relationship could be created among industries of similar characteristics. Subsequently, intermediary processes, such as transportation and pre-requisite treatment systems are determined. Lastly, if there is a by-product availability and opportunity to be used as input exists, then the mapping could be done. Therefore, characteristics of surveyed enterprises such as input(s), output(s), and by-product(s) were analysed to determine where by-products from one firm may be useful, thus, reducing waste and improving resource use (Garner & Keoleian, 1995 and Hinterberger *et al.*, 2003). For instance, if an assessment revealed that by-products of an enterprise could be reused, reduced, or recycled by another, the said resource would be mapped to the potentially receiving enterprise.

3.7 **Validity and Reliability of Data**

Validity and reliability tests have been argued as, perhaps, the most important aspects of a research. Taherdoost (2016) underscored this position, stating that validity refers to how well what is supposed to be measured is actually measured. In other words, validity tests the correctness of measurements (Latif, 2018). Reliability, also, refers to the preciseness of the study that is, the absence of random errors in measurements. Ghauri *et al.* (2020) stressed that when a research methodology is repeated and produces the same results, reliability has been achieved.

In this study, steps, including data collection and corroboration from multiple sources and verifying data from firms' websites where applicable, were taken to ensure that reliability and validity were achieved. For instance, primary data on enterprises were acquired from the Association of Ghana Industries and the Business Advisory Centre of the National Board for Small-Scale Industries. In some cases, the researcher was present at the factory to verify the evidence provided by respondents.

Against the backdrop that, companies were to assess themselves on a 7-point scale, it was possible for some respondents to be conflicted and be compelled to deliberately score themselves higher, resulting in what Banerjee (2002) referred to as "social desirability bias". To mitigate this, questionnaires were given to officials of enterprises considered to be of high integrity. Further, some questions were deliberately transposed or repeated to monitor the consistency of responses. It suffices to say that, responses obtained reflected data as received from respondents and practices in these enterprises. Therefore, any weaknesses could be associated with the inherent weaknesses of the respondents themselves.

4 RESULTS

4.1 Profile of Selected Enterprises

4.1.1 Demography of Respondents

Of the 78 respondents, 60.3 percent (47) were males and 39.7 percent (31) were females. It was established that 77 percent (60 respondents) have received tertiary, while 37 percent were between the age of 30-39. Also, 42.5 percent of the respondents were highly involved in decision-making in their respective enterprises and almost half of the respondents (48.7 percent) worked in the administration department of their respective enterprises. Details of the demography of respondents are shown in Table 4.1.

Table 4.1: Demography of Respondents

Social Characteristics	Description	Percentage (%)
Gender	Male	60.3
	Female	39.7
Age	18-29	12
	30-39	37
	40-49	31
	50-59	18
	>60	3
Education	Tertiary	77
	Secondary	22
	Primary	1

Working Department	Administration	48.7
	Production	50.0
	Environment and Safety	1.3
Degree of Involvement in Decision	highly	42.5
	average	22
	low	35.5

4.1.2 Characteristics of Enterprises

Characteristics of enterprises surveyed were noted. The enterprises were categorised in the following broad areas: food industry, alcoholic beverage industry, non-alcoholic beverage industry, packaging industry and waste management industry, depending on the products that churned out of these enterprises. Table 4.2 details the distribution of the type of industry.

Table 4.2: Type of Industry and Frequency

Industry/Cluster of Enterprises	**Frequency**	**Percentage (%)**
Alcoholic	10	13%
Food	39	50%
Non-Alcoholic	23	29%
Packaging	2	3%
Waste Management	4	5%

Among the cluster of enterprises, input-output analysis techniques were applied to identify the inputs required, products churned out and by-products generated. Figures 4.1 to 4.5 show the results of the input-output analysis. P1 represents the process the inputs undergo while W1 is the process by which waste is discharged in the industry.

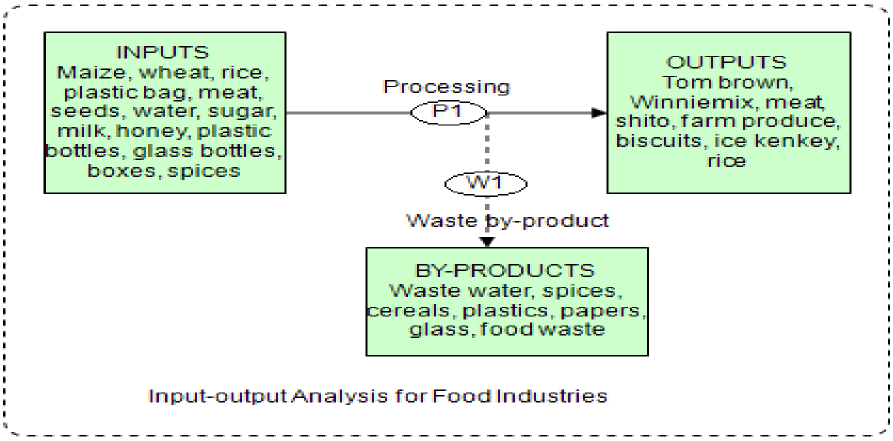

Figure 4.1: Input-Output Analysis for the Food Industry

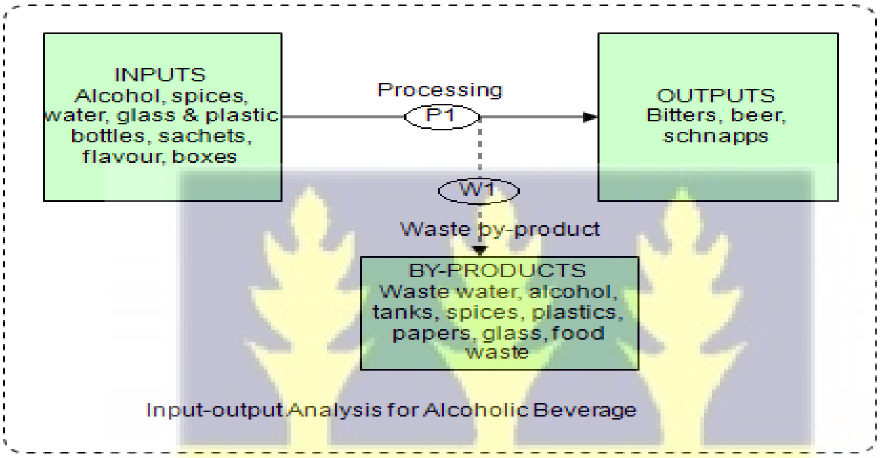

Figure 4.2: Input-Output Analysis for the Alcoholic Beverage Industry

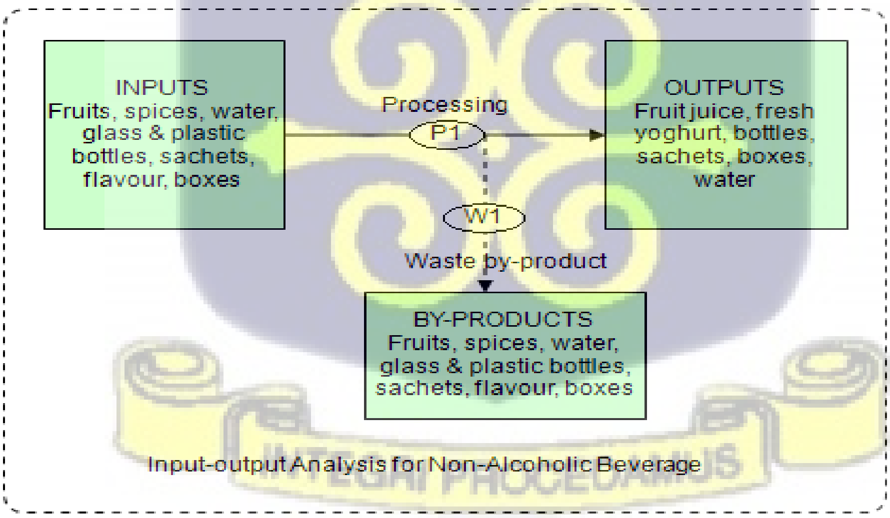

Figure 4.3: Input-Output Analysis for the Non-Alcoholic Beverage Industry

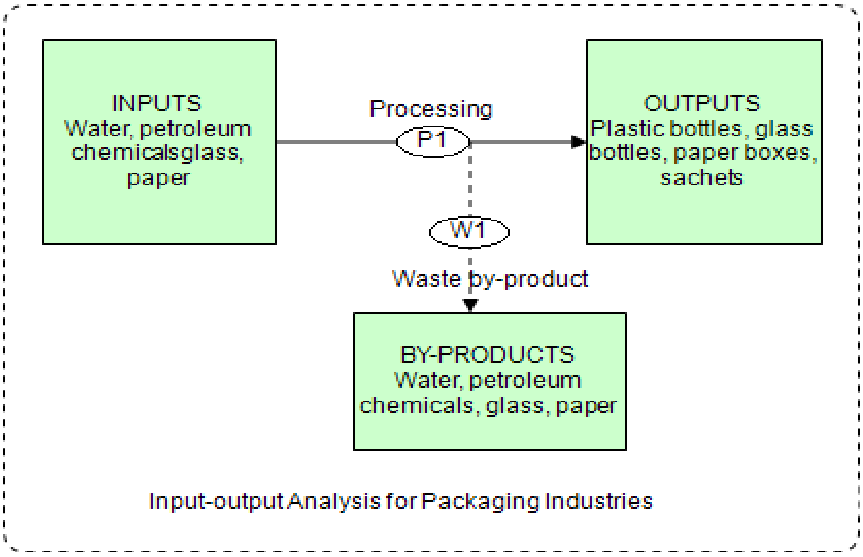

Figure 4.4: Input-Output Analysis for the Packaging Industry

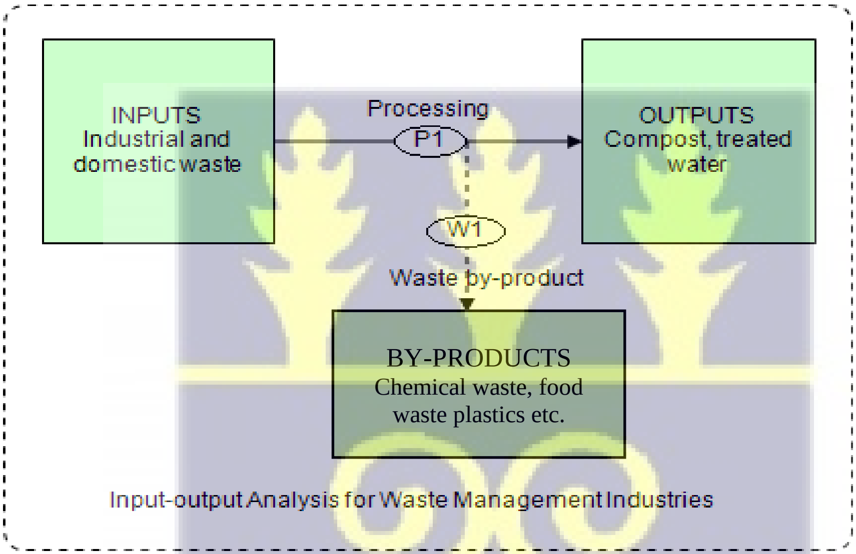

Figure 4.5: Input-Output Analysis for the Waste Management Industry

Meanwhile, the Input-Output Analysis for specific enterprises in addition to other characteristics, including IDs assigned by the researcher to replace company names, type of industry, and region were recorded in Table 4.3.

Table 4.3: Profiles of Enterprises.

ID	Type of Industry	Region	Product	Input	By-Product
IS01	Food	Eastern	Meat and Chicken product	Goat, chicken, piglet, sheep,	Animal Droppings, water, rubber

ID	Type of Industry	Region	Product	Input	By-Product
				water, feed, package rubber	
IS02	Food	Greater Accra	Chocolate powder, skin care products	Cocoa, sugar, water, Bottles	Cocoa husk, & water and bottles
IS03	Food	Greater Accra	Pepper Sauce	Pepper, oil, water, fish, spices, packaging	water, packaging, vegetables, fish
IS04	Food	Greater Accra	food spices	vegetable	vegetables
IS05	Food	Greater Accra	Tom Brown, winnemix	Maize, groundnut, Containers, cowpeas	waste cereals, waste containers
IS06	Food	Eastern	dry fruits	Mango, pineapple, banana, coconut, water	Fruit waste, water, waste package, coconut Husk
IS07	Food	Greater Accra	Ice Kenkey	Maize, Sugar, Milk, Water, Groundnut	Wastewater, sacks, containers
IS08	Food	Greater Accra	vegetables, pineapple and maize production	Seeds, animal droppings, fertilizers	post-harvest losses
IS09	Food	Greater Accra	Rice flour, Samolina, Rice	sugar	Sacks, Rice Husk, Package Bags, Residue, water

ID	Type of Industry	Region	Product	Input	By-Product
IS10	Food	Greater Accra	Rice	Rice, Package Bags, water/Steam	sacks, Rice Husk, Waste Package Bags
IS11	Food	Greater Accra	Honey	honey, packaging	honey, packaging
IS12	Food	Greater Accra	Cereal flour	Maize, groundnut, Containers, cowpeas	waste cereals, waste containers
IS13	Food	Greater Accra	Green leaf tea	Leaves, vegetables	Leaves, vegetables
IS14	Food	Eastern	pork	Piglets, pig feed, plastic Bags, water	Pig Droppings, Waste waster
IS15	Food	Greater Accra	Cereal Meal Production	Maize, beans, groundnut, Wheat	Cereal Waste
IS16	Food	Greater Accra	Winnemix, Tom Brown	Maize, beans, groundnut	Cereal Waste
IS17	Food	Greater Accra	Tom Brown, winnemix	Maize, groundnut, Containers, cowpeas	waste cereals, waste containers
IS18	Food	Greater Accra	Tom brown, Fried Groundnut, Winnemix	Millet, Corn, wheat, water	Husk, wastewater
IS19	Food	Greater Accra	Tom Brown	Maize, groundnut, Gas, Beans	Cereal Waste
IS20	Food	Greater Accra	Shito (black Pepper sauce)	Pepper, oil, water, fish, spices, packaging	wastewater, packaging, vegetables, fish
IS21	Food	Greater Accra	palm oil	palm fruits, water, heat, packaging bags & bottles	Water, fibre, palm kennel, husk, soup

ID	Type of Industry	Region	Product	Input	By-Product
IS22	Food	Greater Accra	pastries	Flour, food flavor, sugar, margarine, spices	Sacks, plastics, water
IS23	Food	Greater Accra	Tom brown	Maize, beans, groundnut, rice	Cereal, water
IS24	Food	Greater Accra	Honey	Honey, packaging	Honey, packaging
IS25	Food	Greater Accra	Cocoa Powder	Cocoa, water, Bottles	Cocoa husk, water, bottles
IS26	Food	Greater Accra	Packaged Beans	Beans, package	beans, water, package
IS27	Food	Greater Accra	soybean food and cereal	soya beans, cereals, packaging	soya beans, cereals, packaging
IS28	Food	Greater Accra	coconut oil	Coconut, Plastic packaging containers, water	coconut husk, Plastic packaging containers, water
IS29	Food	Greater Accra	Yam, cocoyam, shito	Yam, cocoyam, water, pepper, oil, additives	wastewater, shito residue
IS30	Food	Greater Accra	palm oil production	palm fruits, water, heat	Water, fibre, palm kennel, husk, soup
IS31	Food	Greater Accra	shito (black Pepper sauce)	Shrimps, pepper, beef, gizzard, mushroom, oil, paper boxes, bottles	bottles & paper, additives, water
IS32	Food	Greater Accra	palm oil production	palm fruits, water, heat	Water, fibre, palm kennel, husk, soup

ID	Type of Industry	Region	Product	Input	By-Product
IS33	Food	Greater Accra	processing of dry food	tubers	tubers
IS34	Food	Greater Accra	Tom Brown, winnemix	Maize, groundnut, Containers, cowpeas	waste cereals, waste containers
IS35	Food	Greater Accra	maize and cassava food processing	Maize, cassava, heat	maize, cassava, water
IS36	Food	Greater Accra	Chicken, duck, geese, animal feed, vegetables and cereal farm	Tuna, maize, feed additives, poultry, piglet, water, ducks, geese, animal droppings	dead animals, wastewater, animal droppings, feed waste
IS37	Food	Greater Accra	Farm, production of Gari for export	Seeds, cassava, heat	post-harvest losses
IS38	Food	Greater Accra	cereal mix	Maize, groundnut, Containers, beans, vegetables	waste cereals, waste containers,
IS39	Food	Greater Accra	Tom Brown, winnemix, shito	Maize, groundnut, Containers, cowpeas, vegetables	waste cereals, waste containers
IS40	Alcoholic	Greater Accra	Alcoholic Beverage	Alcohol, Bottles, Water, Paper Boxes, Spices/Additives	Additives, Bottles, Water, Alcohol, Paper Boxes, tanks

ID	Type of Industry	Region	Product	Input	By-Product
IS41	Alcoholic	Greater Accra	Alcoholic, Non-Alcoholic Beverage	Alcohol, Bottles, Water, Paper Boxes, Spices/Additives, Sugar, Fruits	Additives, Bottles, Water, Alcohol, Paper Boxes
IS42	Alcoholic	Greater Accra	Gin Bitters	Alcohol, Bottles, Water, Paper Boxes, Spices/Additives	Additives, Bottles, Water, Alcohol, Paper Boxes
IS43	Alcoholic	Greater Accra	Alcoholic Beverage	Alcohol, Bottles, Water, Paper Boxes, Spices/Additives	Additives, Bottles, Water, Alcohol, Paper Boxes
IS44	Alcoholic	Greater Accra	Alcoholic Beverage	Alcohol, Bottles, Water, Paper Boxes, Spices/Additives	Additives, Bottles, Water, Waste Alcohol, Paper Boxes
IS45	Alcoholic	Greater Accra	Alcoholic Beverages	Alcohol, Bottles, Water, Paper Boxes, Spices/Additives	Additives, Bottles, Water, Alcohol, Paper Boxes
IS46	Alcoholic	Greater Accra	Alcoholic Beverage	Alcohol, bottles, Water, Paper Boxes, Spices/Additives	Additives, Bottles, Water, Alcohol, Paper Boxes
IS47	Alcoholic	Greater Accra	Alcoholic Beverage, Bottled Water, sachet Water	Akpeteshie & Alcohol, Food Flavour, Water, Spices, Rubber Rolls	Spices Waste, Waste rubber

ID	Type of Industry	Region	Product	Input	By-Product
IS48	Alcoholic	Greater Accra	alcoholic and non-alcoholic beverages	Mango, Hibiscus, corn, water, Akpeteshie & Alcohol, Food Flavour, Spices, Rubber Rolls, Bottles	Fiber and Peels, Wastewater, Sacks, Bottles
IS49	Alcoholic	Greater Accra	Bitters	Alcohol, Bottles, Water, Paper Boxes, Spices/Additives	Additives, Bottles, Water, Alcohol, Paper Boxes
IS50	Non-Alcoholic	Eastern	pineapple Juice, Mango Juice, Pineapple Ginger Juice	Pineapple, Mango, Ginger, water, Bottles	Waste Fibre, Peels, Ginger, Water, Bottles
IS51	Non-Alcoholic	Eastern	non-alcoholic beverage	sugar, water, flavour, spices	water, bottles, spices
IS52	Non-Alcoholic	Greater Accra	Chocolate Drink	Cocoa, sugar, water, Bottles	Cocoa husk & wastewater and bottles
IS53	Non-Alcoholic	Greater Accra	Vegetable Juice	vegetable	vegetables
IS54	Non-Alcoholic	Eastern	Fruit Juice, Fruit Ice Cream, Fresh Cut	Mango, passion fruit, banana, coconut, fruit waste, water, Pineapple,	Fruit waste, water, waste package, coconut Husk

ID	Type of Industry	Region	Product	Input	By-Product
			Fruits, compost		
IS55	Non-Alcoholic	Greater Accra	bottled water	ground water, Pre-Form, cartons	Plastics waste, wastewater
IS56	Non-Alcoholic	Greater Accra	communion wine	imported Wine	boxes, barrels
IS57	Non-Alcoholic	Greater Accra	Fruit Juice	Mango, Pineapple, Orange, water	Fruit waste, water, waste package
IS58	Non-Alcoholic	Greater Accra	Fruit Juice	Mango, Pineapple, coconut, water	Fruit waste, Wastewater, waste package, coconut Husk
IS59	Non-Alcoholic	Greater Accra	dried Mango, dried pineapple, dried coconut, compost	Mango, pineapple, coconut, coconut Husk, water, fruit waste	Fruit waste, water, waste package, coconut Husk
IS60	Non-Alcoholic	Greater Accra	fruit Juice	Mango, Pineapple, coconut, water	Fruit waste, water, package, coconut Husk
IS61	Non-Alcoholic	Greater Accra	Bissap Drink	Hibiscus, water, Bottles	Fiber and Peels, Water, Sacks, Bottles
IS62	Non-Alcoholic	Greater Accra	flavoured Drinks	sugar, water, flavour, spices	water, bottles, spices
IS63	Non-Alcoholic	Greater Accra	Bissap Drink	Mango, Hibiscus, corn, Aloe Vera,	Fiber and Peels, Water, Sacks, Bottles

ID	Type of Industry	Region	Product	Input	By-Product
				Shea Butter, water, Bottles	
IS64	Non-Alcoholic	Greater Accra	Dry Coconut, Coconut Juice	Coconut, Coconut Husk, Plastic package bag, water	coconut husk, water, sacks, plastics bags
IS65	Non-Alcoholic	Greater Accra	coconut Juice	coconut, package	coconut husk, water package
IS66	Non-Alcoholic	Greater Accra	Mango, Juice, Sobolo, Asana, Skin Care products	Mango, Hibiscus, corn, Aloe Vera, Shea Butter, water, Bottles	Waste Fiber and Peels, Water, Sacks, Bottles
IS67	Non-Alcoholic	Greater Accra	Kaas drink	Mango, Hibiscus, corn, Aloe Vera, Shea Butter, water, Bottles	Waste Fiber and Peels, Water, Sacks, Bottles
IS68	Non-Alcoholic	Eastern	fruit Juice	Mango, Pineapple, banana, millet, water	Fruit, water, packages, coconut Husk
IS69	Non-Alcoholic	Greater Accra	Biscuit, Bottled water, non-Alcoholic Beverage	Flour, food flavor, sugar, water, colour, additives, sachet rolls, plastics bottles	waste flour, water, sachet waster, bottles, Residue
IS70	Non-Alcoholic	Eastern	Fruit Juice	Mango, Pineapple, prekese, papaya, water/steam, bottles	fruit waste, Wastewater, waste paper package, broken bottles

ID	Type of Industry	Region	Product	Input	By-Product
IS71	Non-Alcoholic	Greater Accra	fresh yoghurt, tombrown	Yoghurt, Milk, Maize, Water, Millet, Beans	waste milk, wastewater, waste cereals
IS72	Non-Alcoholic	Greater Accra	yoghurt	Yoghurt, Milk, Water, containers	waste milk, wastewater
IS73	Packaging	Greater Accra	Bottle water, glass bottles, plastic Bottles, non-alcoholic, Beverages	water, food flavour, glass and plastic bottles, sugar	Wastewater, waste paper
IS74	Packaging	Greater Accra	plastic Bottles, Drums, tanks	rubber	Water, paper
IS75	Waste Management	Eastern	Compost, pellet, Bagged Waste Plastics	industrial and domestics waste including Septic waste)	unprocessed waste
IS76	Waste Management	Greater Accra	Compost, Bagged Waste Plastics	industrial and domestic waste	unprocessed waste
IS77	Waste Management	Greater Accra	Compost, Waste Transporters	biodegradable waste, residential and industrial waste	non-biodegradable waste

ID	Type of Industry	Region	Product	Input	By-Product
IS78	Waste Management	Greater Accra	Compost, pellet, Plastics	industrial and domestic waste	unprocessed waste

Staff strength for these enterprises was classified into two (2) categories, namely permanent and casual staff. However, a significant proportion of enterprises (71) did not provide data on the number of employees at their firm.

4.2 Interdependencies at Firm Level

At the firm level, respondents assessed their understanding of Industrial Ecology (IE) and Industrial Symbiosis (IS). It was determined that 88.7 percent of respondents had knowledge in IE/IS, while 17.95 percent had no knowledge of IE/IS. The specifics per type of industry are shown in Figure 4.6.

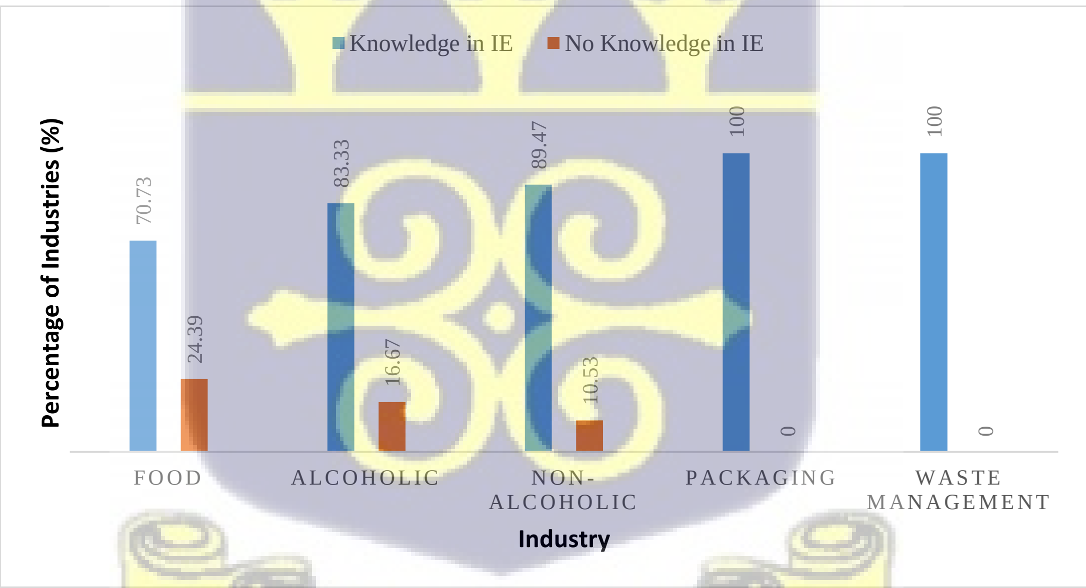

Figure 4.6: Knowledge of Industrial Ecology and Industrial Symbiosis

In providing details of their understanding of IE or IS, 35.9 percent indicated that IE refers to how inputs are utilised and reutilised in an industrial setting; 17.94 percent explained IE as practices that ensure waste or by-product reuse within and among enterprises and the movement of materials from one section of the company to another in a manner that reduces waste, stressing that such enterprises could include waste management service provider; 12.82 percent described IE as input management schemes instituted by industries to reduce waste; 6.41 percent described IE as the study of material flow in the industry; 5.13 percent noted that IE relates to how material and energy flows in an industrial system in order to produce a product; and 1.28 percent said IE involves regulating the use of material and energy in an industry.

However, when respondents were required to explain their understanding 20.51 percent offered no explanation. It was determined that 78.8 percent engaged in IE practices, while 19.6 percent did not engage in any IE practices at the firm level. Figure 4.7 shows the ratio among the types of industries.

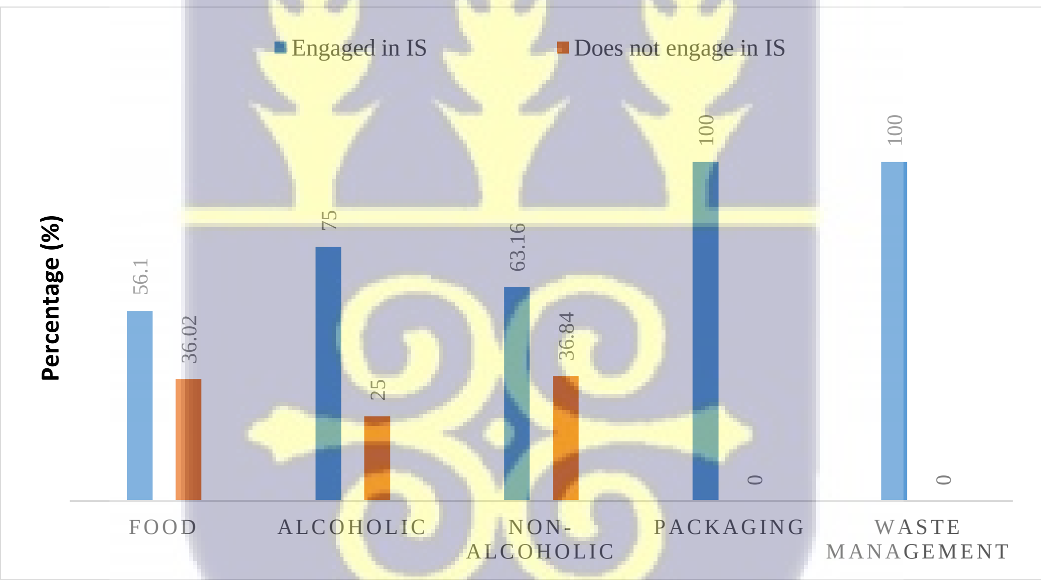

Figure 4.7: Industries Engaged in IS

4.2.1 Industrial Ecology at Firm Level

Interdependency initiatives outlined by respondents include the internal production of water, aligning production systems to reduce leakage of material and energy waste, building factories to allow natural light and air to enhance energy efficiency, and reuse of solid waste among others. For instance, an alcoholic beverage company in Osu indicated that it reuses alcoholic tanks as water reservoirs. A liquid and solid waste management company in Medea indicated that it recycles liquid waste from enterprise and household septic tanks, extracting water for irrigation and cleaning purposes while converting the faecal matter into bio char. It further indicated that it converts biodegradable waste into compost for its lawns. The study also established that 12 percent of food and non-alcoholic industries reused wastewater for irrigation and cleaning. IE initiatives adopted by some enterprises are indicated in Figure 4.8.

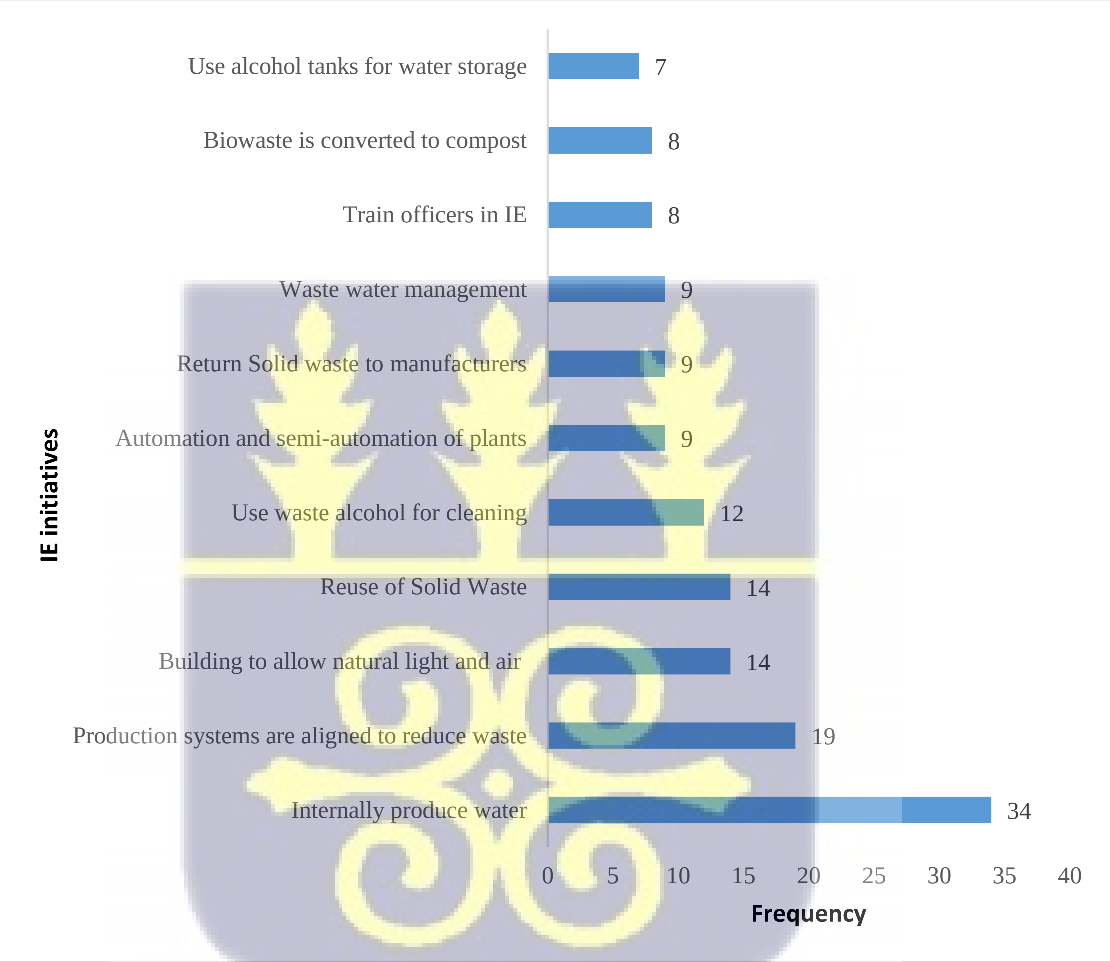

Figure 4.8: IE within Enterprises

It was also established that 94 percent of enterprises made deliberate efforts to educate staff on the importance of environmental and energy conservation, while 90 percent prioritised customer concerns over shareholder concerns (see Table 4.4). For instance, 8 alcoholic and non-alcoholic enterprises stated that their building and roofing styles are purposefully designed to allow natural light and air through the roofs and the extralarge windows. However, only 81 percent (63 enterprises) had environmental policies, indicating that about 19 percent of enterprises that deliberately educated staff had no policy to guide the staff. Indeed, of the 63 enterprises, 44 (69.8 percent) have not documented their environmental policies. This raises questions about the environmental standards upheld in these enterprises. It was also noted that 25 percent, 8 percent, and 5 percent of waste management, alcoholic, and food industries, respectively, used solar PV lighting systems to augment grid-powered lights on their premises. These indicate that, although IS exists among enterprises, its adoption is low and very informal.

Table 4.4: IE within Enterprises

IE within enterprises	Mean Score	Percentage Score	SD	SE
At our firm, we make a deliberate effort to let all staff to understand the importance of environmental conservation.	6.58	94	0.55	0.06
Our firm has a clear policy statement urging environmental awareness in every area.	5.67	81	1.16	0.13
Our firm's responsibility to its customers and stakeholders is more important than our responsibility toward environmental preservation.	6.30	90	0.94	0.11
Raw materials have become more expensive due to scarcity of resources from the natural environment.	6.65	95	0.68	0.08
We prioritise energy conservation.	6.37	91	0.69	0.08
Energy efficiency is a paramount factor when adopting new technology.	6.44	92	0.68	0.08
We have alternative source(s) of energy.	4.13	59	1.45	0.16

The Standard Deviation (SD) values of less than 1.5 indicate that responses did not deviate significantly from the mean (score). Likewise, a Standard Error (SE) of less than 0.5 indicates that the sample score reflects the population.

At the enterprise level, some firms highlighted sustainability practices between them and customers. For instance, among the ten (10) alcoholic beverage enterprises, two (2) indicated that large alcohol tanks were sold to residential homeowners for water storage, while four (4) returned defective or waste bottles, sachets and boxes to manufacturers for recycling. Three (3) non-alcoholic and one (1) alcoholic beverage industries indicated that they incentivise customers to return bottles after use. Although the exchange between enterprises and homeowners and/or customers is not IS as it is not between two or more enterprises, the principle promotes circularity of the said material or by-products and hence the relevance to this study.

4.2.2 Pollution Prevention Initiatives and Community Initiatives at the Firm Level

On pollution prevention initiative at the firm level, the study identified strong firm-level initiatives and adherence to regulatory standards (see Table 4.5).

Table 4.5: Pollution Prevention Initiatives at Firm Level

Pollution Prevention Initiatives	**Mean score**	**Percentage score**	**SD**	**ER**
We ensure energy conservation among all staff members.	6.51	93	0.55	0.06
We use alternate sources of energy.	3.99	57	1.71	0.19
We often replace obsolete polluting technology with energy efficient ones.	5.53	79	1.21	0.14
Our decision for technology adoption is influenced by environmental pollution concerns.	5.95	85	1.32	0.15
Pollution issues are considered when developing new products.	5.60	80	1.17	0.13

We integrate pollution prevention issues with strategic planning.	5.67	81	1.11	0.13
We monitor and control emission/effluent.	5.60	80	1.24	0.14
We treat solid and liquid waste before discharge.	4.76	68	1.47	0.17
We have an environmental policy.	5.32	76	1.39	0.16
We have set environmental targets.	5.04	72	1.13	0.13
We always achieve our set environmental targets.	4.76	68	1.02	0.12
We meet EPA standards.	5.81	83	0.93	0.10

It was further established that industries contributed to the uplift of their host communities by employing local persons and supporting communal projects and activities including schools, potable water projects, clinics, durbars (see Figure 4.9).

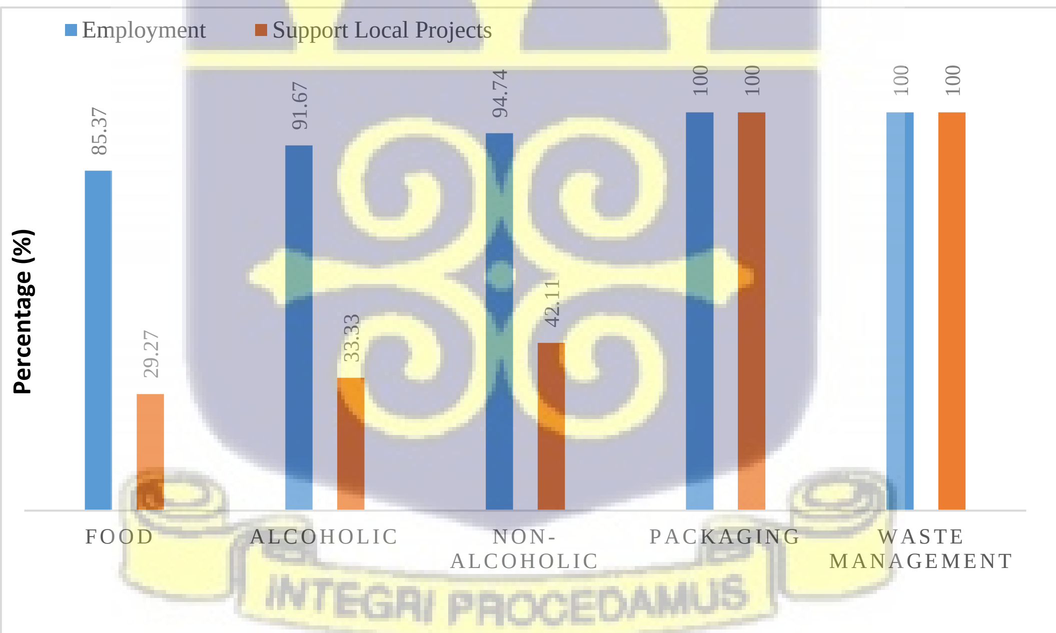

Figure 4.9: Social and Community Connections among industries

4.3 IE among Enterprises: Industrial Symbiosis

4.3.1 Material and Energy Synergies among Firms

Levels of recycling among enterprises were identified to be average (53.84 percent) among respondents (see Figure 4.10), out of which an estimated 32 percent occurred in another firm while 22 percent occurred both within the same firm and in another firm. However, the 'recycling' did not fully constitute IS among industries as, according to some respondents, the exchange mostly involves interdependency with waste management enterprises and some of these waste management enterprises do not recycle or reuse by-products. Rather, these waste management enterprises ensured safe disposal at landfill sites. This indicates that, actual interdependency may be far lower, estimated at about half of the 53.84 percent (between 27 percent and 32 percent), according to some respondents. Indeed, when respondents were asked whether they have identified new useful by-products from other enterprises, only 7.7 percent responded positively (yes).

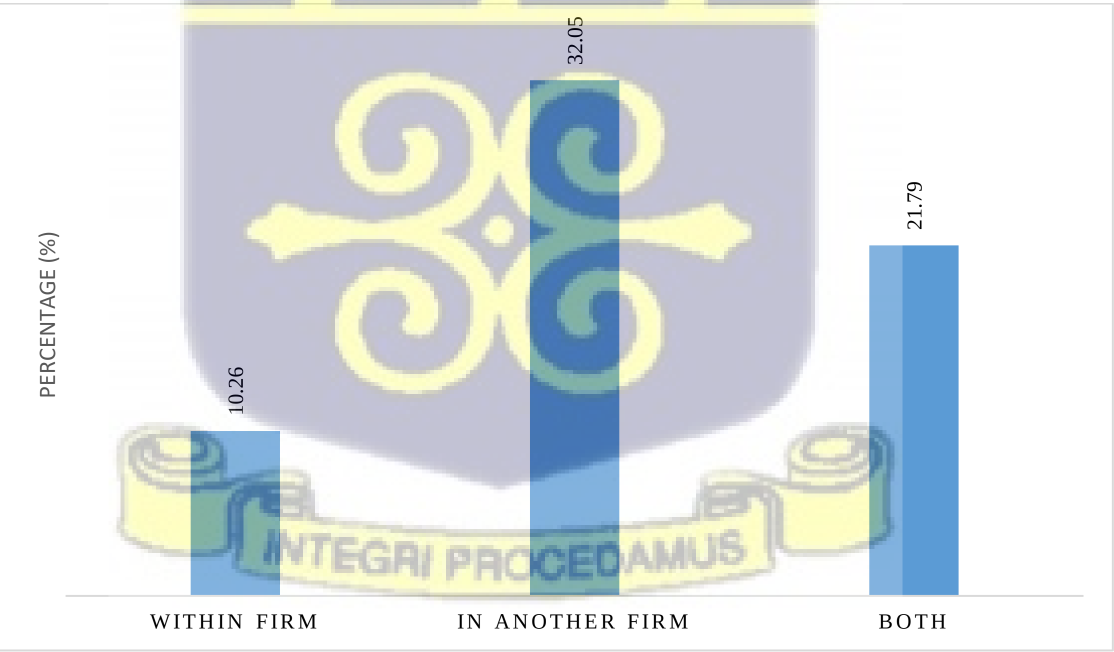

Figure 4.10: Level of Recycling

The nature of exchanges varied, with some existing between enterprises and others, between production firms and between firms and waste management enterprises. For instance, there exist an interdependency among some food and non-alcoholic industries and between the duo and out-grower associations (see Table 4.6).

Table 4.6: Existing Exchanges among Firms

Primary Firm	**Dependent Firm**	**By-Products Exchanged**
IS54	6 non-alcoholic enterprises, Out-grower farms, local markets	Waste fruits, rejected fruits, compost
IS06	3 non-alcoholic enterprises, Farms, local markets	Waste fruits, rejected fruits,
Packaging Companies (Plastic/Paper)	17 enterprises depend on the Packaging companies	Waste bottles and sachets, waste paper boxes
Waste management companies	42 enterprises depend waste management companies	General waste materials
All 74 enterprises	Waste management companies	Waste and by-products
Cocoa Processor	IS25, Briquette company	Waste cocoa Cocoa husk
Briquette company	IS59	Briquette
IS70	Local farmers, market	Waste and rejected fruits
Fish processor	IS36	Fish for animal feed
IS40	Residential facilities	Alcohol Tanks

Firms prefixed with IS are described in Table 4.3.

However, there was no energy-based interdependency among enterprises surveyed. All surveyed firms relied on the national grid, with 68 percent of food, 58 percent of alcoholic and 53 percent of non-alcoholic, and all packaging and waste management industry operating diesel generators in addition. Table 4.7 supports this finding. That said, there were high indications among firms (25 percent) to pay for useful by-products and to participate in an environmental management system (78.8 percent). Despite this, 76.1 percent of respondents expressed concerns over potential customer reaction should enterprises adopt the use of by-products.

Table 4.7: IS among Enterprises

IS among Enterprises	Mean Score	Percentage Score (%)	SD	SE
Raw materials have become more expensive due to the scarcity of resources from the natural environment.	6.65	95	0.68	0.08
We engage in the reuse and recycling of waste to reduce our cost of raw materials.	5.11	73	1.52	0.17
We take advantage of our proximity to other industries to source their by-products/waste as our input materials.	4.34	62	1.33	0.15
Other industries are interested in using our by-products/waste for their production.	4.20	60	1.27	0.14
We don't have any use for our waste.	1.68	24	1.41	0.16
There is no advantage for us in the use of by-products/waste	1.61	23	1.11	0.13

The use of by-products is detrimental to the quality of our final products.	2.03	29	1.88	0.21
We have our internal processes and do not interact with other industries.	5.67	81	1.40	0.16

The Standard Deviation (SD) values of less than 2 indicate that responses did not deviate significantly from the mean (score). Likewise, a Standard Error (SE) of less than 0.5 indicates that the sample score reflects the population.

Respondents also indicated the relationship between them and State regulatory agencies (see Figure 4.11). Some indicated that State agencies facilitated their access to the European Union (EU), the United Kingdom (UK), and the United States (US) markets. In addition, State agencies were integral in establishing relationships between certification training agencies for these markets and development partners. On training and monitoring, some enterprises acknowledged the role of State agencies, including the Ministries of Health and Food and Agriculture in upgrading capacities of staff and monitoring operations of their respective enterprises.

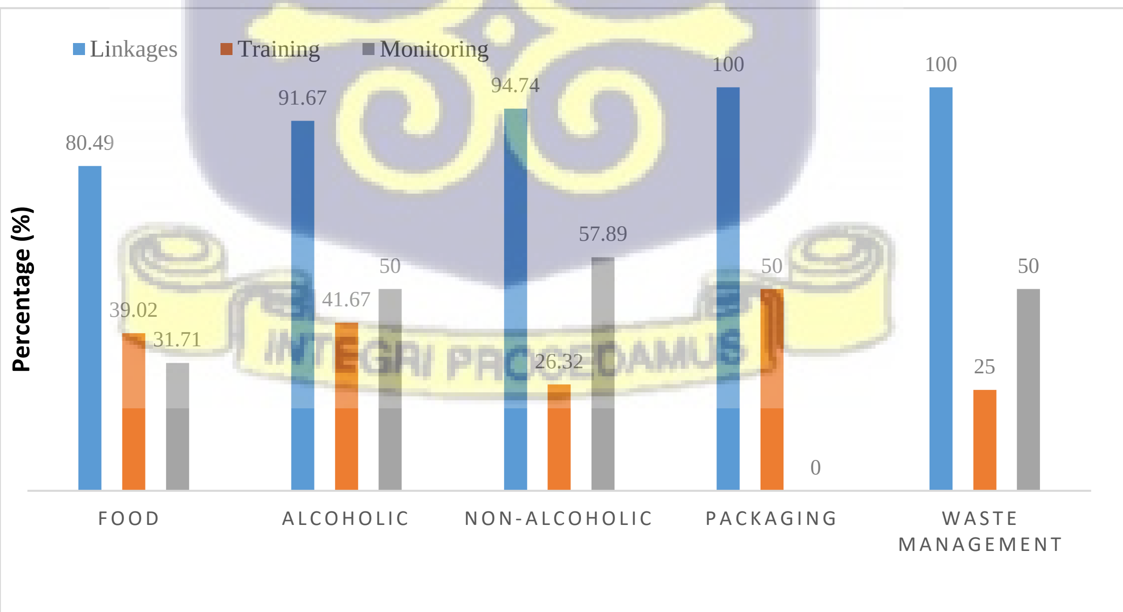

Figure 4.11: Relationship between Industries and State Regulatory Agencies

4.4 Model of Potential Exchanges among Enterprises

After analysing the inputs and outputs of the different enterprises, a model for potential exchanges were developed. Synergy Compliance and Synergy Characterisation were done in accordance with the TVAIS framework. However, Synergy Feasibility was not assessed due to the data paucity on the quantum of waste generated. Observations were that, the waste from the food industry such as wastewater, fibre/food waste, waste spices and paper, plastic, glass, and sacks could be utilised by animal feed enterprises, compost manufacturing enterprises, wastewater treatment enterprises, and paper, plastic, glass (PPG) manufacturing and recycling. Again, the non-alcoholic and fruit juice enterprises saw similar modelling based on their inputs, outputs, and by-products. Additionally, the alcoholic industry's by-product was modelled as seen in Figure 4.12. Ultimately, PPG enterprises will utilise waste and by-products that remain from the various transitions for recycling and re-engineering processing. The model was developed using the Stan application for material flow analysis (See Appendix 2 for the Stan interface). This model hinges on the establishment of water and alcohol treatment enterprises,

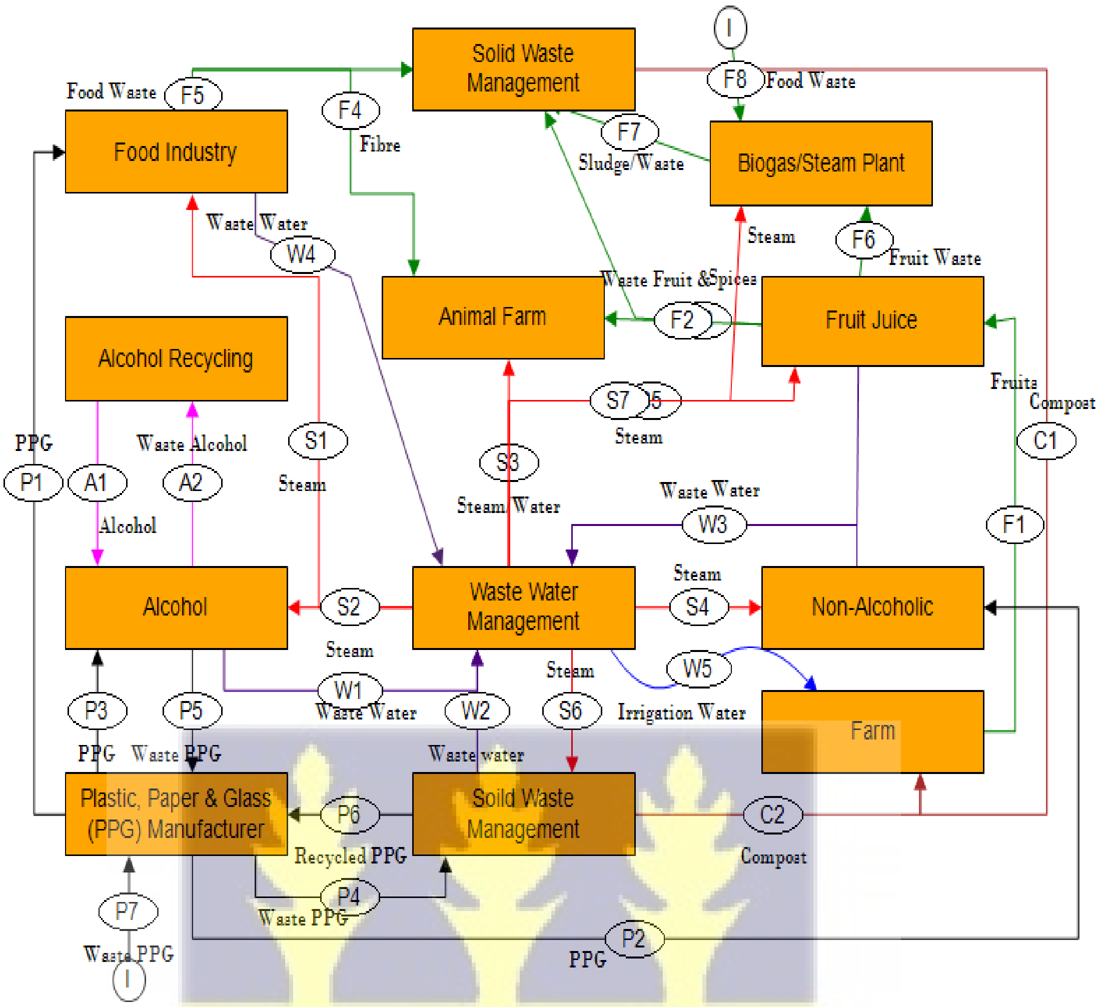

Figure 4.12: Modelled Interdependencies among Industries

LEGEND

	Flow of Alcohol
	Flow of irrigable water
	Flow of Compost
	Flow of Plastics, Paper, Sachet, Sacks & Glass
	Flow of steam
	Flow of Wastewater

The modelled interdependencies are explained in Table 4.8

Table 4.8: Interpretation of Modelled Flows in Figure 4.7

CODE	Interpretation of Synergy
A1	Waste alcohol from alcoholic beverage industries transferred to recycling plants for treatment and reuse

A2	Treated alcohol reused by alcoholic beverage industries
C1 & C2	Compost from solid waste management industries transferred to farms
F1	Fruit from farms utilising compost and treated water from other enterprises supplied to fruit juice enterprises
F2	Fruit by-product or waste converted to animal feed at animal farms
F3	Fruit by-product waste transported to solid waste management enterprises for the manufacture of compost
F4	Food waste or by-products converted to animal feed at animal farms
F5	Food by-products waste transported to solid waste management enterprises for the manufacture of compost
F6	Fruit by-products or waste utilised as feedstock by biogas plants for the generation of electricity
F7	Sludge or waste from biogas plant converted to compost by solid waste management industries
F8	Food waste from food enterprises and other sourced used as input for biogas plant for the generation of electricity
P1	Recycled plastics, sachets, glasses and papers used as packaging material among food enterprises
P2	Recycled plastics, sachets, glasses and papers used as packaging material among non-alcoholic beverage enterprises
P3	Recycled plastics, sachets, glasses and papers used as packaging material among alcoholic beverage enterprises
P4	Waste plastics, sachets, glasses and papers transferred to solid waste management enterprises for recycling
P5	Waste plastics, sachets, glasses and papers from alcoholic enterprises transferred to plastic, paper and glass (PPG) manufacturers for recycling
P6	Recycled plastics, sachets, glasses and papers transferred back to PPG manufacturers
P7	Waste plastics, sachets, glasses and papers other sources including residential homes, transferred to plastic, paper and glass (PPG) manufacturers for recycling

S1	Wastewater treatment facility supplies food enterprises with steam generated from wastewater
S2	Wastewater treatment facility supplies Alcoholic beverage enterprises with steam generated from wastewater
S3	Wastewater treatment facility supplies Animal farms with steam or water generated from wastewater
S4	Wastewater treatment facility supplies non-alcoholic enterprises with steam generated from wastewater
S5	Wastewater treatment facility supplies fruit juice enterprises with steam generated from wastewater
S6	Wastewater treatment facility supplies solid waste management enterprises with steam generated from wastewater
S7	Wastewater treatment facility supplies Steam Plant for electricity generation with steam generated from wastewater
W1	Wastewater from alcohol enterprises transferred to a Wastewater treatment facility where it is treated and converted to steam or irrigable water
W2	Wastewater from Solid Waste Management enterprises transferred to a Wastewater treatment facility where it is treated and converted to steam or irrigable water
W3	Wastewater from Non-alcoholic beverage enterprises transferred to a Wastewater treatment facility where it is treated and converted to steam or irrigable water
W4	Wastewater from Food enterprises transferred to a Wastewater treatment facility where it is treated and converted to steam or irrigable water
W5	Treated water used for irrigation on farms and lawns

5 DISCUSSION

5.1 Profile of Enterprises

Profile of enterprises, including GPS location, input, output, by-products, and description, was in accordance with standards set out by Jensen *et al. (*2012); Song *et al. (*2017), and Yeo *et al. (*2019). This provided the information needed to generate a material flow analysis and the input-output analysis diagrams in Figures 4.1 to 4.5, despite the lack of data on quantities of inputs, outputs, and by-products. The data paucity notwithstanding, the questionnaire generated enough data for the analysis.

The study noted the diversity of enterprises in the agro-food value chain. The types of enterprises sampled include food production enterprises, alcoholic and non-alcoholic enterprises, waste management enterprises, and packaging enterprises. Similarly, this culminated in a diversity in the inputs, outputs, and by-products. For instance, among food enterprises, inputs ranged from cereals to fruits, spices, and vegetables, and even meat and fish. Indicatively, similar observations were made regarding the outputs and by-products from the enterprises. Again, among non-alcoholic and alcoholic beverage, waste management, and packaging industries there was also diversity which in turn influenced the outputs and by-products.

Accordingly, the high diversity provides the opportunity for achieving two important ecosystem principles: diversity and gradual change, as outlined in the seminal work of Korhoenen (2001). It is equally critical to satisfying the requirements for IS: identification, assessment, and implementation phases, as argued by van Capelleveen *et al. (*2018), that diversity would mitigate the risk of lack of incentive among enterprises and redistribute synergistic advantages. Boons *et al. (*2016) and Yeo *et al.*

*(*2019) reinforced this, stating that the preliminary assessment stage of IS creation does not only focus on quantities of by-products but also its diversity to induce and facilitate inclusion.

It was also established that not all enterprises were co-located. The study revealed that some enterprises were within a common area, although not directly adjacent or opposite one another. This means that Type 3 of IS, that is, IS among firms co-located in a defined eco-industrial park (Chertow, 2000) is not solely applicable. Instead Type 4: IS among local firms that are not co-located may be ideal if applied in conjunction with Type 3. For instance, per the map in Figure 3.1, a number of these enterprises are co-located around Tesano, some are also around Labadi, etc. For these enterprises, the Type 3 approach could apply to the synergies identified. However, across all industries, Type 4, which involves the creation of a virtual network may be ideal. Such exchanges already exist, as have been noted by the synergies between IS54 and some out-grower associations, and non-alcoholic enterprises; IS25 and a cocoa processor; packaging enterprises and several enterprises; and IS06 and farms, non-alcoholic beverage enterprises (see again Table 4.6). This suggests that only the scaling up of such synergies would be required. In sum, the Song *et al. (*2017); van Capelleveen *et al. (*2018); and Yeo *et al. (*2019) methodologies for evaluating the characteristics of enterprises for the creation of IS can be deemed viable approaches to enhancing by-product reuse and recycling in firms and among firms.

5.2 IE at Enterprise Level

At the firm level, the adoption of IE or interdependency was high (78.85 percent), as some enterprises were aware of IS (88 percent), conscious of cost, production efficiency, environmental initiatives, and had policies to support IE. The present study established that the understanding of IS among enterprises as illustrated in Figure 4.8 was reflective of the various definitions of IS, as stated by Geng *et al.* (2019); Mhatre *et al. (*2021); Bogle and Fairweather, (2012); and seminal works of Chertow (2000 and 2007). That is, the overarching goal of IE is to propel economies toward sustainable development by reducing input consumption and extending the usefulness of products. This sets the basis for enhanced interdependencies, sustainable environmental practices, and pollution prevention initiatives in firms.

Currently, interdependencies at firm levels exist. However, there are opportunities to explore. There were barriers impeding the attainment of the ecosystem principles: roundput, locality, diversity, and gradual change argued by Korhoenen (2001). On roundput, the study noted that water treatment was inadequate, despite the high interdependency at the enterprise level. Importantly, there was no complete circularity within any enterprise. Further, it was noted that respect for environmental limits for an area (locality) was poor, as some enterprises alluded to supplying inputs (mostly chemical-based) to out-grower associations to aggressively expand crop fields. Of note, a number of enterprises sourced input materials from outside Ghana and utilised diesel-powered generators to augment shortfalls from the national grid, the operation of which emitted greenhouse gases. On diversity, the study established that interdependency among parts of the same enterprise was high, as have been discussed earlier. However, industries were yet to scale up fully to complete the raw material reuse cycle. Lastly, on gradual change, the study established that 81 percent of enterprises had a clear policy on environmental awareness and 94 percent made deliberate efforts to train staff in that regard, signifying willingness to change. Further, it noted the critical role of environmental safety in the adoption of new technologies, strategic planning, and waste management. However, with 44 of the 63 enterprises with environmental policies yet to document their policies, it would be difficult to monitor growth and adoption. Importantly, with enterprises scoring 81 percent in prioritising customer and shareholder concerns (mostly financial) over environment sustainability, and 76.1 percent indicating that they are concerned with potential consumer backlash over the use of by-products in the manufacture of food, it would be difficult for enterprises to initiate measures to nudge customers and shareholders towards sustainability, necessitating measures to overcome these techno-economic and strategic barriers. Similar studies on barriers to circular economy in the Netherlands revealed that customer concerns were important and if customers are not interested in environmental sustainability, they are likely not to pay a premium for a product. Nonetheless, the studies outlined firm-level initiatives such as improving system efficiency and re-orienting enterprise design to improve material flow, and public policy directions to influence consumer behaviour. (Hartley *et al.*, 2022). These recommendations largely built upon the findings of Fraccascia *et al.*, (2016).

According to Fraccascia *et al.*, (2016), the adoption of IS is enhanced by overcoming technical, economic, and strategic barriers. On technical, firms need to identify by-products that could replace or complement their raw input materials or develop new products using their by-products. For instance, the technology to convert biological bio-waste to compost or animal feed already exists and could be harnessed by other enterprises. IS36 is already implementing this technology. This suggests that some by-products could be utilised as animal feed before the subsequent by-products from animal farms are converted to compost. Again, enterprises may explore technical requirements to convert bio-waste to biogas or briquettes, as is being implemented by IS25 and IS59. The gas or briquette could be used to heat treated wastewater to steam for industrial use. Others may explore identifying new materials for industrial activities or improve industrial processes to reduce waste or by-products altogether.

On economic barriers, firms must understand the economics of replacing raw materials with efficient ones, reusing by-products, or converting the by-products into new products. It must also weigh customer concerns over the approach it is adopting and take steps to mitigate related economic downturns. Perhaps, customer education and/or sensitisation is a pre-requisite to widespread adoption of IE. Indeed, Chertow (2000) highlighted the need for stakeholders, including customers, 'buy-in' in designing interdependencies and symbiotic relationships. Hoffman *et al. (*2014) asserted that enterprises could equally take initiatives to transition markets towards sustainability to gain a competitive advantage and improve resource efficiency. However, at the firm level, it may not be economically expedient to implement resource roundput measures, especially when customers and regulatory support are not equally progressive. Essentially, the economic benefits would be important in determining which IE model to adapt. Such analysis must eventually inform the strategic direction of the enterprise.

5.3 IE among Enterprises: Industrial Symbiosis

Although knowledge of IS was 88.7 percent, the adoption of interdependencies among firms was 53.84 percent, largely between enterprises and waste management companies. Discounting the relationship with waste management enterprises due to the assertion that not all waste management enterprises extend the life cycles of by-products collected, respondents indicated that only about half of the stated exchanges are toward by-product reuse and recycling. Further, only 7.7 percent of sampled enterprises had identified new useful by-products from other enterprises. To emphasise, 53.84 percent involved exchanges with waste management enterprises, some of which do not recycle or reuse the by-products, casting doubt on the actual level of interdependency.

Also, it was established that data on waste generation capacities, relevant IS technologies, pricing of by-products, and customer concerns, among others, are inadequate, underscoring the need for much more rigorous assessment to overcome the technical, economic, and strategic barriers. As affirmed by Boons *et al. (*2016) and Yeo *et al. (*2019) under the phases of IS, such data reveals an understanding of local conditions and is critical to the preliminary assessment and overall deployment of IS. Therefore, the lack of insight into the waste generation capacities, relevant IS technologies, pricing of by-products, and customer concerns, among others, could account for the low number of enterprises (7.7 percent) that have identified useful by-products from others and ultimately, undermine efforts to deepen interdependencies among the involved enterprises.

It must be added that, in accordance with the ecosystem principles as discussed by Korhoenen (2001), the following revelations were made. On roundput, discounting interdependency with waste management enterprises highlights a very low relationship among the other categories of industries. Indeed, wastewater management was a major deficit among industries surveyed, as many dislodged in gutters indiscriminately. On locality, enterprises scored 4.34 out of 7 on the Likert scale, for how they have maximised their proximity to others to source by-products as input materials. This is an average score that could be improved, especially since the score equally included proximity to waste management enterprises. On whether other enterprises sourced or were interested in their by-products, the assessed enterprises, again, an scored average of 4.20 out of 7. Among the sampled enterprises, there was no interdependency anchored on exchange of energy although some enterprises confirmed that they generated large quantities of food waste that could be converted to feedstock for biogas generation. The aforesaid indicates that existing local respect for environmental limitation is average. In like manner, enterprises have not coordinated well to mimic the special roles of organisms in the environment (diversity). The inadequacies of wastewater or alcohol treatment facilities, again, support this assertion. Despite this, enterprises engaged in reuse and recycling, and understood the opportunities for waste reuse, suggesting that there is a foundation to improve upon. It was also noted that customer concerns over the use of by-products in the manufacture of food products could be the greatest impediment, as enterprises strongly agreed that they had used for by-products and there are opportunities for utilising such resources with minimal or near-zero side effects, yet adoption remained very low.

To improve IS, specialised enterprises to manage wastewater may have to be established, in addition to relevant legislation. This is in view of the fact that only one sampled enterprise had a wastewater treatment subdivision. The said enterprise indicated that although it has not exceeded its capacity, it was constrained by transportation costs. It added that since its establishment, it only treats municipal liquid waste from septic tanks and has yet to manage industrial wastewater. The indication suggests that enterprises would have to build wastewater septic tanks and design transportation systems for their wastewater, the cost of which may discourage the enterprises. It must be highlighted that Madanhire *et al.* (2018) confirmed the relevance of wastewater treatment and an enhanced system in deepening by-product exchanges or transfers. Indeed, over 50 percent of respondents in their study indicated that they required an approach to reuse their wastewater.

This calls for an evaluation of barriers and relationships between enterprises and regulators. Given that 93.8 percent asserted that regulators provide linkages for their enterprises, in addition to monitoring (37.92 percent) and trainings (36.4 percent), this aforesaid barrier with wastewater management could be removed with regulatory intervention. Regulators could harness inherent authority to create such linkage by incentivising enterprises to pursue wastewater interdependencies, as well as removing administrative bureaucratic barriers, facilitating technology adoption, and providing strategic direction for IS in the country, as posited by Henriques *et al. (*2022). This would receive widespread support given that the study identified that 25 percent of enterprises are willing to pay for by-products, while 78.8 percent are ready to participate in an environmental management system. This 'win-win' approach to collaboratively minimise risks and exposures among stakeholders is a critical driver of IS (Tsvetkova, 2014).

The results indicate that IS among enterprises is still at phase one: preliminary assessment (Yeo *et al.*, 2019). This is because although there are exchanges, they are very limited and largely undocumented. However, phases 2 and 3, i.e. engagement of businesses, identification of synergies where business entities are engaged to build and grow an interdependency network, industries and/or facilitation agencies determine available synergies, and assess the economic viability, are unlikely to be difficult given that the study process has already exposed some actors within enterprises to the prospects of IS, the possibility of enhancing synergies for mutual economic, social and environmental gains and documented existing interdependencies. That said, the paucity of data indicates that the feasibility assessment, implementation, and documentation for review phases could face critical challenges. Again, this emphasises the need for regulators to exercise their mandate by providing strategic direction, creating linkages, and removing barriers.

5.4 Modelling Potential Exchanges

Modelling industrial synergies revealed that exchanges among enterprises could be enhanced. For instance, there could be an EIN among all food and fruit juice enterprises, and compost manufacturers, farmers, and/or local markets. This would ensure that by-products, including fruits, husks, and spices, are recycled, reduced, or reused (Laybourn and Morrissey, 2009). A similar study in Liberia articulated the relevance of IS to farms, albeit theoretically, in harnessing opportunities to reuse food waste from agro-based enterprises in farms with limited intermediary processes (Alfaro and Miller, 2013). Packaging enterprises could also establish synergistic relationships with all enterprises to receive plastics, sachets, sacks, glass, and paper waste from them. Similar relationships could exist between the industry and customers to enhance recycling. For instance, in the Netherlands, a study confirmed that Extended Producer Responsibility (EPR), a relationship between enterprises and customers where producers incentivise customers to return products after they have exhausted the products' usefulness, is critical to improving the lifecycle of products and recycling (Campbell-Johnston *et al.*, 2021). Other studies, such as Maitre-Ekern *et al.* (2021), Murthy & Ramakrishna (2022), and Fadeeva and Van Berkel (2021) have equally underscored the critical role of EPR in promoting recycling and reducing waste.

The study opined that it is unlikely and perhaps not economically viable to build physical exchange networks among the enterprises, considering that they are not co-located. Rather, a small-scale network, an eco-industrial park, for co-located firms anchored on a large-scale enterprise could be created, in line with Type 3 of IE

(Chertow, 2000). Also, a virtual exchange system could be created, identifying by-products availability and quantities and, mapping them to enterprises in need of such for inputs. This approach would be similar to NISP or NISN (Laybourn and Morrissey, 2009 and Moodie *et al.*, 2019). Like the exchanges among enterprises, government oversight and incentives may be important to a sustainable IS, as has been confirmed by Henriques *et al. (*2022) in Portugal.

On the assessment of by-products in accordance with TVAIS, it was determined that by-products such as wastewater or alcohol, food, and fruit waste may be direct given that no major intermediary process is required. However, wastewater and alcohol treatment strategies may differ depending on the source of the wastewater or alcohol and the level of contamination.

6 CONCLUSION AND RECOMMENDATION

6.1 Conclusion

The study assessed the inputs, outputs, and by-products of selected enterprises in the agro-food value chain in Ghana, analysed the prevailing practice of IE within and among these enterprises, and modelled potential exchanges and synergies that could exist among these enterprises. This is critical to deepening the adoption of IS in the country. The study focused on relevant enterprises in the Greater Accra and Eastern regions. The study established that 78.85 percent of enterprises implemented interdependency and environmental initiatives exist at the firm level, however, they are largely undocumented, restricting opportunities for advancement. At the inter-firm level, only 7.7 percent had identified new useful by-products from others. Nonetheless, 25 percent indicated their willingness to pay for useful by-products, while 78.8 percent were willing to participate in an environmental management system. The contribution of this study is modelling potential exchanges for the involved enterprises, which is based on enterprises creating new products of their by-products, identifying useful by-products from other enterprises, or establishing a virtual by-products exchange scheme for the selected enterprises, akin to Nordic Industrial Symbiosis Network (NISN) for Nordic countries and the National Industrial Symbiosis Programme (NISP). Such projects have proven essential to reducing environmental footprints and enhancing the profitability of collaborating industries in Nordic countries and the United Kingdom.

In sum, the study concludes with the following key findings as outlined in Table 6.1

Table 6.1: Summary of Key Findings

Objective	**Key findings**	**Conclusion**
Profile selected enterprises within Greater Accra and parts of the Eastern Regions	1. There was high diversity among sampled enterprises. 2. Indicatively, there was diversity in inputs, outputs, and by-products. 3. Enterprises were not co-located	1. The diversity indicates that a variety of inputs and by-products are available for enterprises that participate in any potential IS project. 2. IS for co-located enterprises i.e. Type 3 and IS for local firms that are not co-located i.e. Type 4 could apply simultaneously.
Determine interdependency within the enterprises in the agro-food value chain in Ghana.	78.8 percent engaged in IE practices at the firm-level.	Most enterprises practiced IE at the firm level.
Assess interdependencies or Industrial Symbiosis (IS) among enterprises.	At the inter-firm-level, only 7.7 percent had identified useful by-products from others. Nonetheless, 25 percent indicated their	Inter-firm level exchanges are low; however, most enterprises are willing to participate in an

	willingness to pay for useful by-products, while 78.8 percent were willing to participate in an environmental management system.	IS project to reduce environmental impacts and boost profits.
Model an eco-industrial network of potential exchanges among agro-food enterprises.	Modelling industrial synergies revealed that exchanges among enterprises could be enhanced.	The creation of an eco-industrial network (EIN), a virtual network of enterprises to facilitate the exchange of by-products among enterprises akin to the NISP and NISN approach appears most viable.

6.2 Recommendation

The study assessed the potential materials and energy exchanges that can be achieved and ensure sustainability of resources. However, further academic investigations into the techno-economic potential for IS is recommended. This would evaluate two (2) critical areas. Firstly, the quantities of by-products generated by enterprises and simulate an economic viability for IS and the suitability for expanded compost, briquette or biogas plant. Secondly, the study into the feasibility of building and operating wastewater treatment enterprise, for industrial steam generation could be investigated. Additional studies could focus on roles of regulatory agencies in deepening IS in Ghana. Meanwhile, it is imperative for regulators to formulate regulations to govern IE and IS, nudging consumers towards acceptability. Government may initiate steps to facilitate interdependencies among industries, prioritising the creation and/or facilitation of adaptable transfer mediums for identified by-products.

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APPENDIX

Appendix 1 – **Questionnaire**

UNIVERSITY OF GHANA

INSTITUTE FOR ENVIRONMENT AND SANITATION STUDIES

Questionnaire for agro-industries

*My name is S. Yeboah Owusu, a Sustainability Science student from the Institute for Environment and Sanitation Studies at University of Ghana. This instrument is to help gather data to aid in my research on the topic **"Assessing the interdependency of waste/by-products & materials in transition among selected industries in the Agro-food value chain in Ghana."** The purpose of this instrument is strictly for academic purposes in partial fulfilment of requirement for an MPhil degree in Sustainability Science. Please be assured any information provided shall be kept confidential. Thanks for your permission.*

Please tick where appropriate.

SECTION A: DEMOGRAPHIC DATA

1) Sex: male ( ) female ( )

2) Age: less than or equal to 19 ( ) 20-29 ( ) 30-39 ( ) 40-49 ( ) 50-59 ( ) greater than or equal to 60( )

3) What is your level of education? None ( ) Primary ( ) Secondary ( ) Tertiary ( )

4) What is the name of your industry?

5) What type of products do you produce?

6) What is your production capacity (tonnes per month)?

7) Are you a formal or an informal staff of the firm? Formal ( ) Informal ( )

8) Which department do you belong to?

9) What position do you hold in the firm?

10) Are you part of the management of your firm? Yes ( ) No ( )

11) Describe the environmental activities your firm engages in.

12) What is your degree of involvement in your firm's environmental decisions?

a) no involvement b) low c) average d) High

SECTION B: GENERAL PERCEPTION ON INTERDEPENDENCIES AMONGST INDUSTRIES

This section evaluates your understanding of the terms of in the research topic. ***Industrial ecology (IE)*** *describes the study of the materials and energy flow in industrial and consumer activities.* ***Interdependency*** *relates to how one industry/firm rely on another for material, energy, water etc in order to achieve any on its industrial process.*

13) Have you heard of the term industrial ecology?

a) Yes b) No

14) If Yes, can you briefly describe how you understand it?

Does your firm engage in practices that align with industrial ecology?

a) Yes b) No

15) What are the practices your firm engages in that align with industrial ecology?

Perception on material and energy exchanges amongst industries.	Strongly Disagree	2	3	4	5	6	Strongly Agree
At our firm, we make a deliberate effort to let *all* staff to understand the importance of environmental preservation.							
Our firm has a clear policy statement urging environmental awareness in every area.							
Our firm's responsibility to its customers and stakeholders is more important than our responsibility toward environmental preservation.							
Raw materials have become more expensive due to scarcity of resources from the natural environment.							
We engage in reuse and recycling of waste to reduce our cost of raw materials.							
We take advantage of our proximity to other industries to source their by-products/waste as our input materials.							
Other industries are interested in using our by-products/waste for their production.							

We don't have any use for our waste.							
There is no advantage for us in the use of by-products/waste							
The use of by-products is detrimental to the quality of our final products.							
We have our own internal processes and do not interact with other industries.							
We prioritize energy conservation.							
Energy efficiency is a paramount factor when adopting new technology.							
We have an alternative source(s) of energy.							

SECTION C: MATERIAL EXCHANGES AMONGST INDUSTRIES

This section deals with analysing the nature of raw materials used by your firm, the sources of these materials, the processes involved, waste generated, and how waste is handled in your firm. It also describes how your firm relies on others for materials, energy, and water either as raw material or as a by-product of an industrial process. This reliance can either be your firm 'giving out' or 'taking in'.

16) What is your source of materials for production?

A) Recycled materials b) Raw materials. C) mixed

17) What are your input materials for production?

18) Do you segregate your waste?

A) Yes b) No

19) What are the types and quantities of by-products or waste realised from production within the industry?

a) …… b) …c) … d) … e) …

20) How is each of the by-products or waste stated above managed?

A) … b)… c) …… d)…… e)……

21) Are the by-products or waste recycled or reused?

A) Yes b) No

22) If yes to (6), is the recycling done within the firm or transferred to another firm?

23) Is the reuse done within the firm or transferred to another firm?

24) What is the cost (monthly) incurred in transferring waste/by-products from your firm?

25) Is there use of by-products/waste from other industries for production?

A) Yes b) No

26) If yes to (8), state the industry and type of materials

27) Has your company identified any by-product from any business that can be useful to your company?

A) Yes b) No

28) Will you be willing to pay for such by-products from another business?

A) Yes b) No

29) What does your firm do to ensure judicious use of materials for production?

30) Do you have an environmental management system (EMS)?

A) Yes b) No

31) For each answer given in (15), give a reason.

32) Would you be willing to participate in an EMS?

A) Yes b) No

SECTION D: ENERGY AND WATER EXCHANGES

33) What is/are your sources of energy?

A) National Grid alone B) National Grid and Diesel Generator C) Diesel generator alone D) Thermal E) Solar energy F) Others (specify)………………

34) What is your average monthly energy consumption?

35) Do you generate energy internally? A) Yes b) No

36) If yes to (21), what is your energy generation capacity?

37) Do you depend on other industry (ies) within the north and south industrial area for power? A) Yes b) No

38) If yes to (23), mention the industry (ies) and their energy source.

39) How do you ensure energy efficiency at your firm?

40) What factors does your industry consider when adopting new technology? *(tick as many as apply)*

A) Price b) Pollution control c) Energy efficiency d) Innovativeness/ convenience e) Others (specify) …

41) What is/are your source(s) of water for production? *(tick as many as apply)*

A) Ghana water company b) Borehole c) Recycled water d) others (specify)…

42) What is your average monthly water consumption?

43) How do you ensure water efficiency at your firm?

SECTION E: POLLUTION PREVENTION STRATEGIES

44) What form/type of pollution do you generate?

45) How do you manage pollution generated?

46) What community support do you provide to compensate for the emission generated by your firm?

47) What collaboration exists between your firm and the municipal/district assembly?

Please indicate how much you agree or disagree with each of the following statements by ticking each row.

Pollution prevention strategies.	Strongly disagree	2	3	4	5	6	Strongly agree
We ensure energy conservation among all staff members.							
We use alternate sources of energy.							
We often replace obsolete polluting technology with energy-efficient ones.							
Our decision for technology adoption is influenced by environmental pollution concerns.							
Pollution issues are considered when developing new products.							
We integrate pollution prevention issues with strategic planning.							
We monitor and control emission/effluent.							
We treat solid and liquid waste before discharge.							
We have an environmental policy.							
We have set environmental targets.							
We always achieve our set environmental targets.							
We meet EPA standards.							

Appendix 2 – Stan Software Interface