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Food-energy-water nexus: Food waste recycling system for energy

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ABSTRACT

A humongous amount of food goes to waste yearly. The use of renewable energy sources is encouraged to reduce global warming. Food waste as a source of energy and water as a food-water-energy nexus has shown to be a viable source of renewable energy. This paper proposes a food waste recycling system that uses a mechanical presser to the extraction of moisture from the food waste with its desiccate being fed to an anaerobic digester to produce biogas. Literature on the topic is reviewed and the benefits and limitations of the system are also discussed.

I. Introduction

As biological creatures, the relation between our food, water, and energy use plays an important role in our survival and the extension of our species. With the production of food taking up 30% of our energy consumption and up to 70% of our freshwater bodies [1], we must become more efficient in the production of our food and more so, we must use the produced food wisely. The food-energy-water nexus describes the links between food, water, and energy and how undertakings of each affect the others. As the world population continues to increase, there is an increase in demand for food, energy, and water.

There has also been a great increase in the amount of food waste produced yearly. Food waste can be defined as food that does not get consumed as a result of being discarded, whether or not after it has been left to spoil or is expired. Food waste typically occurs at the retail and consumption stages of a food supply chain [2]. According to the Food and Agriculture Authority of the United Nations (UN), a third of the world's food-nearly 1.3 billion tons- goes to waste annually. However, this should not be the case as the population keeps increasing and there is a distressing need for more resources to be poured into the system [25]. As such, to ensure sustainability and the efficient use of resources, it is paramount to see this food waste as raw material and put it to use. Using food waste to obtain water and energy reduces the burden placed on existing systems that produce these resources, i.e., water and energy [3]. These existing systems include but are not limited to, water treatment systems for homes and industries which supply clean water; reverse osmosis water filtration, ultraviolet water sterilization, and filtration and distillation [4], and energy generation systems such as hydroelectric stations, nuclear power plants, and solar power plants.

This paper shall discuss the feasibility of producing energy and water from food waste. Using dual technology, the moisture from food waste can be extracted for irrigation purposes whilst its desiccate is used to produce energy. The dual technology mentioned here is an integrated system comprising the use of a mechanical expeller press for the extraction of moisture and an anaerobic digester for producing biogas from the desiccate obtained. Biogas is a gaseous product that contains about 50–60% of methane (CH4), other gasses such as carbon dioxide, ammonia, water vapor, hydrogen sulfide and other components [5]. A third system is also made use of in treating the moisture obtained from the extraction process. This is to ensure that harmful bacteria are not used in irrigating crops.

Whilst there are existing systems that turn food waste into energy using anaerobic digesters, these systems use co-digestion where there is a simultaneous breakdown of multiple organic waste present in a digester. Furthermore, in these systems, priority is not placed on extracting moisture for use in irrigation thus recycling nutrients obtained from food. This paper focuses solely on turning food waste into energy with an initial process of extracting moisture from the food waste.

Section II of this paper shall discuss research and review papers that have looked at the subject matter at hand Section III. describes the materials to be used and details the process used in obtaining energy and moisture from food waste Section IV. discusses the benefits and limitations of the implementation of such a system. The paper ends with Section V which gives a suitable conclusion.

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II. Related systems

In this paper, the different aspects of anaerobic digestion and the effect it poses on certain factors are discussed. The paper highlights that incinerating food waste is not a good practice as the carbon footprint of food waste contributes to greenhouse gasses and effectively global warming. Furthermore, nutrients that could have been obtained from the waste are rendered useless. It goes ahead to state why anaerobic digestion is most suitable for recycling food waste. With anaerobic digestion, nutrients in food waste can be recovered and be made use of. It is also an environmentally friendly option. The paper describes in detail the process of anaerobic digestion of food waste. It mentions four phases of anaerobic bio digestion; enzymatic hydrolysis, acidogenesis, acetogenesis, and gas production. Equations are given to support the breakdown of substances and the formation of new ones that occur at each phase. The paper looks at certain factors which affect the rate at which methanation occurs. Methanogen is a sensitive bacterium and is affected by temperature, pH, and organic loading rate. The paper embraced the idea of pre-treating food waste before subjecting it to anaerobic digestion. It stated that pre-treating the waste breaks it down and increases its biodegradability. This means that after pre-treatment, it is easier for micro-organisms in the anaerobic digester to work on the food substrate to obtain methane and carbon dioxide. The paper also discusses the possibility of co-digestion, where the food waste is worked on together with manure and other organic materials [6].

A review paper on the Water, Waste and Food Nexus in Brazil talks about improving resource management and food-energy-water nexus in Brazil. In the paper, it is identified that Brazil has a lot of agricultural and energy commodities. However, these commodities are handled singly such that there are rare interactions between these commodities. The paper speaks extensively on the commodities available such as hydropower, sugar cane, soybeans, and a lot more. It gives figures which show the production rate of these commodities over the years. The paper then looks at the different types of interactions that can be obtained by merging the workings of some of these sectors. It discusses water and food linkages, water and energy interactions, and food, energy, and water interactions. Under water and food linkages, the paper cites crop irrigation and expresses that more can be done in using wastewater for plant irrigation [7].

[30] analyzes the food-energy-water system of urban metabolism for sustainable resources management. Urban metabolism refers to the investigation of the supply and consumption of nutrition, energy, and other resources within cities. They develop a system dynamics model which is used in the analysis of food, energy, and water resources. The dynamics model is capable of simulating different uncertain scenarios for uncertain analysis. The case study for the research is the Shihmen Reservoir system, paddy rice irrigation of Taoyuan and Shihmen Irrigation Associations, hydropower generation, and water consumption in Taoyuan, New Taipei, and the Hsinchu cities. They also develop a framework for assessing the competition/cooperation of different resources. The result of their case study buttresses this.

[26] used the Wabe River catchment in the Omo-Gibe basin in the tropical data-sparse region of East Africa as a case study to show the importance of water management to the security of the food-water-energy nexus in the region. They applied methods in the study that aided in the increase of spatial understanding of the water-related ecosystem services mainly for data-sparse catchments in the tropics. This led to the enhancement of water management which improved the security of the nexus. The results of the study showed that there were high annual water yields in the region due to low actual evapotranspiration and high annual precipitation but due to poor water management and inaccessibility, the annual demands of the people in the region were not met.

[28] considered a university as a small community and ascertained the impact a university has on the food-water-energy nexus and the water-energy nexus by developing an environmental footprint framework using life cycle analysis. With the University in question being the Keele University in the UK during the 2015/16 academic year, their total energy footprint, carbon footprint, and water footprint were recorded to better understand how universities interact with the hydrologic cycle, energy resources, and climate. The tools developed in this paper help in improving the understanding of the indirect and direct correlations between universities and water and energy resources which further aid in the assessment and implementation of green campus strategies.

In this paper, a mobile food waste to energy system with an anaerobic digester and a biogas engine was developed for the treatment of waste and the production of energy. With this configuration, a food waste grinder was used to grind the food waste to a thickness of 3 mm. Before the food waste is fed to the grinder, bones and inorganic materials are removed to ensure the smooth running of the grinder. The contents of the grinder are then given to a feeding tank which periodically gives its content to the Anaerobic Digester. After biogas is produced in the AD, moisture and H2S are absorbed from the biogas and then the gas is stored which is then fed to the biogas engine through a booster. Their setup also utilizes a heat exchanger to minimize the heat loss in the biogas engine. This initial system is then further optimized. The system has a yield of 0.55 CH4/g VS and has a biogas efficiency of 47% at its highest load of 30 kg FW/d [8].

[9] presents a nexus optimization framework that seeks to alleviate the health and environmental concerns due to the covid-19 pandemic. The framework presented is a mathematical one that maps out constraints for the food waste feedstock supply system, waste to energy facilities, food waste supply logistics, material flows between facilities with the objectives of the paper expressed by two equations. The first equation is for the total cost objective and the second for the unit processing cost. With New York as the case study, the mathematical model shows promise of a reduction in the food waste disposal amounts by 38%. The minimum cost of implementation of such a system was 27.1 million while the optimal unit processing profit was $11.9 per ton of processed food waste.

In this paper, they take a look at the food-energy-water nexus from a transdisciplinary perspective. They give a systematic review of concepts and methods of transdisciplinarity on the food-energy-water nexus as a guide to socially inclusive sustainable development. With the view of transdisciplinarity's practicability being under-utilized, they propose a framework with the aim of exploring the use of transdisciplinarity in linking food-energy-water nexus practices and sustainability outcomes in real-world situations. It is concluded that food water energy can aid the integrated accomplishment of sustainable development goals from the transdisciplinary perspective [29].

In this paper, they present a framework to be used in identifying and analyzing rooftops that would be feasible for the implementation of urban agricultural practices such as rainwater harvesting, photovoltaic systems amongst others. The city of El Valles Occidental which is north of Barcelona was used as the case study. The city has predominantly sunny weather and also offers the possibility of winter agriculture without the need for the heating of the greenhouses on the rooftops. The roofs suitable for the study were determined using remote sensing. It was concluded that 8% of the roof area was suitable for tomato and lettuce production, which would cater for 210% of the average intake of tomatoes and 21% of the yearly intake of lettuce in the region. It was also concluded that using rainwater harvesting systems, 94.26% of the water requirement for lettuce growing would be satisfied. The results from their study showed that 80% of roof area had the potential to be used for rainwater harvesting systems with only 50% of the roofs being feasible for that of photovoltaic panels [24].

[23] reviews a number of water-energy extended nexuses. These nexuses were looked at from the perspective of their practicality and also their relationship in alleviating problems that are related to sustainable development goals pertaining to the environment. It was concluded that the word "nexus" was mostly being used as a more attractive term for the relationships described thereby making the word rather ambiguous. To create a more standardized understanding of the use of the

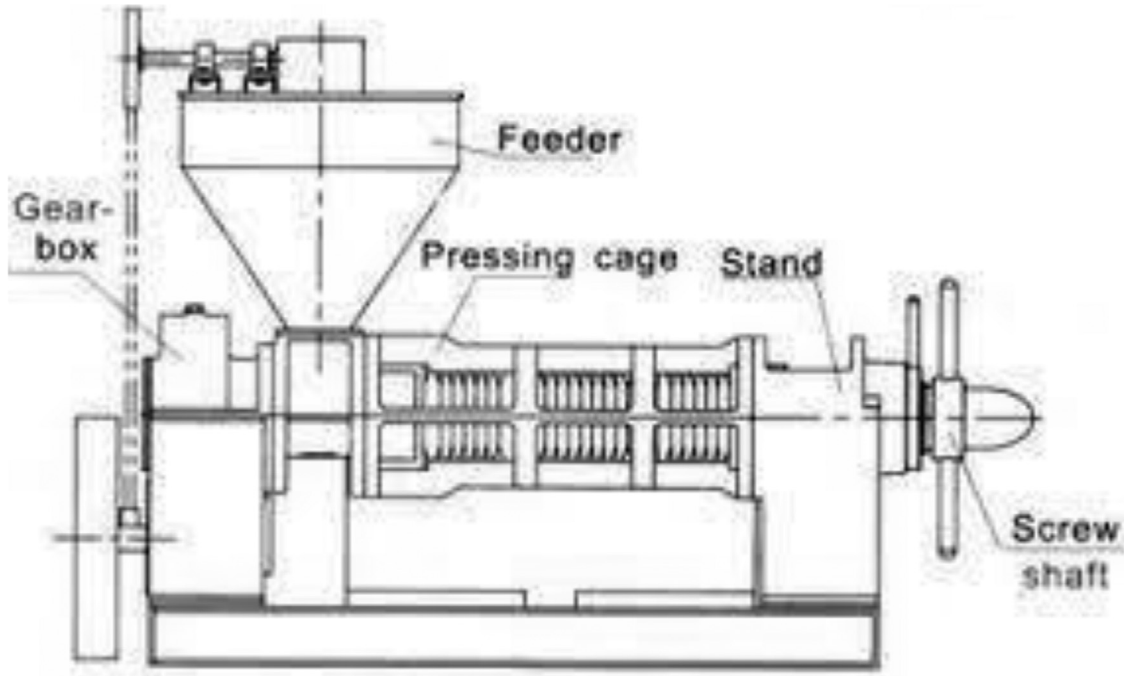

Fig 1. Labeled diagram of mechanical expeller press [14].

word nexus, they established quantifiable components or characteristics which would better serve in classifying nexuses and the approaches used in them.

In this paper, several biological methods were thoroughly investigated for energy and resource recovery from food waste. With the central idea being to achieve a zero solid waste discharge, modern ways of utilizing combined biological methods for energy recovery were proposed while taking into consideration the drawbacks of the biological processes. The paper also presented the integration of these processes from the perspective of achieving circular bioeconomy to ensure that the integrations are sustainable. From this paper, it is realized that food waste can be managed efficiently for the recovery of energy and also resources concurrently [10].

In this paper, they focus on the relation between two research areas, redistributed manufacturing and the food-energy-water nexus. By concentrating on two food products, bread and tomato paste, they elaborate on the feasibility and the capacity of redistributed manufacturing being dependent on the type of food product and the constituents of its supply chain. Looking at the issue from a business perspective, they ascertain that novel products, new business models, and new markets would aid redistributed manufacturing in penetrating the established food trade. They also propose a framework for assessing food redistributed manufacturing and the food-water-energy nexus [27].

III. Materials and methodology

A. Materials

The main material required for the food waste recycling system would be the raw material, food waste. This includes leftovers from meals, expired and stale foods, fruits and vegetables with defects, portions of food not meant for consumption such as chicken bones, plant parts that have been uprooted after harvesting, and processed foods [11].

For this paper, the focus shall be placed on recycling mainly leftovers from meals, expired and stale foods, fruits and vegetables with defects. This is because these kinds of food waste retain a lot of moisture and can easily be broken down to obtain biogas when passed through an anaerobic digester. Aside from this, a mechanical press and an anaerobic digester would be required as the dual technology which would recycle the food waste.

B. Methodology

The proposed food waste recycling begins with sorting through waste materials and placing aside materials that are non-biodegradable thus leaving the desired food waste. Non-biodegradable waste can be described as products that cannot be decomposed naturally through the use of oxygen and microorganisms [12]. They include glass and plastic waste. In addition to this, portions of food not meant for consumption, like eggshells and plant parts that have been uprooted after harvesting will be set aside as well. These can undergo co-digestion with other biodegradable substrates such as animal manure and green waste.

After this process occurs successfully, the waste is passed through a mechanical press to extract moisture which will be used for irrigation purposes Fig. 1. shows a labeled diagram of the mechanical expeller press. The mechanical press used is based on the design used for the extraction of oil, the expeller press. The press can extract up to 80% percent of the oil [13]. The seed is however heated before being pressed. This will not be the case with the food waste which shall not undergo heating before pressing. Heating the food waste would destroy certain nutrients thus defeating the purpose of extracting them for irrigation. is an image of an expeller press.

The food waste is placed in the feeder of the mechanical press. As it passes through the pressing cage, the screw shaft uses friction to move and compress the waste. There are small openings in the pressing cage which are designed to allow just liquid to pass through, leaving solid material behind, thus causing the liquid to be extracted. The waste material remaining is gathered and serves as the desiccate of the food waste.

The wastewater gathered cannot be directly used for irrigation as it also contains certain bacteria which could be harmful to plants. Hence, the resulting wastewater is treated to obtain a nutrient-filled solution that is safe for irrigation use.

Lastly, the food waste desiccate is placed in an anaerobic digester for decomposition to occur to obtain biogas. The anaerobic digester is a tank devoid of air. It has microorganisms present which aids in breaking

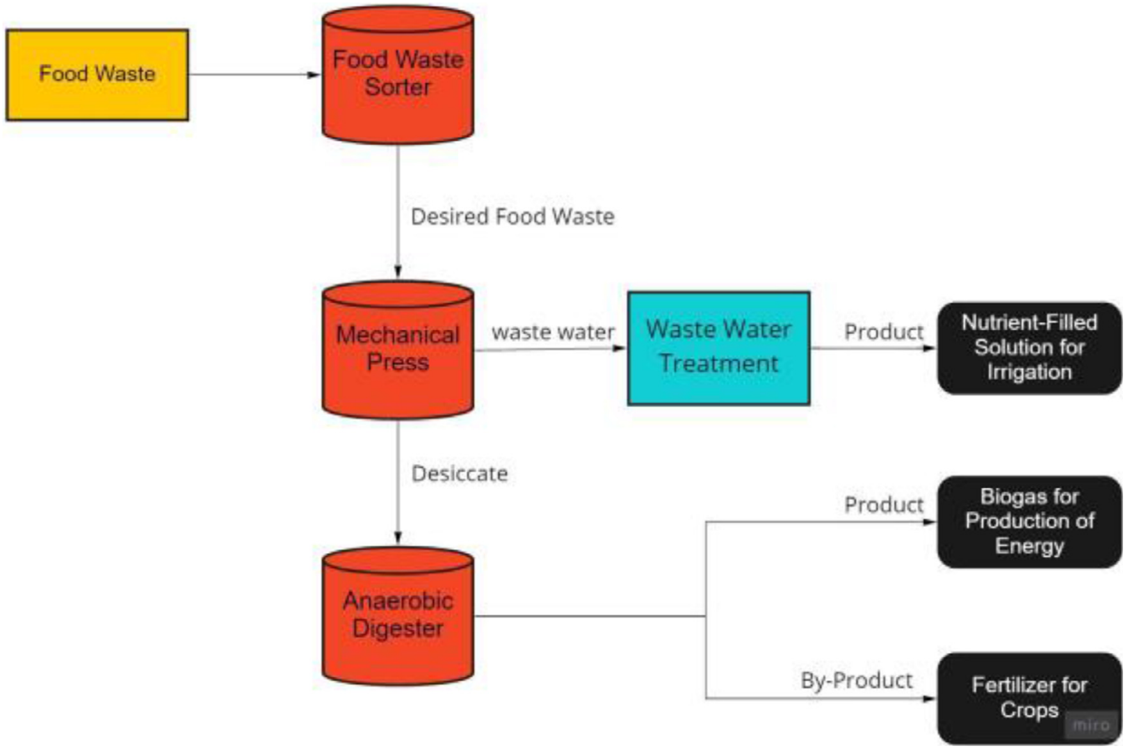

Fig. 2. Flowchart of food waste recycling process.

down its contents. The desiccate is crushed to ensure that it is of uniform sizes before being placed in the digester. The substrate is heated to approximately 37 or 38° [13] and stirred constantly.

Three phases of anaerobic digestion occur in the digester. Enzymatic hydrolysis, acetogenesis, and gas formation. In enzymatic hydrolysis, bacteria break down the desiccate into soluble derivatives. This is further acted upon by bacteria to form acids as well as compounds such as ammonia, carbon dioxide, and hydrogen in the acetogenesis phase. Lastly, methanogens - catalysts used in the production of methane [15]- act on the resulting solution to produce methane and carbon dioxide in gas formation. A flowchart of the proposed system is shown in Fig. 2.

IV. Design considerations

A. Wastewater extraction

The expeller press proposed for use is based on the design used for extracting oil from seeds. It is a mechanical method that involves the use of friction and compression to obtain about 68% to 80% of the liquid found in food waste [16]. Whilst the food waste undergoes compression in the pressing cage of the expeller press, heat is created – with a temperature of about 60 - 100° C. Hence, it would be advisable to operate the expeller press in a cool environment such that the nutrients in the obtained liquid are not adversely affected [17]. The press uses a single, three-phase 20HP motor. When used efficiently, the expeller press can produce about 5 to 6 tons of liquid per day [18].

In liquid extraction, two methods can be employed; using a mechanical press machine – as is proposed for use in this paper - and using chemical solvents. Using both methods would allow more liquid to be extracted from our food waste. Chemical solvents such as diethyl ether, ethanol, n-heptane, and n-hexane can be used for liquid extraction [19]; the best-being n-hexane as it can be used to extract more oil than the other solvents. Using these solvents, however, has many disadvantages such as contributing to air pollution and the liquid obtained containing harmful toxins [20]. Hence the decision to use just the mechanical press.

B. Biogas production

In the design of the anaerobic digester, several factors have to be taken into consideration as all these factors impact the efficient production of biogas and the quantity of biogas produced. These factors can be blanketly referred to as process control and feedstock characteristics. Some of these factors include the pH in the digester, the nutrient content of the feedstock, the particle size of the feedstock, the presence of inhibitory compounds in the feedstock, feedstock load of the digester, the feed rate of the digester, the hydrogen concentration in the digester and many others [8].

The pH in the digester affects the methane yield. For example, if there is a lot of acetic acid being produced in the acetogenesis phase of anaerobic digestion, the pH in the digester reduces, that is, it becomes more acidic. This would reduce the amount of methane produced in the digester. An increase in the feed load does not translate to an increase in methane yield. From one study, it was found that proteins gave the highest yield in methane, with proportions reaching up to 69.5% [10]. Performing a biochemical methane potential analysis would aid in the selection of a suitable substrate and the necessary process parameters to go along with it.

After the selection of a suitable substrate and process parameters, experimental design approaches such as the Taguchi method, artificial neural networks, and the response surface methodology can also be employed. These approaches when applied can help reduce costs and also improve the efficiency of the system [21].

V. Discussions

A. Benefits

The proposed food waste recycling system will produce a nutrient-filled solution to irrigate farmlands for the further production of food. The mechanical presser used on food waste churns out a solution filled with minerals such as Calcium (Ca), Potassium (K), Zinc (Z), and Iron, and vitamins such as B and C [22]. This rich solution can be used for

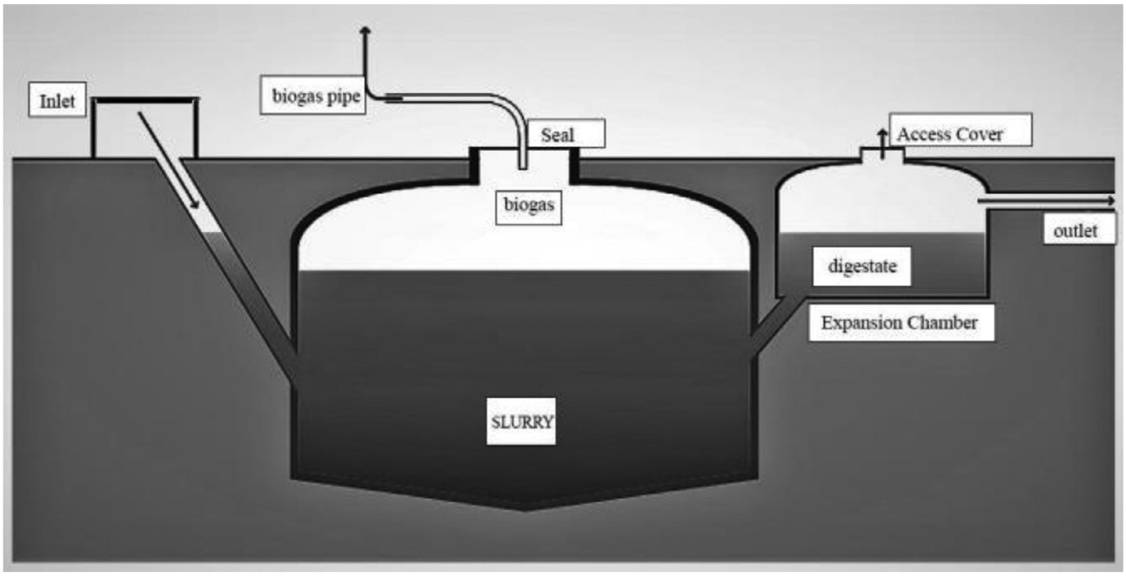

Fig. 3. Labeled diagram of an anaerobic digester.

plant irrigation thus once again providing the minerals needed by plants for growth. By doing this, a new source of moisture is provided for plants thus relieving water of the role it plays in plant irrigation.

In addition, Through the use of the anaerobic digester, the desiccate of the food waste is turned into energy in the form of biogas. The biogas produced is capable of powering farm equipment, providing electrical energy, fueling cars, and a source of renewable natural gas. Thus, a secondary source of energy is provided to cater to the needs of a growing world population. Less burden is placed on currently existing energy-producing systems. Furthermore, the biogas produced from anaerobic digestion is a renewable source of energy and environmentally friendly. Its source, i.e., food waste, will not be depleted anytime soon. The digestate, the product left in the digester after anaerobic digestion has occurred, can also be used as manure and fertilizer for crops. Granted, digestate is usually a semi-solid solution. This will however not be the case in our solution due to the extraction that occurred before anaerobic digestion.

Lastly, the process of extracting moisture from food waste for plant irrigation and using the digestate from the anaerobic digester as fertilizer and manure for plants allows nutrients, which would have otherwise gone to waste, to be recycled. Food waste retains a lot of unused nutrients which may go to waste if not processed. By using the proposed food waste recycling system, these nutrients can be made use of to further the growth of plants on farmlands thus giving rise to abundant and healthier produce.

B. Limitations

The combined cost of the mechanical press and the anaerobic digester makes the setup of this proposed food waste recycling system costly during its implementation. Also, other costs such as the culturing of the bacteria and the maintenance of the system add to the financial constraints of the implementation of such a system. Funds would also be required in treating the wastewater obtained from the mechanical presser. Remunerations for personnel handling the anaerobic digestion process would also add to costs.

Furthermore, due to the use of a mechanical device with moving parts, i.e., the mechanical press and also the digester, one requires some level of technical ability to run this system efficiently. Anaerobic digestion is a delicate process that involves several minor processes that include acidogenesis and acetogenesis. The sensitive nature of all these would require dedicated and highly skilled personnel to handle the digester. Therefore, if it were to be left in the hands of farmers to run, training programs would have to be held to empower them in the use of such a system.

VI. Conclusion

With such a high amount of food waste produced yearly and the need to find ways to use renewable sources of energy instead of fossil fuels, it stands to reason that food waste is looked at as an efficient source of renewable energy. Water is also an important part of our survival as a species given that it has a myriad of uses and it also makes up a majority of our human bodies. Therefore, the efficient use and recycling of water are also paramount. This paper prospects the use of a food waste recycling system that makes use of a mechanical presser for the extraction of water from food waste and the production of biogas from its desiccate with the use of an anaerobic digester. Previous research has shown and the methodology prospected go to show the feasibility of such a system and its viability in the alleviation of difficulties concerning a positive food-water-energy nexus Fig 3.

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Mathew Nana Kyei Siaw: Conceptualization, Methodology, Writing – review & editing, Writing – original draft. **Elizabeth Ayaw Oduro-Koranteng:** Conceptualization, Writing – review & editing, Writing – original draft. **Yaw Obeng Okofo Dartey:** Conceptualization, Visualization, Writing – review & editing.

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