Closed-loop Organic Waste Management Systems for Family Farmers in Brazil

Accepted author version posted online: 05 Jan 2021

Download citation https://doi.org/10.1080/09593330.2021.1871660 Check for updates

# Closed-loop Organic Waste Management Systems for Family Farmers in Brazil

René van der Velden[1], Warde da Fonseca-Zang[2,5], Joachim Zang[2,5], Dominic Clyde-Smith[1], Wilson M. Leandro[3,5], Priti Parikh[4], Aiduan Borrion[1], Luiza C. Campos[1*]

[1] Dept. Civil, Environmental & Geomatic Engineering, Chadwick Building, University College London- UCL, Gower St, London WC1E 6BT.

[2] Sustainable Process Technology, Department 2, Federal Institute of Goiás, IFG, Rua 75, 46, Centro, CEP 74055110, Goiânia - GO.

[3] Agronomy Faculty, Federal University of Goiás – UFG, Av. Esperança s/n, Campus Samambaia, CEP 74690-900, Goiânia - Goiás – Brazil.

[4] Engineering for International Development Research Centre, UCL, Gower St, London WC1E 6BT.

[5] Apinaje Technological Vocational Centre - Federal University of Goiás – UFG – Rodovia Goiânia – Nova Veneza , Km 0, S/N, Campus Samambaia. CEP: 74690-900, Goiânia - Goiás – Brazil.

**Corresponding Author:** l.campos@ucl.ac.uk

**Abstract**

Family farmers in Brazil could diversify their sources of income source and improve agriculture practices by adopting circular economy principles on their farms. Closed-loop technological systems can be used to manage organic waste and produce fertilizer and biogas thereby generating revenue. Anaerobic digestion is a proven technology that can produce digestate (i.e. fertilizer) and biogas from organic waste, although digestate application in soil and crops without treatment can have adverse effects. However, in practice, there is a lack of knowledge about the benefits of recycling organic waste in farming communities in Brazil. Therefore, the main aim of this paper is to provide conceptual design configurations of closed-loop systems that manage organic waste and generate revenue for small farms in Brazil. A literature review of selected technologies and interviews with Brazilian family farmers were used to inform the components of the proposed conceptual designs. The proposed designs are based on circular economy principles, incorporating anaerobic digestion, pyrolysis for biochar, hydroponics and vermifiltration in various configurations. A complete closed-loop system consisting of a 7.5 $m^3$ digester, pyrolysis unit, a combined hydroponic and vermifilter unit and a shredder is estimated to cost around USD$1600 (R$ 6600). The flexibility of the proposed systems has the potential to increase resilience and income for small-scale farmers, whist encouraging good practices for waste management. The conceptual designs can be used as a basis for further research and development of small-scale organic waste management solutions in Brazil.

**Keywords:** family farmers, organic waste, closed-loop, biogas, technologies

## Introduction

The agricultural sector in Brazil is characterised by two types of farms: family farms and non-family farms [1]. Family farmers in Brazil are legally defined by Law No. 11.326 of 2006, using four criteria; regionally defined maximum land tenure, use of predominantly family labour on the farm, main income from on-farm activities, and the farm is run by family members [1]. In 2006, 84 % of all farms in Brazil were classified as family farms [1], producing only 38 % of all agricultural value, but providing 75 % of Brazil's domestic food consumption [2].

Unfortunately, the income of family farmers is often below the minimum wage and escaping poverty is difficult due to limited land ownership and low levels of capital [1]. Organic farming could potentially foster sustainable rural development, increasing cost-effectiveness of farming practices, and farmers can benefit from the growing market of organic products [3]. Furthermore, organic farming has recently gained more attention, socially and politically, through subsidies offered by the government, research institutes and development agencies [4]. Transitioning to organic practices increases resilience by reducing dependency on external inputs [5] and presents a market opportunity. Therefore, organic farming practices could potentially benefit family farmers in Brazil.

In addition, the disposal of agri-waste from family farmers is a major problem in Brazil because of use of usual and inappropriate techniques such as incineration, grounding, irregular disposal, and other solid waste disposal impactful techniques [6]. According to the Primary Care Information System (SIAB) of the Ministry of Health [7], in Brazil, approximately 7% of families deposit their waste to open areas and 13.5% burn or bury. Also, wastewater in places without sanitary installation is discharged into open areas, posing a risk to human health [8].

Closed-loop systems in small farms, which apply circular economic principles, not only have the potential to decrease negative environmental impacts and improve efficiencies [9] but they can also recover nutrients and energy, thus offsetting further costs. An ideal way to valorise organic waste is by using Anaerobic Digestion (AD), which enables both closed-loop and organic practices. AD is the microbial conversion of biomass into biogas and a nutrient-rich fertiliser know as digestate [10]. Land application of digestate replaces chemical fertiliser, but overuse comes with its risks such as leaching of nutrients, soil acidification and ammonium toxicity [11, 12]. Various alternative systems for the recovery of nutrients from digestate exist [13], however they are mainly used on macro scales and few designs exist that are appropriate for micro-scale, for family farmers.

AD has proven successful on small-scale farms as a first step to closing the loop [14]. These systems are relatively simple to operate and can turn organic waste into biogas for cooking, heating or electricity generation, and organic fertiliser [15]. However, ligneous wastes such as cassava branches are not suitable for AD [16]. Instead, they can be converted into biochar through small-scale pyrolysis, where organic waste is heated in anoxic conditions [17]. Biochar is known for improving moisture and nutrient retention of soil and as a way to successfully store carbon [18, 19]. In Goiás State, Brazil which lies within the '*Cerrado*' (a type of Brazilian savanna), the soil has high acidity [20], and to obtain satisfactory agricultural production in these soils, the use of soil amendments is recommended [21]. Therefore, biochar from agricultural waste may be helpful, given that biochar is mainly beneficial to acidic soils [22]

One technology which can be used to recover nutrients from digestate is hydroponics, where crops are grown in soilless conditions with only a solution to provide the necessary nutrients [23]. Where most hydroponic implementations are large scale and in controlled conditions, new developments explore small-scale options and the use of digestate as a nutrient solution [23]. Another option for cleaning the digestate is by using a vermifilter, a filter in which earthworms aid the breakdown of nutrients cleaning the digestate [24]. Additionally, vermifiltration provides nutrient-rich compost [25]. Other options include using microalgae and struvite precipitation; however, these are not suitable for small scale operations due to the need for economies of scale [26, 27].

Despite having technical solutions to support sustainable rural development, Neto et al. [28] emphasise that environmental education is fundamental to assist rural families in protecting the environment and diversification of their income sources. Also, the lack of technical knowledge limits the rural producer in decision making [29]. Therefore, this paper aims to provide closed-loop conceptual designs to manage organic waste and generate revenue in small farms in Brazil. These conceptual designs could be used by researchers, engineers and agricultural experts as a basis to design context specific solutions for family farmers across Brazil. It is also expected that the paper will serve as a source of practical support for small-scale farmers. Although other technological options can be considered in the design of closed-loop systems, this paper focuses on small-scale anaerobic digestion, pyrolysis, use of digestate in hydroponic systems and vermifiltration because they have been identified as cost-benefit solutions that incorporate circular economy principles. Interviews with family farmers were undertaken in Brazil to get an idea of the culture of these farmers to allow for a more human-centred design focus [30]. These interviews combined with the literature review form the basis of the conceptual designs of an organic waste management system suitable for family farmers in Brazil.

## Technologies for the closed-loop model

### *Small-scale anaerobic digestion*

AD is the conversion of organic matter by microbes in the absence of oxygen. The organic matter is converted into biogas and digestate, a nutrient-rich fertiliser [10]. Figure 1 shows the typical in- and outputs and their contents of the AD of crop residues based on [10], [31], [32] and [33]. As can be seen, the feedstock consists of organic matter combined with water with a ratio of 1:1 to decrease the solid content of the feedstock [31]. The desired value of the solid content in a tubular tank is between 10 % and 14 % [16]. About 10 % of the mass of the feedstock is converted to biogas, while the rest forms the digestate [33]. The biogas typically consists of 50-75 % biomethane, 25-45 % carbon dioxide, <2 % nitrogen, 0.1-2 % hydrogen sulphide and some additional trace elements [10]. The digestate can be divided into 95 % liquid fraction and 5 % dry fraction [32]. Each fraction can be used separately, and for this several innovative approaches exist, for example, the use of the dry fraction for the rearing of black soldier fly larvae [34]. Also, some recent studies have suggested the use of digestate as AD pre-treatment for lignocellulosic material [35, 36], thus allowing for more materials to enter the closed-loop cycle.

AD is considered more environmentally friendly than the direct application of manure on land [12], since it reduces nitrous oxide [37] and methane emissions (GHGs) [16]. Also, deforestation can be avoided by the provision of biogas as a cooking fuel instead of firewood [38]. Moreover, farmers spend less time foraging for firewood or spend less money on cooking gas [37]. Biogas can also be used for lighting or heating [15]. Besides gas, farmers are provided with a nutrient-rich fertiliser [39], avoiding chemical fertiliser expenses [40]. Furthermore, pathogens and odours present in manure are reduced [40]. Overall, biogas digesters are well suited in low and middle-income countries on family or community scale [37] and can form the central component of farming systems [38].

However, AD systems pose some challenges. For example, harvesting of crop residues as feedstock can be harmful to soil quality, leading to erosion and reduced plant growth [41]. It is therefore necessary to leave some biomass on the field to cover the soil and part of it go to the biodigester. The necessary water inputs might also form a problem in water-scarce regions [42]. Therefore, water reuse and rainwater harvesting may be helpful. Handling digestate also poses challenges. The digestate cannot be discharged into water bodies because of high BOD levels [42] and thus must be treated before discharging. Additionally, the digestate and animal excreta can pose health risks if not handled with care [43]. Therefore, safe use guidelines should always be followed [44]. In terms of design, biodigesters need expert design and skilled construction [43] and Operations & Maintenance (O&M) can be difficult. Many rural communities or farmers have stopped using biodigesters due to the lack of their knowledge [14], which leads to mistrust in the digester [16]. Common problems are gas leakage, low gas production and inadequate feedstock supply [45]. Furthermore, there is a lack of sizing standards [14] and information on the design of small-scale digesters [42], leading to inefficient designs. To overcome these challenges, in the case of Brazil, support may be sought from the Brazilian Agricultural Research Corporation (EMBRAPA) of the Ministry of Agriculture, Livestock and Supply which provides biodigester guidelines and technical advice for farmers. The high capital costs are an additional barrier for farmers with limited financial resources [37], thus affordable systems must be developed and policies on incentives for biogas generation from the government must be created. The Brazil-Germany project PROBIOGÁS promotes the use of biogas in Brazil to expand the efficient energy use of biogas in basic sanitation and in agricultural and agro-industrial initiatives, inserting biogas and biomethane in the national and national energy matrix.

In low and middle-income countries, AD is usually practised at a small scale in agricultural or community settings [43]. While the basic mechanisms of all digesters are the same, they differ in shape, size, material, insulation, bacteria regulation and mechanical input [14], influencing the properties of biogas and digestate. Three small scale digesters are most commonly used in low and middle-income countries: fixed dome digesters, floating drum digesters and flexible balloon digesters [38, 42]. Fixed dome and floating drum digesters are less susceptible to temperature changes [38], and have a longer life span [46] than balloon digesters. However, balloon digesters are simpler in construction, O&M and require less capital [46]. Balloon digesters are recommended in rural areas which have an average temperature above 20 °C [46]. All three digesters are usually placed partly or completely underground, to avoid temperature fluctuations [47]. Automation of digesters in low and middle-income countries is rare since they have little to no financial return at such small scale [37]. Different contexts require different digesters; however, prefabricated designs have high potential because they are made using specialised materials and are less likely to malfunction [46].

*Pyrolysis for biochar*

Ligneous wastes cannot be fed into a digester. Instead, a simple and low-cost solution is transforming them into biochar through pyrolysis [48]. Pyrolysis is the thermal conversion of biomass in the absence of oxygen [49] into char, bio-oil and syngas [50]. Various types of pyrolysis include slow, fast, rapid and flush, with slow pyrolysis being the most suitable for biochar creation [51]. This work considers only slow pyrolysis given the fact it is a simpler system than fast pyrolysis and produces heat and biochar [52] which can be easily used in small farms.

Biochar is known to be a good soil enhancer and is especially useful on infertile soil or in water restricted regions [38, 17]. Applying biochar to the soil is an effective way to sequester carbon [51], making it a carbon-negative waste management option [17]. It also decreases nitrous oxide and ammonia emissions from fertiliser [48]. For farmers, it is useful because applying biochar improves cation exchange capacity (CEC) of the soil which increases nutrient retention [18], prevents soil acidification, and improves moisture retention [17]. Biochar also improves microbiological soil fertility [51] and disease resistance of plants [50]. These capabilities make the soil more resilient against climate variability [19] and reduce nutrient leaching and fertiliser requirement [18]. Overall, these effects accumulate to improve seed emergence, crop growth and productivity [48]. The technology for creating biochar is well-known, low cost and can be done with locally available materials [18].

The main challenge of pyrolyzing organic wastes is its financial viability. Several studies found that the technology was not financially viable without subsidies [53], or not financially viable for small scale implementation [49]. However, where timber is too expensive, agricultural residues might be a suitable low-cost alternative [18]. Moreover, using timber from the woods might also damage the forest [17]. Vapours that are released form another challenge since they can cause air pollution [54] and have potential health risks [50]. Overall, not enough is known about the viability of small-scale pyrolysis, since most research in developed countries has been undertaken in the laboratory using timber instead of crop residues [55].

Earthmound kilns are used by traditional communities in the Amazon [56], however, these traditional methods are inefficient, waste heat and release GHGs [17]. More modern small-scale kilns are usually batch units made of brick, metal or drums and there are also smaller pyrolytic cook stoves [50]. Single- and double-barrel retort kilns are the most common units [57]. A relatively recent improvement of these kilns is the flame curtain kiln, which creates biochar layer by layer [58]. This design decreases the negative environmental impacts [59], while producing biochar with similar quality [60]. The main advantages are that these kilns do not need additional wood for ignition [61] and they work as a dryer, so feedstock with higher moisture content can be used [58].

*Digestate fertiliser*

Anaerobic digester digestate contains all macro- and micronutrients present in the feedstock [62], making it an excellent fertiliser [11, 39], capable of replacing chemical fertilisers [63]. Various studies find similar or increased growth of crops when using digestate instead of raw animal manure as fertiliser [64]. Compared to untreated animal manure, digestate has higher nitrogen plant availability [64]. Similarly, compared to raw or composted crop residues, digestate has improved nutrient availability [40]. Digestate has benefits over chemical fertiliser such as lower carbon footprint [63], and reducing the effects of drought stress due to water retaining characteristics [12].

Researches on the effects of land application of digestate are not conclusive and often disagree on how digested manure compares to undigested manure [64]. Compared to chemical fertiliser, digestate can lead to higher eutrophication and acidification rates [63] and similarly, care must be taken to prevent leaching into waterways [12]. Moreover, digestate might not be a complete fertiliser for all crops [65], and depending on the feedstock, might not be suitable for land application due to high biological oxygen demand (BOD), low dissolved oxygen (DO) levels, odour issues, possible phytotoxicity [11], and presence of pathogens [66]. Finally, due to pathogen accumulation, unsuitable nutrient compositions and potential nutrient runoff alternative digestate handling options are necessary [66]. Such technologies include hydroponics [67], vermifiltration [68], edible mushroom production [23] and algal biomass production [69]. For simplification, the former two are explored further in this work, while the others are interesting options for the future development of the presented conceptual design. However, it is suggested that other technologies could be explored in future studies.

*Hydroponics using digestate*

Hydroponics allow the growth of plants in soilless conditions, while nutrient-rich water is provided to the roots containing all the nutrients the plants need for growth [70]. Hydroponic systems vary depending on the type of plants, feeding regime, substrate type and system configuration. The most common configuration of such systems is the nutrient film technique (NFT), where roots are partially submerged in a thin layer of flowing water [71].

Literature about the use of digestate in hydroponic systems is scarce but increasing in recent years. Related research is concerned with hydroponics for wastewater treatment [72] and organic hydroponics [73]. Various successfully grown plants in digestate are lettuce [74], tomato [72, 67], peppermint, basil [75], strawberry [76], water spinach [72] and silverbeet [11]. Some plants had lower yields than plants grown in a conventional nutrient solution, however, this is likely to be caused by the use of conventional systems rather than systems designed for digestate use. Moreover, if nutrient composition, electrical conductivity (EC), and nitrogen levels are controlled, yields are similar or higher than conventionally grown hydroponic plants [77]. For example, Lind et al. [78] have investigated the cultivation of bok choy (*Brassica rapa var. chinensis*) in a hydroponic nutrient film technique system with biogas digestate as the only fertilizer source. They found that the use of digestate as a nutrient source resulted in EC levels (i.e. 2.0 mS $cm^{-1}$) well suited for bok choy hydroponic production when diluted to the desired nitrogen concentration (i.e. 200 mg ammonium–nitrogen $L^{-1}$). This work demonstrates the potential of using biogas digestate for hydroponic production of plants.

Hydroponics has several advantages over soil-grown crops. Most notably, less water is needed [79], less land area is necessary [80], yields are higher due to faster and denser growth [71], and leaching of nutrients into the environment is not a risk [66]. The use of digestate in hydroponics avoids the problems posed by using digestate as fertiliser [66], most notably leaching of nutrients and soil harming [79]. Additionally, the right system would increase productivity, reduce the need for pest control and improve ergonomics for workers [79]. Compared to using a conventional nutrient solution, digestate has shown to reduce disease and pests [81], increase yield [81, 82], improve crop quality [82]. For rural farmers hydroponic systems using digestate are especially beneficial because they are less dependent on weather conditions increasing the resilience of farmers, fertilisers do not have to be bought, and organic products can often be sold for higher prices.

Some notable downsides of hydroponics are the complexity of more advanced systems, the high capital costs and the susceptibility to rapid pathogen spread [83]. With regards to using digestate, there exists a lack of literature about the topic [11], making it hard to predict its viability. Specifically, investment and running costs are yet unclear [67] and operation and control of these systems are less well understood [84]. Some known challenges of using digestate in hydroponics are inhibited plant growth due to nutrient deficiencies [67], damage to roots caused by inhibitors in the digestate [13], and toxic conditions caused by nutrient accumulation [85]. Therefore, pH and nutrient levels need to be controlled [86], however, this increases costs and irregular digestate composition make nutrient supplementation difficult [87]. With respect to safety, not enough is known about the microbial aspect of food safety when using digestate in hydroponics [88]. Early results show no dangerous pathogen levels, but more research is needed [76]. Additionally, an ill-designed system might form a habitat for mosquitoes and flies [89].

Microbes are traditionally seen as harmful to hydroponic systems. However, the right microorganisms have proven to aid growth when using organic fertiliser [90]. These microbes are necessary to break down organic matter which is present in digestate and perform nitrification [23], which does not occur in conventional hydroponic systems [67], The microbes are commonly cultured in the substrate or rhizosphere and form a biofilm [89]. Similar to constructed wetlands, these biofilms require an adequate oxygen supply and surface area to oxidise organics so plants can take up the available nutrients [89].

Pre-treatment of digestate is necessary to make it suitable for crop growth [82], remove suspended solids [89], reduce ammonium content [90], increase DO [11] and adjust pH and EC levels [77]. Suspended solids can be removed by filtering the digestate. Ammonium levels can be decreased through dilution, air sparging or using nitrifying bacteria [77]. Filtering and ammonium removal can also be combined in a nitrifying biofilter [91] or a vermifilter [23]. Dilution of the digestate is usually based on the ammonium concentration [76]. The use of chemicals to adjust pH or to supplement specific nutrients has also shown to be successful [87].

*Vermifiltration*

Vermifiltration is a low-cost, environmentally friendly alternative for wastewater treatment highly suitable in low and middle-income countries [24, 92]. In a vermifilter earthworms and microbes break down organics, while a filter medium adsorbs impurities [93]. It is suitable for both rural communities [94] and individual homes [25]. Additionally, experiments have demonstrated the feasibility of combining constructed wetlands and vermifilters, which enhanced each other’s cleaning capabilities [95, 96].

Furthermore, as opposed to conventional wastewater treatment, vermifiltration forms little to no sludge [93, 92], is odour free [25], and little to no electricity is needed [94]. Vermifiltration has comparable treatment capabilities to activated sludge process and trickling filters while being cheaper in both construction and O&M and being simpler in operation [97]. Compared to alternative ecological decentralised wastewater treatment, vermifiltration requires less land [98]. Their ability to deal with fluctuations in input quantity [97] and the output being suitable for crop irrigation [94] make them appropriate for small-scale agriculture. Lastly, vermifilters create additional value by providing compost and earthworms which can be used as fish or poultry feed [25].

While most literature reports on pilot studies, less is known about long term effectiveness and potential operational issues [92]. A difficulty known with the operation is the fact that the worms need to be kept alive. Thus, the input cannot contain high levels of salts or toxicants [96] and wastewater needs to be fed into the system year-round [25]. Studies report on the usage of domestic sewage and swine manure [99]; however, no studies have been found using digestate.

## Material and methods

### *Interviews*

Ten interviews were held with farmers at the Agro Centro-Oeste Fair in Goiania, Goiás State Brazil on the 30$^{th}$ and 31$^{st}$ of May 2019. Notes were taken and questions were asked in English by the researcher and this was translated to Portuguese by a local researcher. However, it must be noted that often the researcher had to clarify and steer the conversation with the interviewee before translating since the answers were often not straightforward. The interviewees were asked questions verbally instead of them filling out the questionnaire, by themselves. To allow people with lower levels of education to participate. Each interview took roughly 35-50 minutes. Ethics approval was granted by the Chair of the UCL Research Ethics Committee at University College London (12927/001, approved on 6 March 2019) and Federal Institute of Goiás in Brazil (IFG ethics CAAE: 97040618.3.0000.8082, and judgement document number 3.022.577, approved 15 November 2018).

The fair was made up of stands with individual families, communities and cooperatives of farmers presenting their products. Interviewees were selected throughout the fair if they produced fruits, vegetables or processed food items and if they were available and willing to talk. Participants were not rewarded for their participation.

The interview questionnaire (See Appendix A) consisted of 12 questions, being 10 closed-ended questions and 2 open questions about challenges and opportunities, as well as two small mapping exercises. The first mapping exercise showed the waste streams in and out of the farms, while the second mapping exercise showed when crops were grown, what activities are involved and when farmers are typically busy.

The answers to the closed questions were combined and averaged or listed. The answers to the open questions and the additional notes were analysed by coding the responses and categorizing similar answers from different respondents together. This way, not only answers given often were counted, but also answers that were related were grouped. The mapping exercises were merged, and patterns were identified by looking both at the merged versions as well as the individual maps and additional notes to find differences and commonalities.

*Design methodology*

The closed-loop design system may be used as a basis for context-specific closed-loop farming systems globally. Using the aforementioned technologies, the system aims to mitigate GHG emissions and leaching of nutrients, while improving farmers' resilience through maximizing the use of organic resources, providing additional income and decreasing the weather dependency of farmers. In order to accomplish this goal, the system needs to 1) be affordable for family farmers in Brazil, 2) be usable for Brazilian family farmers, 3) fit with current family farming practices in Brazil and 4) minimise adverse environmental impact.

The literature review and the interviews were used to inform the design process, where a systems approach was used. The final design consists of various units working together in adaptable configurations. Different configurations of the units create different closed-loop systems which allow the system to be adjusted to the needs of farmers on a case-to-case basis. Before individual units were designed, the overall system and various interplays between the various units were aligned. By mapping out the possible in- and outputs of the separate units, these connections were defined.

All units are based on existing designs. A list of eleven design requirements was established, in decreasing order of importance: capital costs, O&M costs, O&M difficulty, construction difficulty, sustainability, health and safety, flexibility, materials availability, O&M time investment, the lifetime of the units, and value creation. For the anaerobic digester and the pyrolysis units, these design requirements were used to compare and select existing units. The hydroponic unit did not undergo this process since only one small-scale design was available for the treatment of wastewater. The vermifilter unit was based on designs used in literature which are very similar. If necessary the units have been adapted to the local context with regards to available materials, costs, and ease of operation.

Making technical drawings for all units, aided in defining details and improving the unit designs and the various possible unit configurations.

Agri-waste data was acquired from '*Tchê Organicos'*, organic farm in the State of Goiás, Brazil in order to determine the amount of waste generated per hectare by a typical farm in Brazil. Keeping in mind most farms have a small number of animals, the closed-loop system was designed for farms ranging from sizes of 1 to 10 ha of cropland, with animal excreta of 0-20 chickens and/or 0-12 cow and/or 0-10 pigs.

## Results and discussion

### *Interview results*

The results of the interviews were used as a human centered design method [30] to inform the conceptual designs. All interviewees were farmers within Goiás State, Brazil (Table 1). Eight women and two men were interviewed, one of the men was involved in the management of the cooperative and was not a farmer himself, the other participants were all farmers. The income of the interviewees varies a lot between families and throughout the year with an average of two times minimum wage per month per family (R$ 998, or USD $246 in 2019). Table 2 shows a summary of the interview results of the closed questions and the timeline mapping. Both income and produce (fruits and vegetables) varied across the respondents. Half of them (n=10) also practice animal husbandry providing either milk, eggs and/or meat, mainly for personal consumption. None of the respondents had water access problems, with most of them using wells as their main water source. Irrigation is only practised by a few farmers and is mostly done by hand during the dry season.

Challenges and opportunities were gathered from the family farmers (Appendix B, Table S.1). Three farmers (n=10) mentioned the challenge of aligning production of products with market demand since demand is difficult to predict. Another three farmers (n=10) mentioned weather conditions as a challenge, either because of too much or too little rain in different seasons. Finances were mentioned as a barrier by 5 farmers (n=10), relating to the difficulty to invest, the high price of animal food, the market value of products, access to government funding or managing finances. Lastly, four respondents (n=10) mentioned a lack of government support for (organic) family farmers.

The development of the farm was mentioned by three respondents (n=10). They want to increase the number of animals they have or build greenhouses to decrease their dependency on the weather. Two farmers (n=10) mentioned the market as an opportunity, these were farmers who grow novel products or farm organic products. Collaboration is also seen as a future opportunity by 4 farmers (n=10), three of which specifically mentioned their cooperative as an opportunity.

In- and outputs of the respondents' farms were mapped (Appendix B, Table S.2). The most common inputs are electricity, water and gas; however, these are usually not used for agriculture but only for household activities. Additionally, electricity supply is often unreliable. Four of the farmers interviewed (n=10) buy fertilisers externally, while two create it themselves organically. Animal food, pesticides and liquid fuel are additional inputs mentioned less often. The most common outputs are vegetables, milk, eggs and meat. The vegetables grown are mostly sold; however, milk, eggs and meat are often only used for own consumption. Polluted water is discharged directly into the environment by two farmers, whereas the other eight (n=10) reported that they utilise some form of low-cost treatment, most commonly a black trench. Many additional specialised and self-processed products such as baru nut, pitaya fruit, sweets and juice, were often mentioned; however, there is a big variety amongst farmers.

The timeline mapping highlighted that different crops are grown throughout the year on the same farm. The clearest distinction is between crops grown in the wet or dry season, either specifically utilising or avoiding these seasons. Thus, leaf vegetables were only grown in the dry season. All farmers (n=10) indicated they are busy all year round with peaks around planting and harvest season. Often additional help was found within the community or family, either paid or unpaid.

*Closed-loop waste management system*

***System configurations***

As evident from the interviews, family farming agricultural practices vary widely. There is no one-size-fits-all solution and thus the system needs to be flexible and adaptable. The design of each individual system and the interplay between them should be adjustable. For example, some farms have high amounts of ligneous waste such as cassava stems and branches. Thus, pyrolysis might be a good approach. Alternatively, some farmers do not have enough capital for an additional vermifilter so they can use the biochar as a filter instead. Additionally, family farmers are often limited in their investment capabilities [1, 100]. It is thus unlikely they can invest in multiple units at once. Instead, they might invest in additional units over time. This means the units should be able to function independently as well as together. The technologies that are incorporated in the proposed system are: anaerobic digester, pyrolysis unit, vermifilter, hydroponic unit, combined hydroponic and vermifilter unit, and a shredder (see Figure 2). The anaerobic digester, vermifilter and hydroponic system is chosen because jointly they are capable of forming a closed-loop waste management system. The pyrolysis unit was added since some farms have ligneous wastes which are not suitable for AD; additionally, the biochar can serve as a filter for digestate as well as enhance soil conditions. The shredder is necessary to shred organic waste for the digester and biochar before land application, it must be noted that the shredder is not specifically designed but a regular garden waste shredder is assumed to be used. The following diagram (Figure 3) shows the flexibility of the system which ensures it will suit with a wide range of family farming operations. For each system, technical drawings were made to further develop the details of each system (Appendix C, Figures S.1 to S.8), additionally lists of materials were created to determine the costs and difficulty of construction (Appendix D, Tables S.1 to S.4).

Figures 3 to 5 show three multiple functions and possible alternative configurations of the system. The anaerobic digesters have been designed in various sizes, whereas the other units only have one size, since their capacity can easily be increased by adding more units, unlike with AD. To illustrate this, an example configuration is presented in Figure 7. In this configuration, waste from 10 chickens (1 kg [38]), 1 cow (11.25 kg [38]) and 3 hectares of cropland are considered amounting to a total of 44 kg crop residue, calculated based on data from [101]. Half the crop residues (i.e. 22 kg) can be digested while the other half is pyrolyzed.

A suitable Hydraulic Retention Time (HRT) is dependent on the feedstock and the type of digester [15]. Advised HRTs range from 10-15 days [45] to 20-30 days [16]. Thus, for this design, we aimed for an HRT between 10 and 30 days. A commonly recommended organic loading rate (OLR) is 2-5 kg Volatile Solids (VS)*$m^{-3}$*$d^{-1}$ [45].

Based on waste inputs and values of HRT and OLR, a digester of 3.7 $m^3$ was estimated. This AD is used in combination with one pyrolysis unit, two combined hydroponic and vermifiltration units and some digestate applied to the cropland directly. The pyrolysis unit is used twice a month and the biochar that is generated is enough for roughly 1.2 hectares per year.

A second design option is shown in Figure 8 and is suitable for a farm with 5 hectares of land (72.5 kg calculated based on data from Daioglou et al. [101], where 60 % of crop residue is suitable for digestion, and 5 pigs (11.5 kg based on Orskov et al. [38]). This system is formed with a digester of 7.5 $m^3$, a vermifilter and 6 hydroponics units, thus the pyrolysis unit is not included, and the additional residue is left on the land.

As future research, it is suggested that mass- and energy-balances should be carried out for these design configurations to better understand the effectiveness of the system. Additionally, determining the energy flux and product yields by piloting the system could enhance the conceptual design. Finally, other combinations of technologies (e.g. AD followed by pyrolysis of the by-products; pyrolysis of wastes followed by integration of biochar in anaerobic digestion) could be considered to explore ways to reduce costs in relation to the benefits.

***Anaerobic digester unit in the closed-loop system***

AD is a well-established technology which is the foundation of the proposed closed-loop system. The alternative design flowchart as described in Grant & Lawrence [14] was used to determine the appropriate specifications of the biodigester design. The limited investment capabilities of farmers combined with the local ambient temperature and the educational level of farmers determined a non-mixed tubular reactor working in mesophilic conditions to be the most suitable type of reactor, since it is a low cost, needs no additional heating and is easy in operation. Thus, the design for the anaerobic digester is based on the prefabricated tubular design by the company *Sistema Biobolsa* [102], with only adjustments in size to allow for smaller digesters. The following sizes were deemed to fit with the established amount of cropland and animals in the previous section as 1.5 $m^3$, 3.7 $m^3$, 7.5 $m^3$ and 15 $m^3$. With a 2:1 digestate-biogas ratio, which leaves space for biogas capture. These sizes correspond with the reported appropriate biodigester sizes of 2.4 $m^3$ to 15 $m^3$ for small to medium sized farms [16]. Since a conventional design is used, O&M process is the same.

***Pyrolysis unit***

Four pyrolysis units were compared using the design criteria. The traditional earth mound [56], the single barrel retort kiln [57], the double-barrel retort kiln [57] and the Kon-Tiki film curtain kiln [58]. The Kon-Tiki flame curtain kiln was deemed the best unit, based on O&M costs since repairs are rarely needed; sustainability, since harmful gasses are caught by the flame curtain [58]; O&M time investment, since maintenance is rarely needed, operation per batch only takes a couple of hours and drying is not needed [58]; lifetime, since the units are made out of long-lasting materials; and value creation, since the unit does not need additional biomass for initial heating [58]. Thus, the design for the pyrolysis unit is based on the Kon-Tiki flame curtain kiln design as presented by Schmidt & Taylor [58], with slight modifications to reduce costs by reusing waste materials from construction. The input is assumed to be ligneous crop residues, such as cassava branches, and possibly waste wood. The feedstock is ignited on the bottom and layer for layer additional feedstock is applied for a couple of hours. Once full, the batch is quenched with water or digestate and the biochar is ready to be applied on land. One full batch of 0.73 $m^3$ feedstock will give roughly 150 kg biochar. With the advised application density of biochar of 5000 kg per hectare [18], one batch covers 0.03 ha (300 $m^2$) of land. Because the conceptual design assumes a slow pyrolysis system, it is suggested to include fast pyrolysis in a future study to consider the benefit of bio-oil production and its application in small farms.

***Hydroponic unit***

The design for the hydroponic unit is based on the hydroponic unit designed for wastewater treatment by the co-author Clyde-Smith [89]. This unit has been chosen because it can be built with locally obtainable materials and is easy to construct and operate. It is a vertical design in which microbial growth in the substrate and rhizosphere aerobically breaks down organic matter. The nutrient solution is aerated through the recirculation of the nutrient solution and the trickling downwards through the substrate media and the plant roots.

The alterations that have been made to the design are: the additional two towers within one reservoir to increase capacity, the use of one pump for three towers to lower the costs, the addition of an inlet and water level measuring and improvement of watertight connections in the reservoir. Thus, costs are lower and O&M are simpler compared to multiple units side by side. The operation consists of filling up the reservoir with water and digestate (water: digestate ratio 4.5:1) and tending the plants.

***Vermifiltration unit***

The vermifiltration designs given in the literature are relatively simple and similar to each other [93, 97, 25]; as such this design is based on the recommended substrate layers from the literature i.e. from bottom to top: a layer of 20 mm diameter gravel, one or more layers of aggregate possibly mixed with sand of 5-16 mm diameter, a top layer of soil with worms [93, 92], and a combined bed height of 40-60 cm [94]. The reservoir used is identical to the reservoir of the hydroponic unit. This decision was made so the two designs could be combined into one unit. In this unit, digestate is placed in the bottom reservoir. Two tanks are used with the filter material in the top tank and the bottom tank serving as a reservoir. A pump and a perforated tube distribute the wastewater equally over the surface of the filter bed. Concrete bricks are used to elevate the filter. Digestate simply needs to be spread over the vermifilter and depending on subsequent use might need to be recirculated for a while. Once done, the pump can be used to empty the system.

***Combined hydroponic and vermifilter unit***

The hydroponic unit and the vermifilter are also available as a combination of the two separate systems. This reduces the costs further, simplifies the operation and maintenance, reduces operation and maintenance time, and increases the organic loading rate that the unit can handle. Similar to the hydroponic unit, diluted digestate (water: digestate ration 4.5:1) is placed in the bottom reservoir and pumped up through the tower. After the water trickles down, it goes through the vermifilter back into the reservoir. Since the vermifilter requires dry periods, tap switches are used to direct the water straight to the reservoir, instead of through the filter bed.

***System costs***

Apart from the biodigesters and the shredder, the costs of the units were estimated based on the retails price of the various parts needed to assemble them. The biodigester is assumed to be purchased from a certified retailer, instead of self-built. As such, these costs are based on recent loans provided to Mexican farmers for biodigesters from non-profit organisation Kiva [103]. The cost of the shredder is based on a garden waste shredder's costs as found online. Table 3 shows the total costs of these 3 systems using a digester of 7.5 $m^3$ and Table 4 gives the costs of individual units. For example, a completely closed-loop system can cost around R$ 6600 (USD$ 1600), for a system consisting of a 7.5 $m^3$ digester, pyrolysis unit, a combined hydroponic and vermifilter unit and a shredder. The average income of the interviewed farmers was roughly twice the minimum wage (R$ 1996 = USD$ 484), thus the system costs may be covered with approximately four months of income. It is suggested to determine the cost of the conceptual designs according to the local context as the cost may vary from region to region, depending on the availability and costs of materials and labour.

**Challenges and limitations of the design approach**

As a well-established technology, AD gives an idea of the challenges associated with implementing new systems on family farms. One such barrier is the failure of the technology, which in biogas installations can be attributed to ill-designed systems, which do not function as expected [45], are manufactured using low-quality materials [104] or require too much operation and maintenance time [105]. Looking at this aspect for the hydroponic unit, it can be concluded that the technical feasibility of the unit at scale has not been proven [11]. Small-scale and low-cost hydroponic units are gaining more attention as a way to alleviate poverty and improve farmers' resilience [106, 107, 108]. Moreover, the use of digestate in hydroponics is gaining more attention, albeit in industrialised contexts [23]. However, the question remains whether the plants in a small-scale rural hydroponic setup will grow at the same rate as within a commercial hydroponics setup. This is due in particular to the lower skill base and lack of monitoring equipment. As it is important to control the pH and EC to stop nutrient deficiency and toxicity, the digestate from the AD may have excess levels of nutrients leading to toxicity, particularly ammonium toxicity. The level of nutrient can be monitored in rudimental way through visual inspection of the plant, but the time lag may be too great to save the crop [109]. The understanding of the level of dilution needed to mitigate toxicity and deficiency is the case for further research.

Also, vermifilters have limited long-term studies within a rural agricultural context with proven beneficial results [92] and even less literature is available for its use with digestate. Similarly, the combined hydroponic unit and vermifilter reduces costs, but its technical feasibility requires further investigation.

Another biogas implementation challenge is the inadequate training of farmers [104], causing incorrect use [110] and subsequently loss of trust in the system [105]. Additionally, social and cultural barriers can cause people not to accept biogas from human waste [110]. Alternatively, farmers might not understand the benefits of using the new system as opposed to conventional farming practices.

Therefore, to overcome these challenges, participatory processes are crucial for creating solutions that align not only with the needs of all stakeholders but also fit within their current lives and are accepted by all affected parties [111]. In the case of Goiás State, the Apinaje Technological Vocational Centre (CVT) - which develops activities of technological and rural extensions, applied research and training of human resources and socialization of knowledge and techniques of agroecology, organic production and clean production in organic production systems - is engaged with the Organic Agriculture Development Association (ADAO) to promote the conceptual designs proposed in this paper.

The proposed conceptual designs intend to inform technical solutions that are easy to maintain and operate in a closed-loop system. The system has a twofold benefit, one is to reduce the operational costs of the farm by the provision of biogas and fertilizer in the form of digestate, and the other is to reduce any environmental impact caused by potential waste disposal practices. Current trends in Brazil favour organic agriculture and new technologies [114], increasing the likelihood of success for the proposed system. In addition, Caiado Couto et al. [115] found in their review that 'waste, energy, and food' is a common interlinkage that focus on biogas generation from agricultural waste, confirming that researchers seem to expect it to become an important renewable alternative in Brazil.

Therefore, our proposed closed-loop designs offer an opportunity to integrate other technologies to enhance resource recovery in small farms. For example, the hydroponic system which allows for a higher degree of control than soil grown crops is likely to increase the resilience of family farmers against climate conditions and fluctuations in demand [116]. In addition, biochar can be used in agriculture with positive responses up to 20 Mg/ha in crop productivity [117, 118, 119]. Therefore, the effect on input substitution minimizes production costs, offering safe food production at affordable prices. However, it is recommended to develop business models for each conceptual design proposed in this work to support decision making. To support business model development, it is suggested to install pilot plants of the proposed conceptual designs to collect data on system efficiency, capital and operating expenses.

Finally, it is important to emphasize that the design and operation of the anaerobic digester must follow the national codes including electric code, fire safety code, gas code, and building code. In addition, environmental regularization is a legal obligation prior to the installation of any potentially polluting or degrading activity of the environment. Usually, in Brazil regularization and licensing of biogas plants occurs at the state or municipal level, depending on the scope of the impact [121]. Municipalities can carry out the licensing of activities, since that receive state delegation, by signing an agreement. In Europe, there are several policies, regulations and directives (e.g. Directive 2008/98/EC, Directive 2009/28/EC) which govern anaerobic digestion, nutrient, and waste management activities [122]. Therefore, farmers planning an activity related to energy conversion and nutrient recovery from energy crops and agricultural waste are advised to start with considering the European regulatory framework and then turn to the regulatory framework of the Member State where the facility will be located. For example, according to the Anaerobic Digestion and

Bioresources Association in the UK, biogas operators must comply with the requirement set by the Environmental Permitting Regulations (EPR).

## Conclusion

By incorporating the selected technologies, the suggested conceptual designs offer a closed-loop solutions for small-scale farmers. The system is specifically designed for family farmers in Brazil, however it can potentially be implemented on small-scale farms in other low and middle-income countries. A key feature of the design is its flexibility. For example, given fresh water or alternative water sources, such as reclaimed water or rainwater, and the necessary infrastructure are available, only minor alterations are required to successfully implement the system in different contexts. Thus, the proposed system has the potential to increase resilience and income for small-scale farmers in Brazil and beyond, while encouraging best practices for waste management in rural communities and farms.

The proposed conceptual designs can be used as a basis for further development of circular systems for small scale farms. Therefore, future research includes the development of pilot systems in small-farms to support technical and financial feasibility studies and business model creation using participatory methods.

**Acknowledgements**

The authors would like to thank the Tchê Organicos, organic farm in Terezopolis of Goiás, for providing the agri-waste data for the design, and all interviewed farmers attending the Agro Centro-Oeste Fair in Goiania, Goiás.

**Disclosure Statement**

No potential conflict of interest was reported by the authors.

**Funding**

This project was supported by the Institutional Links grant numbers 332266861 and 201710267001279 under the Newton Fund: Institutional Links programme between the United Kingdom and Brazil partnership. The grant is funded by the UK Department of Business, Energy and Industrial Strategy (BEIS) and Fundação de Amparo à Pesquisa do Estado de Goiás (FAPEG, and delivered by the British Council. For further information, please visit www.newtonfund.ac.uk. Some aspects of this research were supported by the Brazilian Research Council CNPq, grant number 402721/2017-9.

**References**

[1] S. M. Helfand, A. R. B. Moreira and D. W. Bresnyan, “Agricultural Productivity and Family Farms in Brazil: Creating Opportunities and Closing Gaps,” 2015.

[2] F. V. Soares, R. Nehring, R. B. Schwengber, C. G. Rodrigues, G. Lambais, D. S. Balaban, C. Jones and A. Galante, “Structured Demand and Smallholder Farmers in Brazil: the Case of PAA and PNAE,” International Policy Centre for Inclusive Growth (IPC - IG), Brasilia, 2013.

[3] L. Kilcher, “How organic agriculture contributes to sustainable development,” *JARTS,* vol. 89, pp. 31-49, 2007.

[4] S. Schneider, S. Shiki and W. Belik, “Rural development in Brazil: overcoming inequalities and building new markets,” *Rivista di Economia Agraria,* vol. 65, no. 2, pp. 225-259, 2010.

[5] C. A. Francis, R. R. Harwood and J. F. Parr, “The potential for regenerative agriculture in the developing world,” *American Journal of Alternative Agriculture,* vol. 1, no. 2, pp. 65-74, 1986.

[6] A. P. R. Ferreira, F. J. M. Vasconcelos and S. A. Meira, “Alternativas para destinação de resíduos sólidos da agricultura familiar,” in *Educação ambiental: ecopedagogia e sustentabilidade dos recursos naturais*, Seabra, 2017.

[7] SIAB, “Famílias com coleta de lixo: Veja número de domicílios atendidos, com lixo a céu aberto, queimado ou enterrado por cidade do Brasil,” 2013. [Online]. Available: http://www.deepask.com/goes?page=barreiros/PE-Confira-a-coleta-de-lixo-no-seu-municipio---lixo-coletado-a-ceu-aberto-queimado-ou-enterrado. [Accessed 10 October 2020].

[8] V. M. F. Miorin, “Agricultura Familiar em Áreas de Degradação Ambiental,” *Rio Grande do Sul Revista OKARA: Geografia em debate,* vol. 3, no. 1, pp. 83-107, 2009.

[9] S. C. Davis, D. Kauneckis, N. A. Kruse, K. E. Miller, M. Zimmer and G. D. Dabelko, “Closing the loop: integrative systems management of waste in food, energy, and water systems,” *Journal of Environmental Studies and Sciences,* vol. 6, no. 1, p. 11–24, 2016.

[10] FNR, Guide to Biogas - From production to use, 5th ed., Fachagentur Nachwachsende Rohstoffe e. V. (FNR), 2012.

[11] K. Krishnasamy, J. Nair and B. Bäuml, “Hydroponic system for the treatment of anaerobic liquid,” *Water Science & Technology,* vol. 65, no. 7, pp. 1164-1171, 2012.

[12] B. J. Chambers and M. Taylor, “The use of digestate as a substitute for manufactured fertilizer,” in *Bioenergy Production by Anaerobic Digestion - Using agricultural biomass and organic wastes*, N. E. Korres, P. O'Kiely, J. A. H. Benzie and J. S. West, Eds., New York, Routledge, 2013, pp. 359-374.

[13] R. Endo, K. Yamashita, T. Shibuya and Y. Kitaya, “Use of Methane Fermentation Digestate for Hydroponic Culture: Analysis of Potential Inhibitors in Digestate to Cucumber Seedling,” *Eco-Engineering,* vol. 28, no. 3, pp. 67-72, 2016.

[14] W. D. Grant and T. M. Lawrence, “A simplified method for the design and sizing of anaerobic digestion systems for smaller farms,” *Environment, Development and Sustainability,* vol. 16, no. 2, p. 345–360, 2014.

[15] M. S. Dhanya, S. Prasad and A. Singh, “Biogas technology for developing countries - An approach to sustainable development,” in *Bioenergy Production by Anaerobic Digestion - Using agricultural biomass and organic wastes*, N. E. Korres, P. O’Kiely and J. A. H. Benzie, Eds., New York, Routledge, 2013, pp. 397-421.

[16] G. Merlin and H. Boileau, “Anaerobic Digestion of Agricultural Waste: State of the Art and Future Trends,” in *Anaerobic Digestion: Types, Processes and Environmental Impact*, A. Torrles, Ed., NY USA, Nova Science Publishers, Inc, 2013.

[17] H. K. Nsamba, S. E. Hale, G. Cornelissen and R. T. Bachmann, “Sustainable Technologies for Small-Scale Biochar Production - A Review,” *Journal of Sustainable Bioenergy Systems,* vol. 5, pp. 10-31, 2015.

[18] B. Glaser, J. Lehmann and W. Zech, “Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal – a review,” *Biology and Fertility of Soils,* vol. 34, no. 4, p. 219–230, 2002.

[19] A. Gathorne-Hardy, J. Knight and J. Woods, “Biochar as a soil amendment positively interacts with nitrogen fertiliser to improve barley yields in the UK,” *IOP Conference Series: Earth and Environmental Science,* vol. 6, 2009.

[20] J. S. S. Carneiro, Á. J. G. Faria, R. R. Fidelis, S. P. Silva Neto, A. C. Santos and R. R. Silva, “Diagnóstico da variabilidade espacial e manejo da fertilidade do solo no Cerrado. Scientia Agraria,” *Scientia Agraria,* vol. 17, no. 3, pp. 38-49, 2017.

[21] J. S. S. Carneiro, S. A. de Sousa, M. Nikkel, T. T. Deusdará, Â. F. Machado and R. R. da Silva, “Supercalagem: alterações em atributos químicos de um Latossolo Vermelho amarelo distrófico,” *Revista de Ciências Agroambientais,* vol. 16, no. 1, pp. 31-38, 2018.

[22] M. Zhang, M. Riaz, L. Zhang, Z. El-desouki and C. Jiang, “Biochar Induces Changes to Basic Soil Properties and Bacterial Communities of Different Soils to Varying Degrees at 25 mm Rainfall: More Efective on Acidic Soils,” *Front. Microbiol,* vol. 10, p. 1321, 2019.

[23] K. Stoknes, f. Scholwin, W. Krzesiński, E. Wojciechowska and A. Jasińska, “Efficiency of a novel ‘‘Food to waste to food” system including anaerobic digestion of food waste and cultivation of vegetables on digestate in a bubble-insulated greenhouse,” *Waste Management,* vol. 56, p. 466–476, 2016.

[24] M. M. Manyuchi, L. Kadzungura and S. Boka, “Vermifiltration of Sewage Wastewater for Potential Use in Irrigation Purposes Using Eisenia fetida Earthworms,” *World Academy of Science, Engineering and Technology,* vol. 78, pp. 538-542, 2013.

[25] R. K. Sinha, G. Bharambe and U. Chaudhari, “Sewage treatment by vermifiltration with synchronous treatment of sludge by earthworms: a low-cost sustainable technology over conventional systems with potential for decentralization,” *Environmentalist,* vol. 28, p. 409–420, 2008.

[26] B. Etter, E. Tilley, R. Khadka and K. M. Udert, “Low-cost struvite production using source-separated urine in Nepal,” *Water Research,* vol. 45, pp. 852-862, 2011.

[27] L. I. Fuldauer, B. M. Parker, R. Yaman and A. Borrion, “Managing anaerobic digestate from food waste in the urban environment: Evaluating the feasibility from an interdisciplinary perspective,” *Journal of Cleaner Production,* vol. 185, pp. 929-940, 2018.

[28] M. Neto, H. Nogueira, M. Mello, A. Sena and R. Filho, “Avaliação da percepção da gestão dos resíduos sólidos provenientes da agricultura familiar nos assentamentos Baeté e Bom Jardim, Barreiros – PE,” in *Agroecologia Congress*, Brasilia, 2017.

[29] L. Mendes and E. Y. Ichikawa, “O desenvolvimento tecnológico e o pequeno produtor rural: construção, desconstrução ou manutenção da sua identidade?,” *CADERNOS EBAPE,* vol. 8, no. 1, 2010.

[30] D. Norman, The Design of Everday Things: Revised and expanded edition, Basic books, 2013.

[31] CONDRIT, “The Tubular Plastic Bio-Digesters,” 1995. [Online]. Available: https://www.build-a-biogas-plant.com/PDF/Low-cost%20Plastic-tube%20Biogas%20Digesters.pdf. [Accessed 21 July 2019].

[32] WRAP, “Using quality anaerobic digestate to benefit crops,” Waste and Resources Action Programme, 2012.

[33] M. Grudziński and A. Pietruszka, “Quantitative reduction of feedstock biomass as a result of conversion in anaerobic digestion in agricultural biogas plant,” *Folia Pomeranae Universitatis Technologiae Stetinensis, Agricultura, Alimentaria, Piscaria et Zootechnica,* vol. 328, no. 39/3, pp. 79-84, 2016.

[34] M. Elsayed, Y. Ran, P. Ai, M. Azab, A. Mansour, K. Jin, Y. Zhang and A. E. Abomohra, “Innovative integrated approach of biofuel production from agricultural wastes by anaerobic digestion and black soldier fly larvae,” *Journal of Cleaner Production,* vol. 263, 2020.

[35] M. Elsayed, A. E. Abomohra, P. Ai, K. Jin, Q. Fan and Y. Zhang, “Acetogenesis and methanogenesis liquid digestates for pretreatment of rice straw: A holistic approach for efficient biomethane production and nutrient recycling,” *Energy Conversion and Management,* vol. 195, pp. 447-456, 2019.

[36] P. Ai, M. Chen, Y. Ran, K. Jin, J. Peng and A. E. Abomohra, “Digestate recirculation through co-digestion with rice straw: Towards high biogas production and efficient waste recycling,” *Journal of Cleaner Production,* vol. 263, 2020.

[37] P. Hobbs and A. Butler, “The sustainability of small-scale anaerobic digesters at farm scale,” in *Bioenergy Production by Anaerobic Digestion - Using agricultural biomass and organic wastes*, N. E. Korres, P. O’Kiely and J. A. H. Benzie, Eds., New York, Routledge, 2013, pp. 375-396.

[38] E. R. Orskov, K. Y. Anchang, M. Subedi and J. Smith, “Overview of holistic application of biogas for small scale farmers in Sub-Saharan Africa,” *Biomass and Bioenergy,* vol. 70, pp. 4-16, 2014.

[39] C. Lukehurst and A. Bywater, “Exploring the viability of small scale anaerobic digesters in livestock farming,” IEA Bioenergy, 2015.

[40] K. E. Ileleji, C. Martin and D. Jones, “Basics of energy Production through Anaerobic digestion of Livestock Manure,” *Purdue Extension BioEnergy series,* August 2008.

[41] M. R. Cherubin, D. M. Da Silva Oliveira, B. J. Feigl, L. G. Pimentel, I. P. Lisboa, M. R. Gmach, L. L. Varanda, M. C. Morais, L. S. Satiro, G. V. Popin, S. R. De Paiva, A. K. B. Dos Santos, A. L. S. De

Vasconcelos, P. L. A. De Melo, C. E. P. Cerri and C. C. Cerri, “Crop residue harvest for bioenergy production and its implications on soil functioning and plant growth: A review,” *Scientia Agricola,* vol. 75, no. 3, pp. 255-272, 2018.

[42] A. K. Singh and R. K. Kaushal, “Design of Small Scale Anaerobic Digester for Application in Indian Village: A Review,” *International Journal of Engineering and Applied Sciences,* vol. 3, no. 8, pp. 11-16, 2016.

[43] E. Tilley, L. Ulrich, C. Lüthi, P. Reymond and C. Zurbrügg, Compendium of Sanitation Systems and Technologies, 2nd ed., Dübendorf: Swiss Federal Institute of Aquatic Science and Technology, 2014.

[44] World Health Organization, “Guidelines for the Safe Use of Wastewater, Excreta and Greywater - Volume 2 Wastewater use in agriculture,” WHO Press, 2006.

[45] K. Rajendran, S. Aslanzadeh and M. J. Taherzadeh, “Household Biogas Digesters—A Review,” *Energies,* vol. 5, pp. 2911-2942, 2012.

[46] S. Cheng, Z. Li, H. Mang, E. Huba, R. Gao and X. Wang, “Development and application of prefabricated biogas digesters in developing countries,” *Renewable and Sustainable Energy Reviews,* vol. 34, pp. 387-400, 2014.

[47] R. Singh and R. C. Anand, “Comparative Performances of Indian Small Solid-State and Conventional Anaerobic Digesters,” *Bioresource Technology,* vol. 47, pp. 235-238, 1994.

[48] J. Lehmann, J. Gaunt and M. Rondon, “Bio-Char Sequestration in Terrestrial Ecosystems - A Review,” *Mitigation and Adaptation Strategies for Global Change,* vol. 11, p. 403–427, 2006.

[49] M. Tripathi, J. N. Sahu and P. Ganesan, “Effect of process parameters on production of biochar from biomass waste through pyrolysis: A review,” *RenewableandSustainableEnergyReviews,* vol. 55, p. 467–481, 2016.

[50] W. Gwenzi, N. Chaukura, F. N. D. Mukome, S. Machado and B. Nyamasoka, “Biochar production and applications in sub-Saharan Africa: Opportunities, constraints, risks and uncertainties,” *Journal of Environmental Management,* vol. 150, p. 250e261, 2015.

[51] A. Zabaniotou, D. Rovas, A. Libutti and M. Monteleone, “Boosting circular economy and closing the loop in agriculture: Case study of a small-scale pyrolysis–biochar based system integrated in an olive farm in symbiosis with an olive mill,” *Environmental Development,* vol. 14, pp. 22-36, 2015.

[52] C. Z. Zaman, K. Pal, W. Yehye, S. Sagadevan, S. T. Shah, G. A. Adebisi, E. Marlian, R. F. Rafique and R. B. Johan, Pyrolysis: A Sustainable Way to Generate Energy from Waste, Intechopen.69036, 2017.

[53] P. Galgani, E. Van der Voet and G. Korevaar, “Composting, anaerobic digestion and biochar production in Ghana. Environmental–economic assessment in the context of voluntary carbon markets,” *Waste Management,* vol. 34, p. 2454–2465, 2014.

[54] J. A. Garcia-Nunez, M. R. Pelaez-Samaniego, M. E. Garcia-Perez, I. Fonts, J. Abrego, R. J. M. Westerhof and M. Garcia-Perez, “Historical Developments of Pyrolysis Reactors: A Review,” *Energy Fuels,* vol. 31, no. 6, pp. 5751-5775, 2017.

[55] D. Zhang, M. Yan, Y. Niu, X. Liu, L. Van Zwieten, D. Chen, R. Bian, K. Cheng, L. Li, S. Joseph, J. Zheng, X. Zhang, J. Zheng, D. Crowley, T. R. Filley and G. Pan, “Is current biochar research addressing global soil constraints for sustainable agriculture?,” *Agriculture, Ecosystems and Environment,* vol. 226, pp. 25-32, 2016.

[56] O. T. Coomes and G. J. Burt, “Peasant charcoal production in the Peruvian Amazon: rainforest use and economic reliance,” *Forest Ecology and Management,* vol. 140, pp. 39-50, 2001.

[57] J. Dennis, “Biochar Manual for Small Farms in BC,” 23 September 2011. [Online]. Available: https://sites.google.com/site/fcfcbiocharmanual/. [Accessed 1 August 2019].

[58] H. Schmidt and P. Taylor, “Kon-Tiki flame curtain pyrolysis for the democratization of biochar production,” *the Biochar Journal,* pp. 14-24, 2014.

[59] A. B. Smebye, M. Sparrevik, H. P. Schmidt and G. Cornelissen, “Life-cycle assessment of biochar production systems in tropical rural areas: Comparing flame curtain kilns to other production methods,” *Biomass and Bioenergy,* vol. 101, pp. 35-43, 2017.

[60] R. N. Pandit, J. Mulder, S. E. Hale, H. P. Schmidt and G. Cornelissen, “Biochar from "Kon Tiki" flame curtain and other kilns: Effects of nutrient enrichment and kiln type on crop yield and soil chemistry,” *PLoS ONE,* vol. 12, no. 4, 2017.

[61] G. Cornelissen, N. P. Pandit, P. Taylor, B. H. Pandit, M. Sparrevik and H. P. Schmidt, “Emissions and Char Quality of Flame-Curtain "Kon Tiki" Kilns for Farmer-Scale Charcoal/ Biochar Production,” *PLoS ONE,* vol. 11, no. 5, 2016.

[62] J. Murphy, R. Braun, P. Weiland and A. Wellinger, “Biogas from Crop Digestion,” IEA Bioenergy, 2011.

[63] Y. L. Chiew, J. Spångberg, A. Baky, P. Hansson and H. Jönsson, “Environmental impact of recycling digested food waste as a fertilizer in agriculture—A case study,” *Resources, Conservation and Recycling*, vol. 95, pp. 1-14, 2015.

[64] K. Möller and T. Müller, “Effects of anaerobic digestion on digestate nutrient availability and crop growth: A review,” *Engineering in Life Sciences,* vol. 12, no. 3, pp. 242-257, 2012.

[65] B. E. Liedl, J. Bombardiere and J. M. Chatfield, “Fertilizer potential of liquid and solid effluent from,” *Water Science & Technology,* vol. 53, no. 8, pp. 69-79, 2006.

[66] J. P. Sheets, L. Yang, X. Ge, Z. Wang and Y. Li, “Beyond land application: Emerging technologies for the treatment and reuse of anaerobically digested agricultural and food waste,” *Waste Management*, vol. 44, pp. 94-115, 2015.

[67] J. Neal and A. C. Wilkie, “Anaerobic Digester Effluent as Fertilizer for Hydroponically Grown Tomatoes,” *Journal of Undergraduate Research,* vol. 15, no. 3, 2014.

[68] H. Lin, S. A. W. Diemont, T. Toland, W. Tao, D. Daley and D. L. Johnson, “Vermifiltration Ecological Treatment for the Re-Use of Food Waste Digestate,” *Water Environment Research,* vol. 85, no. 11, pp. 2184-2193, 2013.

[69] N. Abdel-Raouf, A. A. Al-Homaidan and I. B. M. Ibraheem, “Microalgae and wastewater treatment,” *Saudi Journal of Biological Sciences,* vol. 19, p. 257–275, 2012.

[70] P. A. Chatelier, “Hydroponics,” *The Science Teacher,* vol. 21, no. 2, pp. 74-75, 1954.

[71] M. D. Sardare and S. V. Admane, “A Review on Plants Without Soil - Hydroponics,” *International Journal of Research in Engineering and Technology,* vol. 2, no. 3, pp. 299-304, 2013.

[72] K. Furukawa and M. Fujita, “Advanced Treatment and Food Production by Hydroponic Type Wastewater Treatment Plant,” *Water Science and Technology*, vol. 28, no. 2, pp. 219-228, 1993.

[73] C. Kawamura-Aoyama, K. Fujiwara, M. Shinohara and M. Takano, “Study on the Hydroponic Culture of Lettuce with Microbially Degraded Solid Food Waste as a Nitrate Source,” *Japan Agricultural Research Quarterly*, vol. 48, no. 1, pp. 71-76, 2014.

[74] D. Ronga, L. Setti, C. Salvarani, R. De Leo, E. Bedin, A. Pulvirenti, J. Milc, N. Pecchioni and E. Francia, “Effects of solid and liquid digestate for hydroponic baby leaf lettuce (Lactuca sativa L.) cultivation,” *Scientia Horticulturae,* vol. 244, p. 172–181, 2019.

[75] D. Ronga, F. Pellati, V. Brighenti, K. Laudicella, L. Laviano, M. Fedailaine, S. Benvenuti, N. Pecchioni and E. Francia, “Testing the influence of digestate from biogas on growth and volatile compounds of basil (Ocimum basilicum L.) and peppermint (Mentha x piperita L.) in hydroponics,” *Journal of Applied Research on Medicinal and Aromatic Plants,* vol. 11, pp. 18-26, 2018.

[76] M. Dimambro, J. Steiner, R. Lillywhite and C. Keeling, “Use of quality digestates as a liquid fertiliser in the commercial production of strawberries,” WRAP, 2015.

[77] M. E. Dimambro, “Novel uses for digestate: Protected horticulture,” Manchester, 2015.

[78] O. P. Lind, M. Hultberg, K. Bergstand, H. Larsson-Jönsson, S. Capsersen and H. Asp, “Biogas Digestate in Vegetable Hydroponic Production: pH Dynamics and pH Management by Controlled Nitrification,” *Waste and Biomass Valorization,* 2020.

[79] R. Monteiro Corrêa, S. Isabel do Carmo Pinto, É. Soares Reis and V. Andalo Mendes de Carvalho, “Hydroponic Production of Fruit Tree Seedlings in Brazil,” in *Hydroponics - A Standard Methodology for Plant Biological Researches*, T. Asao, Ed., Rijeka, InTech, 2012, pp. 225-244.

[80] A. G. A. Du Toit and M. T. Labuschagne, “A comparison between hydroponics systems and pots for growing wheat in the greenhouse,” *South African Journal of Plant and Soil,* vol. 24, no. 2, pp. 120-123, 2007.

[81] N. Duan, C. Lin, R. Y. Gao, Y. Wang, J. H. Wang and J. Hou, “Ecological and economic analysis of planting greenhouse cucumbers with anaerobic fermentation residues,” *Procedia Environmental Sciences,* vol. 5, p. 71–76, 2011.

[82] W. K. Liu, Q. Yang and L. Du, “Soilless cultivation for high-quality vegetables with biogas manure in China: Feasibility and benefit analysis,” *Renewable Agriculture and Food Systems,* vol. 24, no. 4, p. 300–307, 2009.

[83] S. Lee and J. Lee, “Beneficial bacteria and fungi in hydroponic systems: Types and characteristics of hydroponic food production methods,” *Scientia Horticulturae*, vol. 195, pp. 206-215, 2015.

[84] T. Weidner, A. Yang and M. W. Hamm, “Consolidating the current knowledge on urban agriculture in productive urban food systems: Learnings, gaps and outlook,” *Journal of Cleaner Production,* vol. 209, pp. 1637-1655, 2019.

[85] C. Chong, P. Purvis, G. Lumis, B. E. Holbein, R. P. Voroney, H. Zhou, H. Liu and M. Z. Alam, “Using mushroom farm and anaerobic digestion wastewaters as supplemental fertilizer sources for growing container nursery stock in a closed system,” *Bioresource Technology,* vol. 99, p. 2050–2060, 2008.

[86] U. J. López-Chuken, “Hydroponics and Environmental Clean-Up,” in *Hydroponics - A Standard Methodology for Plant Biolocial Researches*, T. Asao, Ed., Rijeka, InTech, 2012, pp. 181-198.

[87] W. K. Liu, Q. C. Yang, L. F. Du, R. F. Cheng and W. L. Zhou, “Nutrient supplementation increased growth and nitrate concentration of lettuce cultivated hydroponically with biogas slurry,” *Acta Agriculturae Scandinavica, Section B - Soil & Plant Science,* vol. 61, no. 5, pp. 391-394, 2011.

[88] M. Dimambro, J. Steiner and F. Rayns, “Literature review: Digestate use in protected horticulture,” WRAP, 2015.

[89] D. Clyde-Smith, The development of an urban green infrastructure which is based on hydroponic system and mimics the treatment of wastewater by constructed wetlands for the production of value crops, London: PhD Thesis, University College London, 2016.

[90] M. Shinohara, C. Aoyama, K. Fujiwara, A. Watanabe, H. Ohmori, Y. Uehara and M. Takano, “Microbial mineralization of organic nitrogen into nitrate to allow the use of organic fertilizer in hydroponics,” *Soil Science and Plant Nutrition,* vol. 57, no. 2, p. 190—203, 2011.

[91] J. Cheng, T. E. Shearin, M. M. Peet and D. H. Willits, “Utilization of treated swine wastewater for greenhouse tomato production,” *Water Science and Technology,* vol. 50, no. 2, p. 77–82, 2004.

[92] L. Jiang, Y. Liu, X. Hu, G. Zeng, H. Wang, L. Zhou, X. Tan, B. Huang, S. Liu and S. Liu, “The use of microbial-earthworm ecofilters for wastewater treatment with special attention to influencing factors in performance: A review,” *Bioresource Technology,* vol. 200, pp. 999-1007, 2016.

[93] H. S. Bhise and G. S. Anaokar, “Design and Suitability of Modular Vermifilter for Domestic Sewage Treatment,” *International Journal of Emerging Engineering Research and Technology,* vol. 3, no. 4, pp. 44-51, 2015.

[94] R. Singh, P. Bhunia and R. R. Dash, “A mechanistic review on vermifiltration of wastewater: Design, operation and performance,” *Journal of Environmental Management,* vol. 197, p. 656e672, 2017.

[95] P. Tomar and S. Suthar, “Urban wastewater treatment using vermi-biofiltration system,” *Desalination,* vol. 282, pp. 95-103, 2011.

[96] K. Samal, R. R. Dash and P. Bhunia, “Treatment of wastewater by vermifiltration integrated with macrophyte filter: A review,” *Journal of Environmental Chemical Engineering,* vol. 5, p. 2274–2289, 2017.

[97] Y. Li, Y. Xiao, J. Qiu, Y. Dai and P. Robin, “Continuous village sewage treatment by vermifiltration and activated sludge process,” *Water Science & Technology,* vol. 60, no. 11, pp. 3001-3010, 2009.

[98] M. Xing, X. Li and J. Yang, “Treatment performance of small-scale vermifilter for domestic wastewater and its relationship to earthworm growth, reproduction and enzymatic activity,” *African Journal of Biotechnology,* vol. 9, no. 44, pp. 7513-7520, 2010.

[99] Y. S. Li, P. Robin, D. Cluzeau, M. Bouché, J. P. Qiu, A. Laplanche, M. Hassouna, P. Morand, C. Dappelo and J. Callarec, “Vermifiltration as a stage in reuse of swine wastewater: Monitoring methodology on an experimental farm,” *ecological engineering,* vol. 32, p. 301–309, 2008.

[100] F. Chaddad, The Economics and Organization of Brazilian Agriculture - Recent Evolution and Productivity Gains, Academic Press, 2016.

[101] V. Daioglou, E. Stehfest, B. Wicke, A. Faaij and D. P. Van Vuuren, “Projections of the Availability and Cost of Residues from Agriculture and Forestry,” *Global Change Biology Bioenergy,* vol. 8, p. 456–470, 2016.

[102] Sistema.bio, “Product Catalogue,” Sistema Biobolsa, 2019. [Online]. Available: https://sistema.bio/wp-content/uploads/2.1903_KENYA_CATALOG_LQ.pdf. [Accessed 21 July 2019].

[103] Kiva, “Kiva,” 2019. [Online]. Available: https://www.kiva.org/. [Accessed 5 August 2019].

[104] H. Buckland, “Study of Social Entrepreneurship and Innovation Ecosystems in the Latin American Pacific Alliance Countries - Case Study: Sistema Biobolsa, Mexico,” 2016.

[105] C. Mulinda, Q. Hu and K. Pan, “Dissemination and Problems of African Biogas Technology,” *Energy and Power Engineering,* vol. 5, pp. 506-512, 2013.

[106] F. Orsini, R. Kahane, R. Nono-Womdim and G. Gianquinto, “Urban agriculture in the developing world: a review,” *Agronomy for Sustainable Development*, vol. 33, no. 4, p. 695–720, 2013.

[107] M. M. Croft, S. G. Hallett and M. I. Marshall, “Hydroponic production of vegetable Amaranth (Amaranthus cruentus) for improving nutritional security and economic viability in Kenya,” *Renewable Agriculture and Food Systems,* vol. 32, no. 6, p. 552–561, 2017.

[108] L. Oliver and C. Whitworth, “Climate Smart Farming for Women in East Africa,” 2018.

[109] J. B. Jones, Complete Guide for Growing Plants Hydropononically, Boca Raton: CRC Press, 2014.

[110] S. Mittal, E. O. Ahlgren and P. R. Shukla, “Barriers to biogas dissemination in India: A review,” *Energy Policy,* vol. 112, p. 361–370, 2018.

[111] F. Vanclay, A. M. Esteves, I. Aucamp and D. Franks, “Social Impact Assessment: Guidance for assessing and managing the social impacts of projects,” Fargo ND, 2015.

[112] S. Hussain, E. B. -N. Sanders and M. Steinert, “Participatory Design with Marginalized People in Developing Countries: Challenges and Opportunities Experienced in a Field Study in Cambodia,” *International Journal of Design,* vol. 6, no. 2, pp. 91-109, 2012.

[113] I. Zelenika and J. M. Pearce, “Barriers to Appropriate Technology Growth in Sustainable Development,” *Journal of Sustainable Development,* vol. 4, no. 6, pp. 12-22, 2011.

[114] CE100 Brasil Network, “A Circular Economy in Brazil: An initial exploration,” 2017.

[115] L. C. Cuoto, L. C. Campos, W. da Fonseca-Zang, J. Zang and R. Bleischwitz, “Water, waste, energy and food nexus in Brazil: Identifying a resource interlinkage research agenda through a systematic review,” *Renewable and Sustainable Energy Reviews,* no. https://doi.org/10.1016/j.rser.2020.110554, p. 110554, 2020.

[116] K. Garvey, “Global agriculture, food and land use - How to create resilient agricultural systems in a world of increasing resource scarcity and climate change,” 2013.

[117] B. Madari, A. R. Costa, L. M. Castro, J. L. S. Santos, V. M. Benites, A. O. Rocha and P. L. O. A. Machado, “Charcoal as a soil conditioner for upland rice (cultivar primavera): A prospective study,” *Embrapa Rice and Beans,* vol. 125, p. 2, 2006.

[118] P. G. Oguntunde, M. Fosu, A. Ajayi and N. V. Giesen, “Effects of charcoal production on maize yield, chemical properties and texture of soil,” *Biology and Fertility of Soils*, vol. 39, pp. 295-299, 2004.

[119] B. Singh, B. P. Singh and A. L. Cowie, “Characterization and evaluation of biochars for their application as a soil amendment,” *Australian Journal of Soil Research*, vol. 48, pp. 516-525, 2010.

[120] P. Bradley and C. Marulanda, “Simplified hydroponics to reduce global hunger,” *Acta horticulturae*, vol. 554, pp. 289-295, 2001.

[121] Fundação Estadual do Meio Ambiente, Federação das Indústrias do Estado de Minas Gerais, GIZ, “Guia técnico ambiental de biogás na agroindústria,” Belo Horizonte, 2015.

[122] L. Hermann and R. Hermann, “Report on regulations governing anaerobic digesters and nutrient recovery and reuse in EU member states,” Wageningen Environmental Research, Wageningen, 2019.

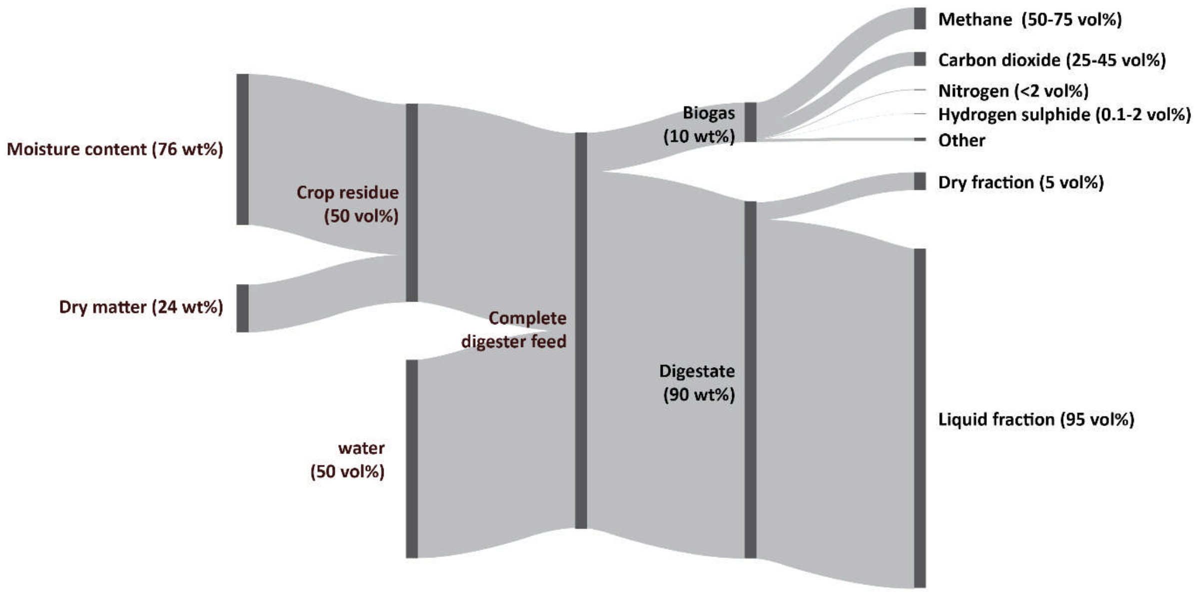


Figure 1 - Typical AD feedstock and effluent contents. Data compiled from [10], [31], [32] and [33]

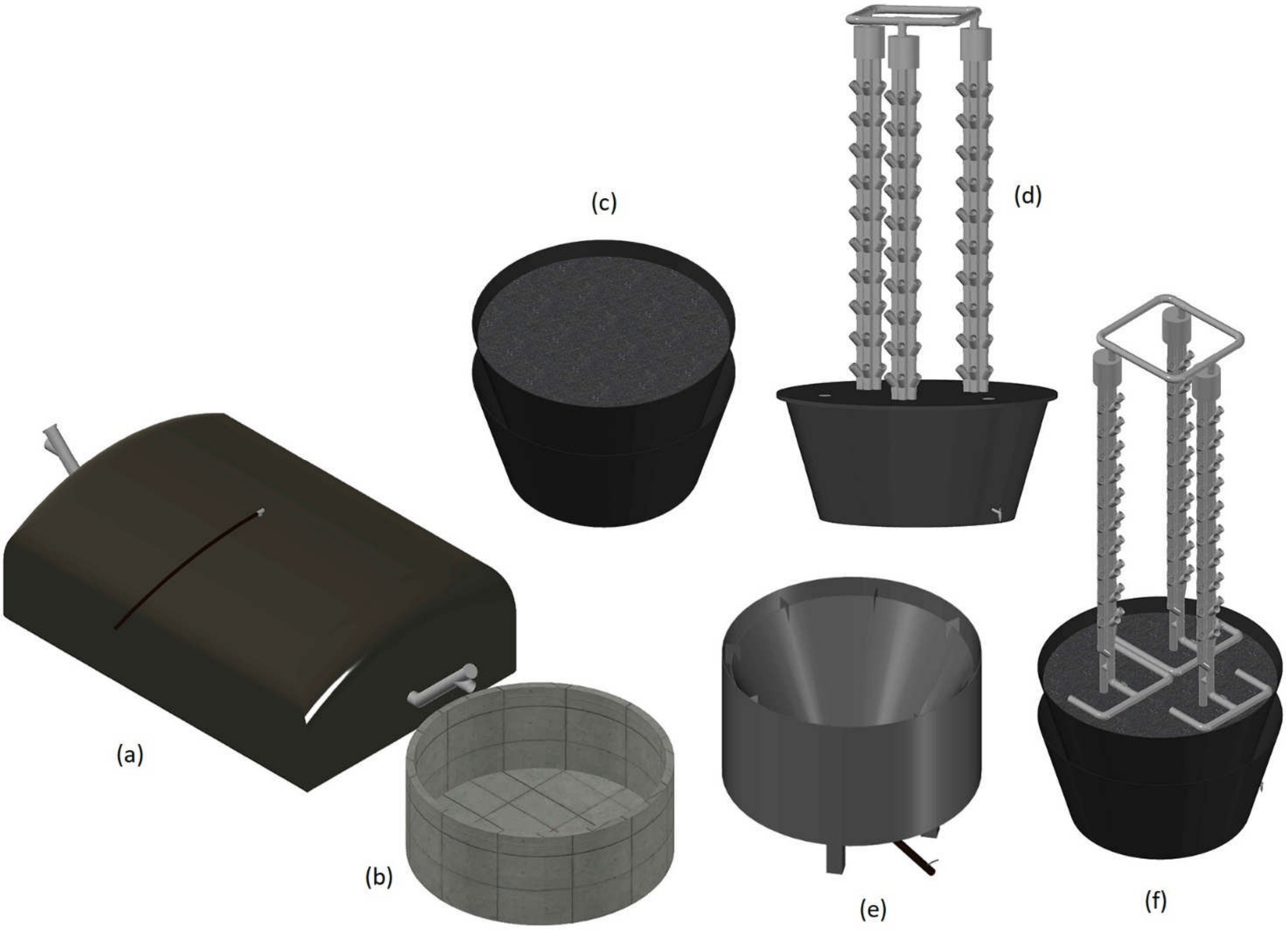


Figure 2 - Conceptual designs of the various units. (a) Anaerobic digester unit 7.5 $m^3$, (b) Digestate storage, (c) Vermifilter unit, (d) Hydroponic unit, (e) Pyrolysis unit, (f) Combined hydroponic and vermifilter unit. The shredder is not included in this figure.

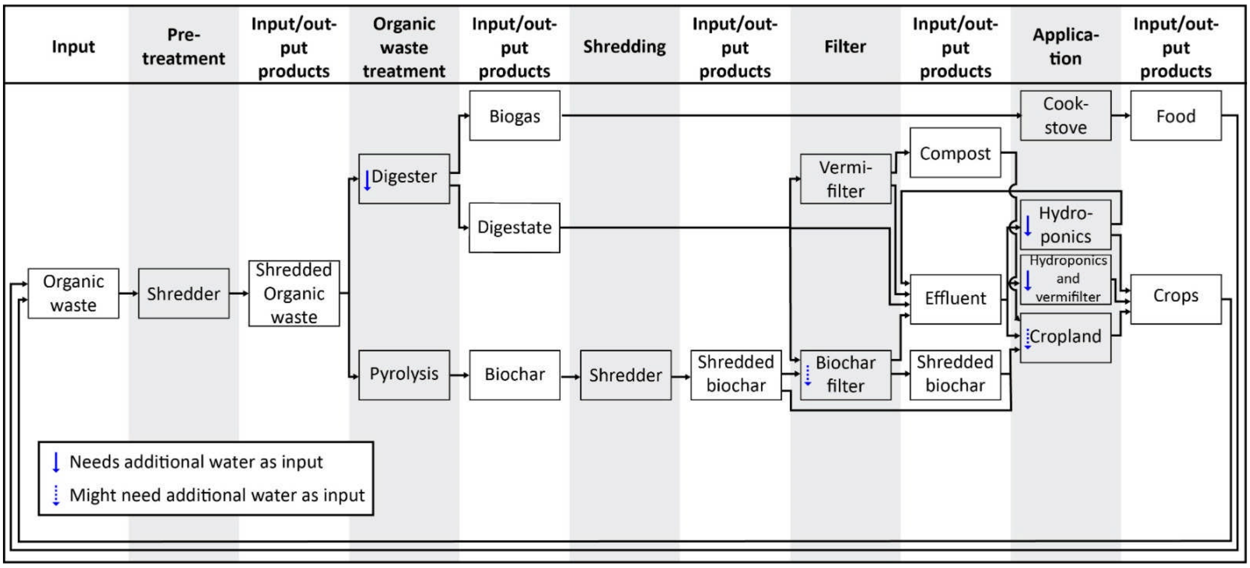


Figure 3 - Complete system design and possible configurations. Solid blue arrows indicate the need for additional water into the system. Dotted blue arrows indicate the potential need for additional water depending on operating conditions.

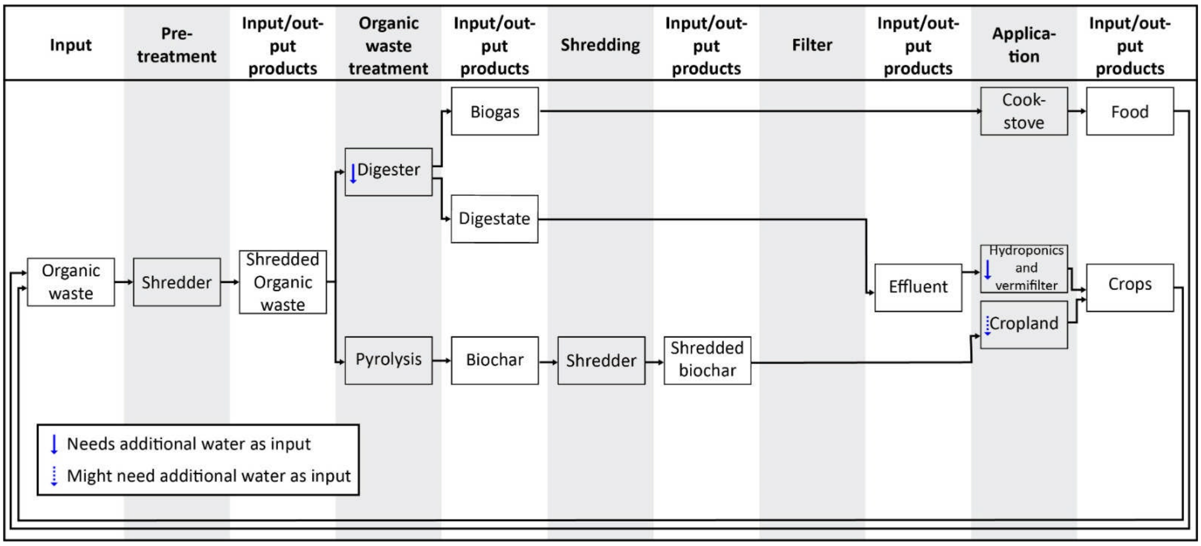


Figure 4 - System configuration with a digester 7.5 m$^3$, pyrolysis unit and a combined hydroponics and vermifilter unit

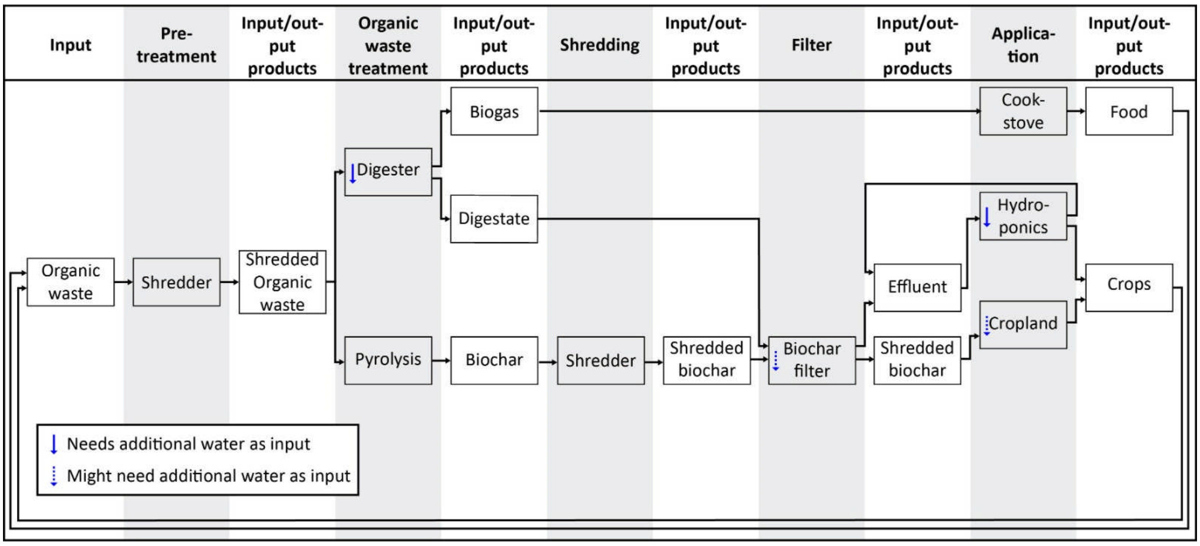


Figure 5 - System configuration with a digester 7.5 m$^3$, pyrolysis unit and a hydroponics unit

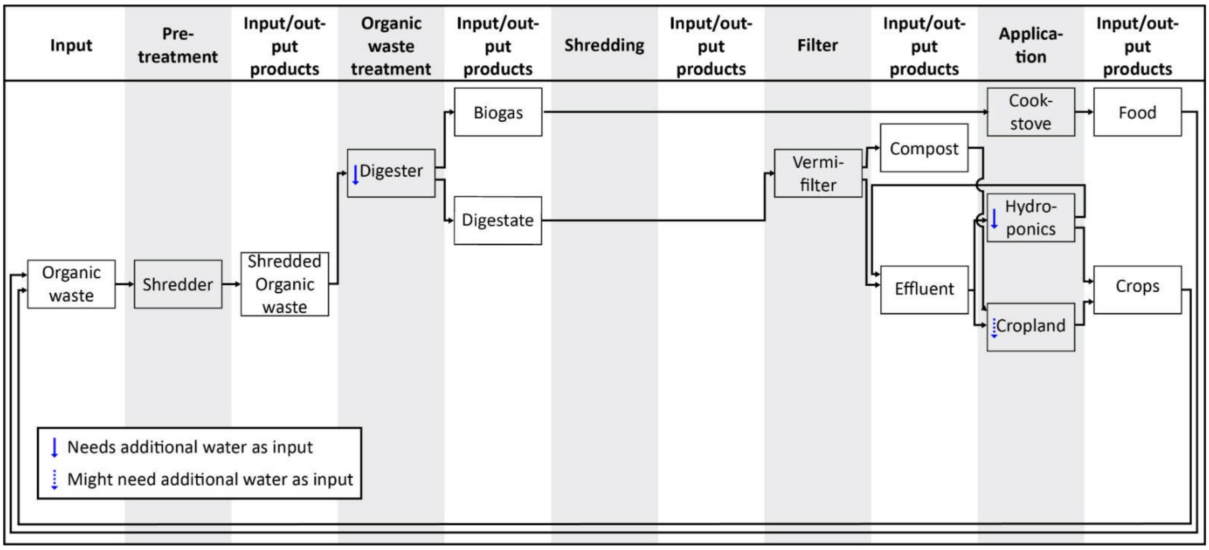


Figure 6 - System configuration with a digester 7.5 m$^3$, a vermifilter and a hydroponics unit

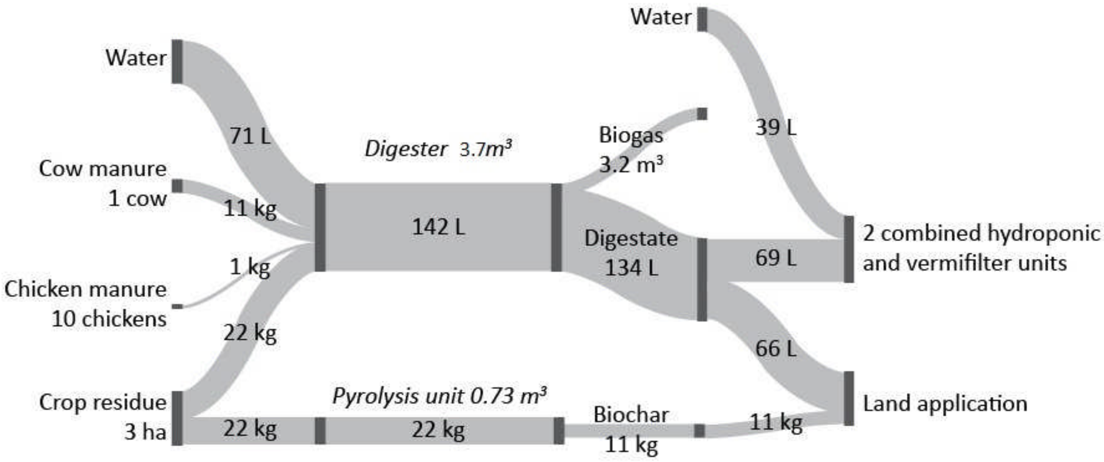


Figure 7 - Example configuration of the system with the average daily in- and outputs for a farm with 3 hectares of cropland (44 kg of crop residue per day), 10 chickens (1 kg of chicken manure per day) and 1 cow (11 kg of cow manure per day). Note that the pyrolysis unit is only used twice a month, feedstock is stored between operations.

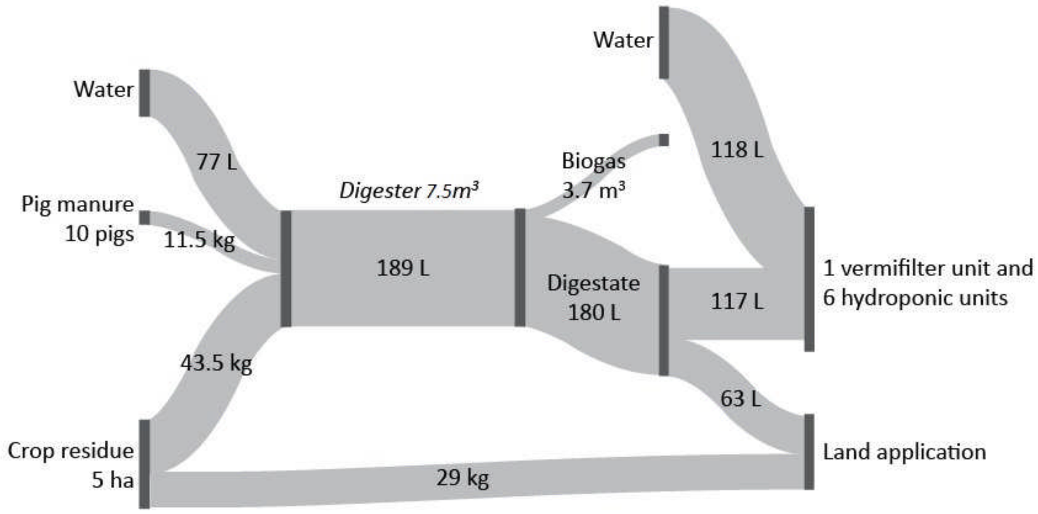


Figure 8 - Example configuration of the systems with the average daily in- and outputs for a farm with 5 hectares of cropland (72.5 kg of crop residue per day), 5 pigs (11.5 kg of pig manure per day).

Table 1 - Overview of interviewees

| # | Gender | Occupation | Education | Family income (multiple of minimum wage)* |
|---|---|---|---|---|
| 1 | F | Farmer | Complete high school | 1-2 |
| 2 | F | Farmer | Complete high school | 1-2 |
| 3 | M | Farmer | Professional technical education - high school level | >1 |
| 4 | F | Farmer | Complete high school | 1-2 |
| 5 | M | Cooperative manager | Complete higher education | 2-4 |
| 6 | F | Farmer | Complete primary education | 2-3 |
| 7 | F | Farmer | Complete higher education | 2-4 |
| 8 | F | Farmer | Incomplete elementary school | 2-3 |
| 9 | F | Farmer | Complete higher education | 2-3 |
| 10 | F | Farmer | Incomplete elementary school | <1 |

(*) monthly minimum wage = R$ 998

Table 2 - Short summary of the interview results, closed questions and timeline exercise

| | |
|---|---|
| **Number of participants** | 10 |
| **Production on farm, most stated products** | Farmers have a big variety themselves and mix animals and crop production. Exceptions are usually milk production |
| **Water sources** | Mainly wells, some rainwater. Differs much per farm, but water is usually available |
| **Irrigation** | Usually no irrigation, if used mostly by hand and mainly in dry season |
| **Waste destination** | Different for every farm. Some residues, burning and collection most prominent. |
| **Separate garbage** | 8 yes, 2 no |
| **Use food leftovers** | 9 yes, 1 no |
| **Purpose of food leftovers** | 7/10 practice composting, 3/10 use it for animal food, 2/10 use food on land (directly and after burning) |
| **Notes on timelines** | Varying crops with varying planting times are often planted on the same farm.<br>Most find it difficult to pinpoint the most difficult time of the year, as they are always busy.<br>Help from neighbours is often leveraged (paid or unpaid). |

Table 3 – Comparison of the total costs of the three presented configurations

| Presented configuration | Total costs (R$) | Total costs ($USD) |
|---|---|---|
| Digester 7.5 $m^3$, Combined hydroponic and vermifilter unit, pyrolysis unit, shredder (Figure 4) | 6589 | 1622 |
| Digester 7.5 $m^3$, Hydroponic unit, pyrolysis unit, shredder (Figure 5) | 5450 | 1341 |
| Digester 7.5 $m^3$, vermifilter unit, hydroponic unit (Figure 6) | 4316 | 1087 |

Table 4 - Costs in Brazilian real and US-dollar currencies of the units for a closed-loop system

| **Unit** | **Total costs (R$)** | **Total costs ($USD)** | **Source** |
|---|---|---|---|
| Digester 1.5 $m^3$ (2:1 digestate: biogas) | 800 | 197 | Estimation based on [103] |
| Digester 3.7 $m^3$ (2:1 digestate: biogas) | 1200 | 295 | Estimation based on [103] |
| Digester 7.5 $m^3$ (2:1 digestate: biogas) | 2000 | 492 | Estimation based on [103] |
| Digester 15 $m^3$ (2:1 digestate: biogas) | 4000 | 985 | Estimation based on [103] |
| Pyrolysis unit (0.73 $m^3$) | 1382 | 340 | Sum of parts at local retail price |
| Hydroponic unit (0.73 $m^3$) | 1118 | 275 | Sum of parts at local retail price |
| Vermifilter (0.73 $m^3$) | 1298 | 320 | Sum of parts at local retail price |
| Combined hydroponic and vermifilter unit (0.73 $m^3$) | 2257 | 556 | Sum of parts at local retail price |
| Organic waste shredder | 950 | 234 | Local retail price |

## Appendix A: Questionnaire

**Número do formulário bilíngue/bilingual form Number: ________________**

### Questionário 01 – Características Socioeconômicas e Saneamento Rural
**(Questionnaire 01 – Socio Economic Characteristics and Rural Sanitation)**

**Desenvolvimento Rural Sustentável - Institucional Links do Reino Unido e FAPEG, Goiás, Brasil**
**(Sustainable Rural Development – Institutional Links/British Council and FAPEG)**
com o /with the
**Project title: Water-Waste-Energy-Food Nexus Supporting Organic Farming in Rural Communities - WWEFood Nexus**
Título do projeto: Sistema Integrado Resíduo-Água-Energia-Alimento para comunidades de produção orgânica

Outro projeto aprovado/CNPq/Another Grant:
**Project Title/CNPq: CVT APINAJÉ – TRAINING OF YOUTH AND WOMEN**
Título do Projeto do CNPq: Centro Vocacional Tecnológico CVT APINAJÉ: Jovens e Mulheres

Data da aplicação/Date of application: ____/_____/___________

Responsável pela aplicação/ Responsible for the application: ________________________________

Assinatura do responsável /Responsable Signature:________________________________________

Local/Local: _____________, cidade/city:___________________________ Estado/State:___________

| PERSONAL DATA | |
|---|---|
| | |
| **Características socioeconômicas/SOCIO ECONOMIC CHARACTERISTICS** | |
| **Educação/ Education:** | [ ] Ensino fundamental incompleto (menos de 9 anos escola)/Incomplete Elementary School<br>[ ] Ensino fundamental completo (9 anos)/Complete Primary Education<br>[ ] Ensino médio incompleto/Incomplete High School<br>[ ] Ensino médio completo/Complete High School<br>[ ] Educação profissional técnica de nível médio/ Professional |

| | |
|---|---|
| | Technical Education – High School level<br>[ ] Ensino superior incompleto/Incomplete Higher Education<br>[ ] Ensino superior completo/Complete Higher Education |
| **Renda familiar/Family Income:** | [ ] Até 1 salário mínimo/Up to 1 minimum wage<br>[ ] 1 a 2 salários mínimos/from 1 to 2 minimum wages<br>[ ] 2 a 3 salários mínimos/2 to 3 minimum wages<br>[ ] 3 a 4 salários mínimos/3 to 4 minimum wages<br>[ ] acima de 4 salários mínimos/Above 4 minimum wages |
| **Produção principal na propriedade/Main production at the farm:** | [ ] arroz/Rice<br>[ ] Feijão/Beans<br>[ ] Mandioca/Cassava/Yuca<br>[ ] Milho/Corn<br>[ ] Leite/Milk<br>[ ] Porco/Pig<br>[ ] Frango/Chicken<br>[ ] Outro/Other:______________ |
| **RURAL SANITATION CHARACTERISTICS** | |
| **Água para a agricultura/Water for farming:** | **[ ] Encanada/Well**<br>**[ ] Captação de rio ou córrego/River capture**<br>**[ ] Abastecimento público/Supply network**<br>**[ ] Outro/Other: ___________** |

**Quantidade de água usada diariamente? How much water does your farm need per day?**

**De onde vem a água usada para as atividades rurais tais como irrigação e dessedentação de animais? Where does the water for farming activities such as irrigation and animals come from?**

[ ] rio/lago / river/lake [ ] poço artesiano/deep well [ ] cisterna/shallow well

**De onde vem a água para as atividades domesticas? Where does the water for domestic activities come from?**

[ ] rio/lago / river/lake [ ] poço artesiano/deep well [ ] cisterna/shallow well

**Qual tipo de cultura irrigada há na área rural? What type of irrigated culture the farm has?**

[ ] arroz/rice [ ] soja/soya beans [ ] cana-de-açúcar/sugar cane [ ] tomates/tomatoes

[ ] outro/Other: ____________________________________________________________

| | |
|---|---|
| **Destinação dos resíduos (lixo)/ Waste destination:** | [ ] Queima no local/ Burning on site |
| | [ ] Joga em lixão/Thrown in a waste dump<br>[ ] Joga no quintal/ Thrown in the backyard<br>[ ] Enterrado/ Buried<br>[ ] Outro / Other: _____________ |

**Faz separação do lixo? Do you separate the garbage?**

[ ] Sim/Yes [ ] Não/No

**Caso afirmativo, faz uso do resto de alimento para algum propósito? If yes, do you use leftover food for any purpose?**

[ ] Sim/Yes [ ] Não/No

**Em caso afirmativo, para qual fim? If yes, for what purpose?**

[ ] Compostagem/Composting [ ] alimento para animais/animal feed

[ ] Outro/other: _______________________________________________

**O que faz com os recicláveis tais como latas de alumínio, vidro e plásticos/ What do you do with recyclables such as cans, glas and plastic?**

[ ] Leva para pontos de coleta/take them to a collection point [ ] vende/sell them

[ ] Outro/other: ____________________________________________

**O que faz com as embalagens de pesticidas? What do you do with pesticide packaging?**

[ ] Logística reversa desde quando? _______________ e para onde ou quem?_____________________________________________________ Em inglês: Reverse logistic since when? _______ to where/whom? __________________

[ ] Descarta com o lixo comum/ Thrown them away with normal waste
[ ] Reusa as embalagens/ Reuse them

**Qual o destino dos resíduos perigosos tais como medicamentos, óleos, graxas, lâmpadas fluorescentes, bulbos de lâmpadas, baterias, pneus, eletrônicos? / Hazardous waste such as medicines, oils, greases, light, bulbs, batteries, tires, electronics, go to which destination/disposal?**

[ ] Descarta com o lixo comum/Thrown them away with normal waste
[ ] Leva para a reciclagem/ Take them to a recycling station
[ ] Outro/Other: _______________________________

**Esgoto doméstico/ Domestic sewage:**

**Água da chuva / Rain water:**

**Já teve algum problema com inundação na sua propriedade? Have you ever had any problems with flooding on the property?**
[ ] Sim/Yes [ ] Não/ No

**Retém a água da chuva ? Is rain water stored?**
[ ] Sim/Yes [ ] Não/ No

**Em caso afirmativo, o que tem usado? If yes, what it is used for?**
[ ] domestic use [ ] animal supply [ ] irrigation [ ] other: _______________

**De onde coleta a água da chuva? Where is the rain water harvested from?**
[ ] Telhados construídos/ building roofs [ ] solo ou terreno/ ground

[ ] Outro/other: ___________________________________

| CHALLENGES, OPPORTUNITIES AND FUTURE<br>Desafios, oportunidade e futuro | |
|---|---|
| **Quais 3 maiores desafios que tem na sua propriedade? What 3 main challenges do you face as a farmer?** | 1:____________________<br>2:____________________<br>3:____________________ |
| **Quais 3 oportunidades que vê para futuro? What 3 opportunities do you see for the future?** | 1:____________________<br>2:____________________<br>3:____________________ |
| **O que espera para seu futuro? What do you hope for in the future?** | |

| SPENDING | | |
|---|---|---|
| **Onde investiria R$ 1.000,00 na sua propriedade?<br><br>How would you divide 1000 Reas over the following farm related investments?** | **Novas ferramentas / New tools** | |
| | **Sementes / Seeds** | |
| | **Fertilizantes e herbicidas /Fertilisers and herbicides** | |
| | **Água/ Water** | |
| | **Manter infraestrutura na propriedade / Physical upkeep of buildings** | |
| | **Alimentação e cuidado animal /Animal food and care** | |
| | **melhorando sistemas antigos / Improving old systems** | |
| | **Trabalhadores/ workers** | |
| | **Outros / other:** | |
| | **Outros / other:** | |

| | |
|---|---|
| **Outros / other:** | |

## Appendix B: Interview Results

Table S.5 – Interview results, combined outcome of the challenges and opportunities open questions

| Challenges | Number of farmers with this challenge | | Opportunities | Number of farmers recognising this opportunity |
|---|---|---|---|---|
| Climate/weather | 3 | | Development of farm/settlement | 3 |
| Aligning production with demand | 3 | | Leverage the market | 2 |
| Electricity | 2 | | Legal documents for land | 1 |
| Work force | 2 | | Presenting products/fairs | 1 |
| Milk price | 2 | | Improving cooperative | 1 |
| Register land | 2 | | Financial support | 1 |
| Animal food price | 1 | | Development of farm/settlement | 3 |
| Investing/access to funds | 1 | | | |
| Managing finances | 1 | | | |
| Protect water | 1 | | | |

Table S.6 - Interview results, combined outcome of the waste and energy mapping exercise

| **Inputs** | **Number of farmers with this input** | **Additional notes on input** | | **Output** | **Number of farmers with this output** | **Notes on output** |
|---|---|---|---|---|---|---|
| Electricity | 9 | Electricity usually from grid | | Vegetables | 8 | |
| water | 9 | usually not for agriculture | | Milk | 4 | With only 2 that produce milk as their main income |
| Gas | 7 | Mostly for home cooking | | Eggs | 3 | Sometimes just for own consumptions |
| Fertiliser | 6 | of which 2 organic and self-produced | | Meat | 2 | Sometimes just for own consumptions |
| seeds | 3 | | | Dirty water | 2 | Disposed in environment |
| wood | 3 | Collected from nature | | Processed food | 2 | |
| animal food | 3 | Externally bought | | Fish | 1 | |
| Gasoline | 2 | For generator and vehicles | | Waste ashes | 1 | |
| Pesticides | 2 | | | Juice | 1 | |
| Diesel | 1 | For milking machine | | Sweets | 1 | |
| packaging | 1 | | | Yoghurt/butter | 1 | |
| | | | | Plant extract | 1 | |
| | | | | Bulls | 1 | |

## Appendix C: System Design

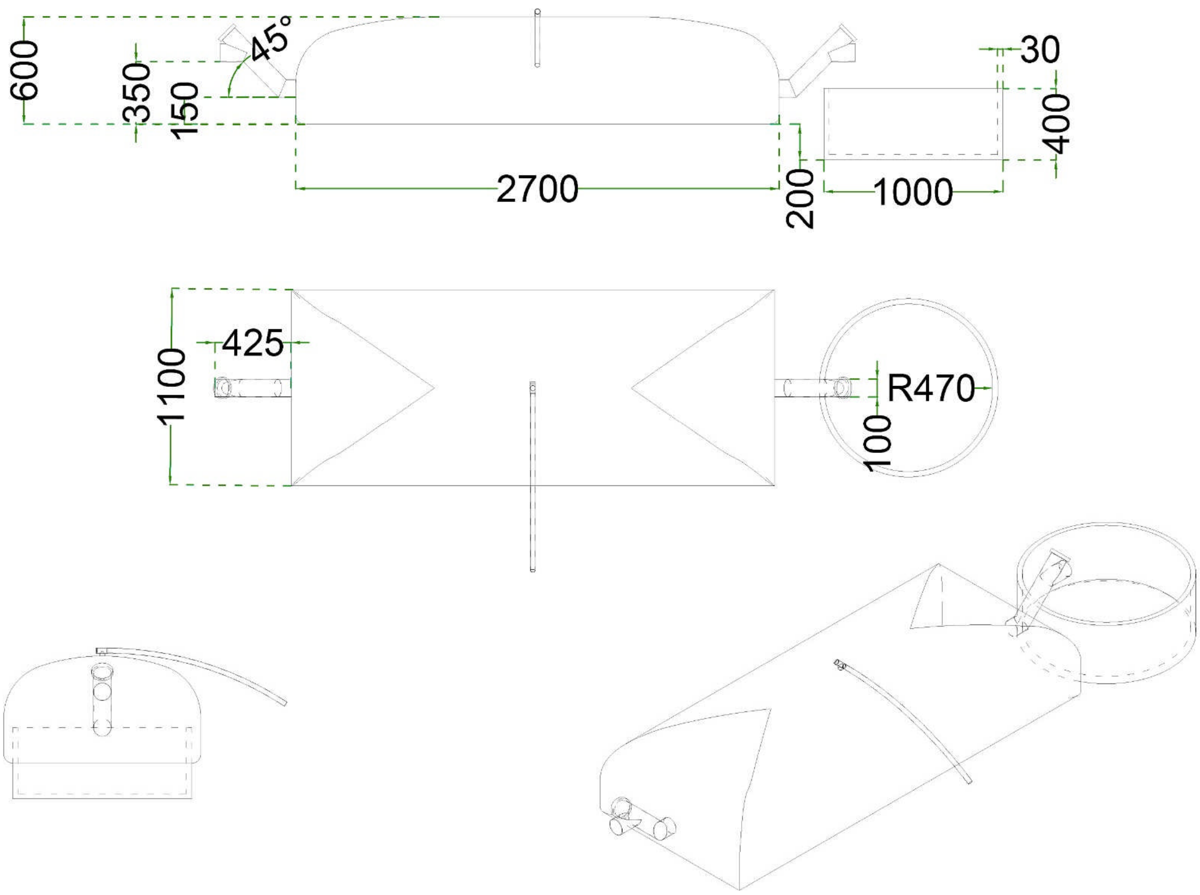


Figure S.9 - Technical drawing digester 1.5 m$^3$

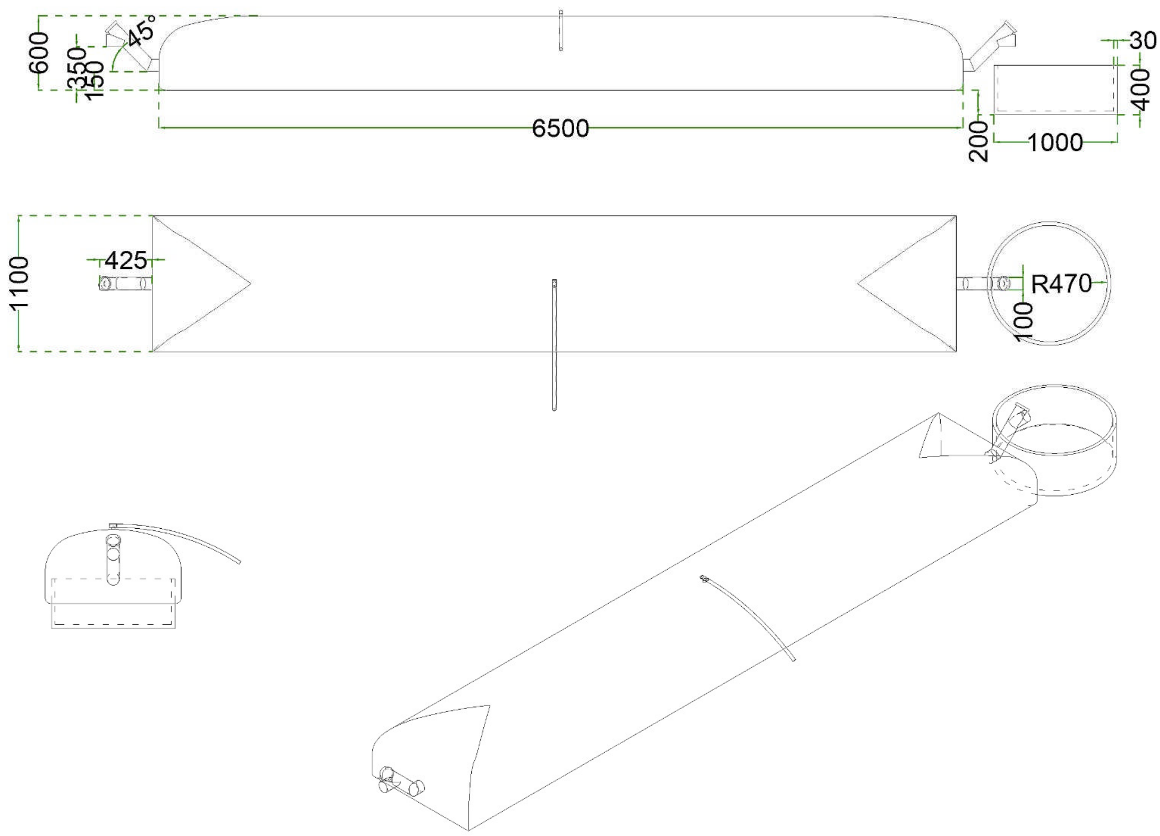


Figure S.10 - Technical drawing digester 3.7 m$^3$

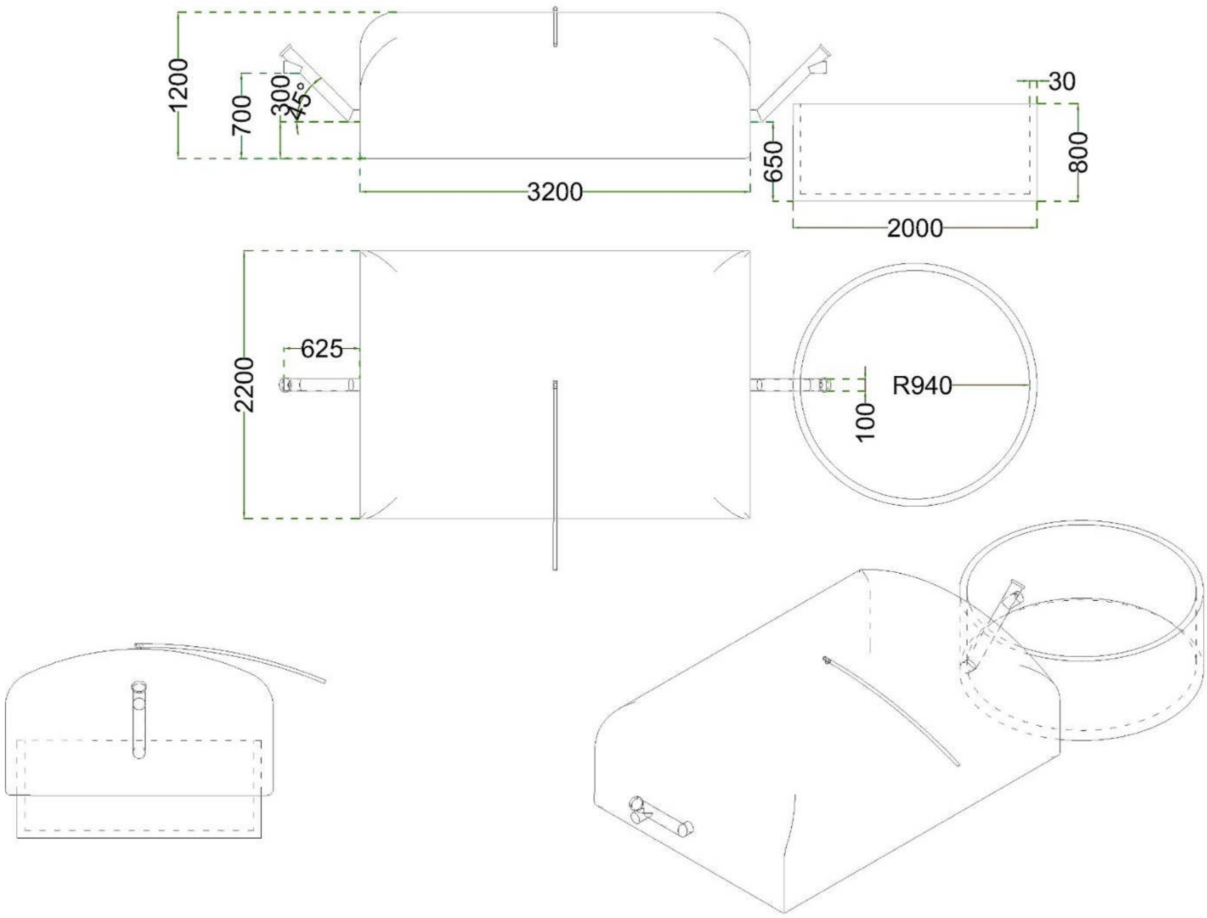


Figure S.11 - Technical drawing digester 7.5 m$^3$

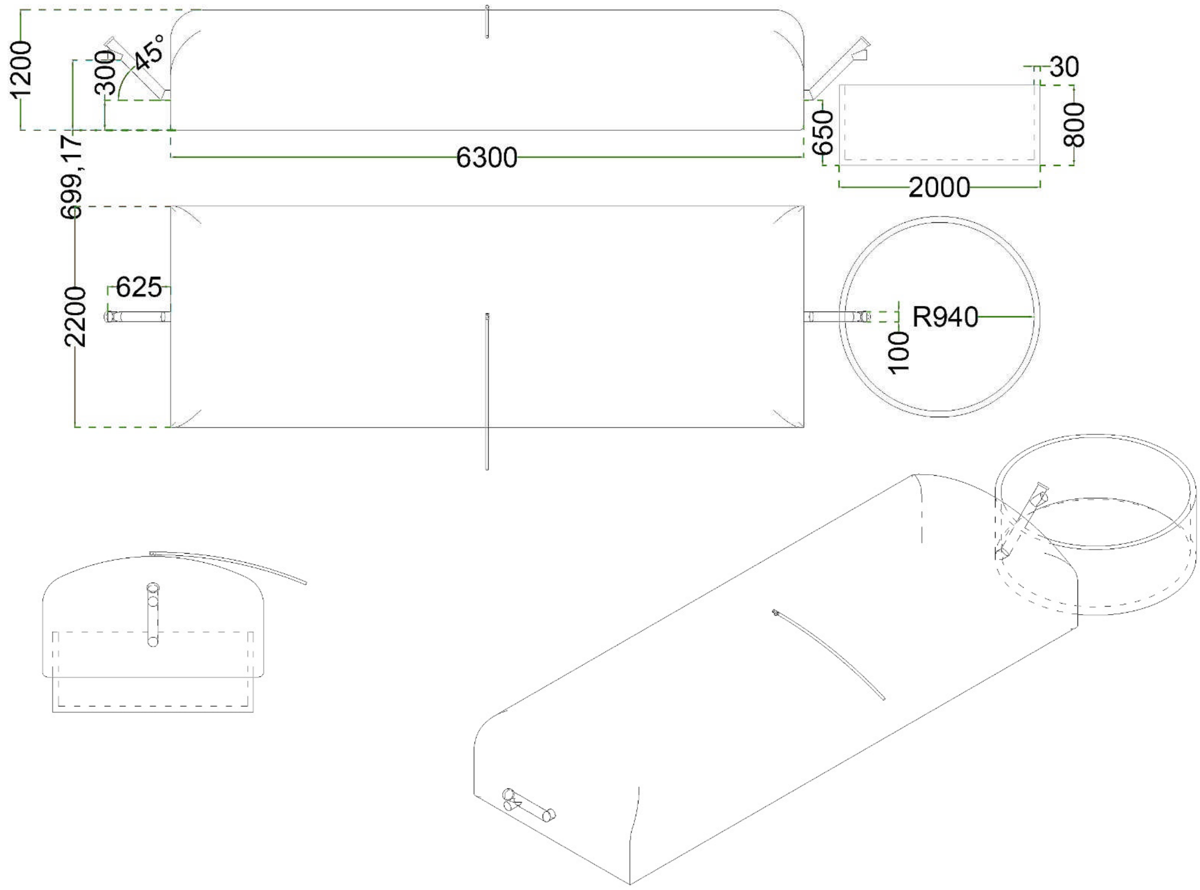


Figure S.12 - Technical drawing digester 15 m$^3$

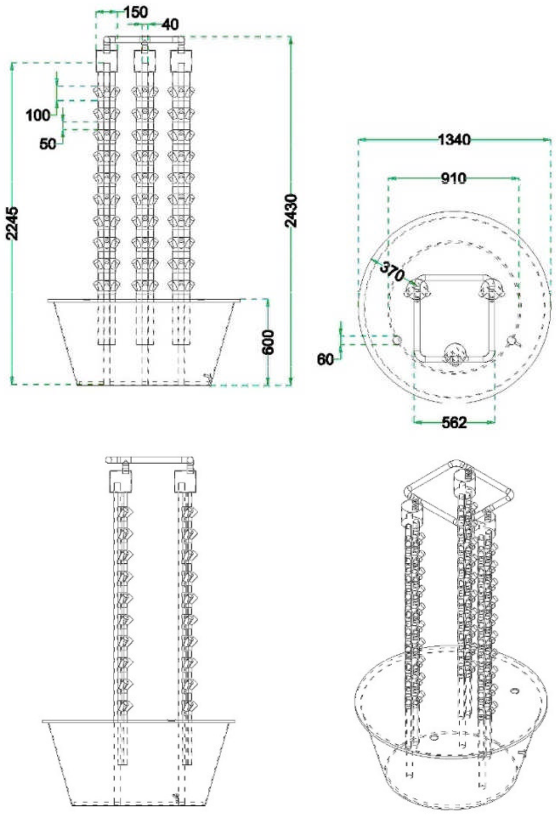


Figure S.13 - Technical drawing hydroponic unit

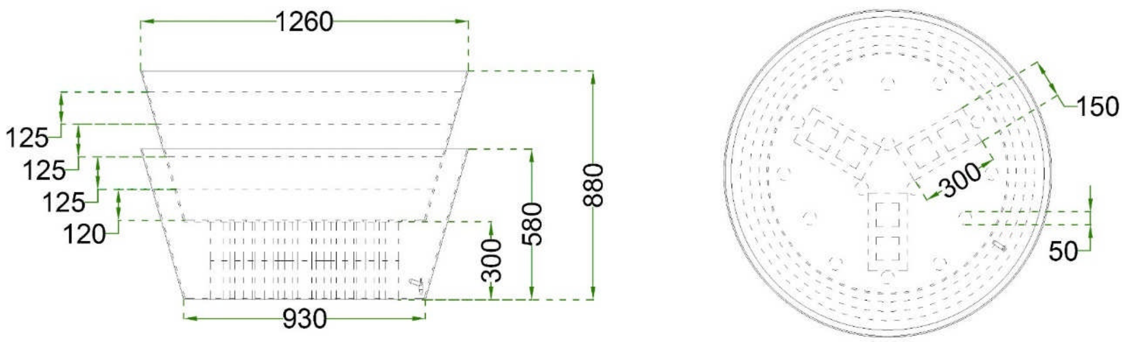


Figure S.14 - Technical drawing vermifilter unit

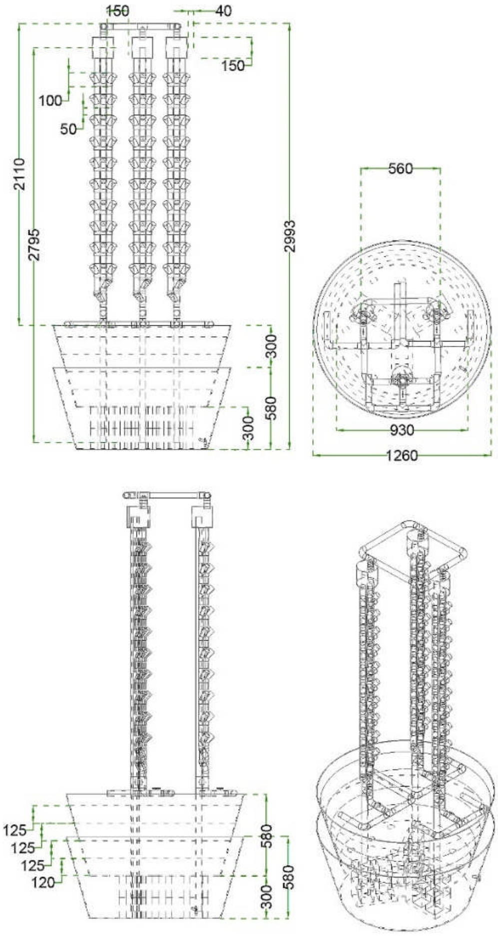


Figure S.15 - Technical drawing combined hydroponic and vermifilter unit

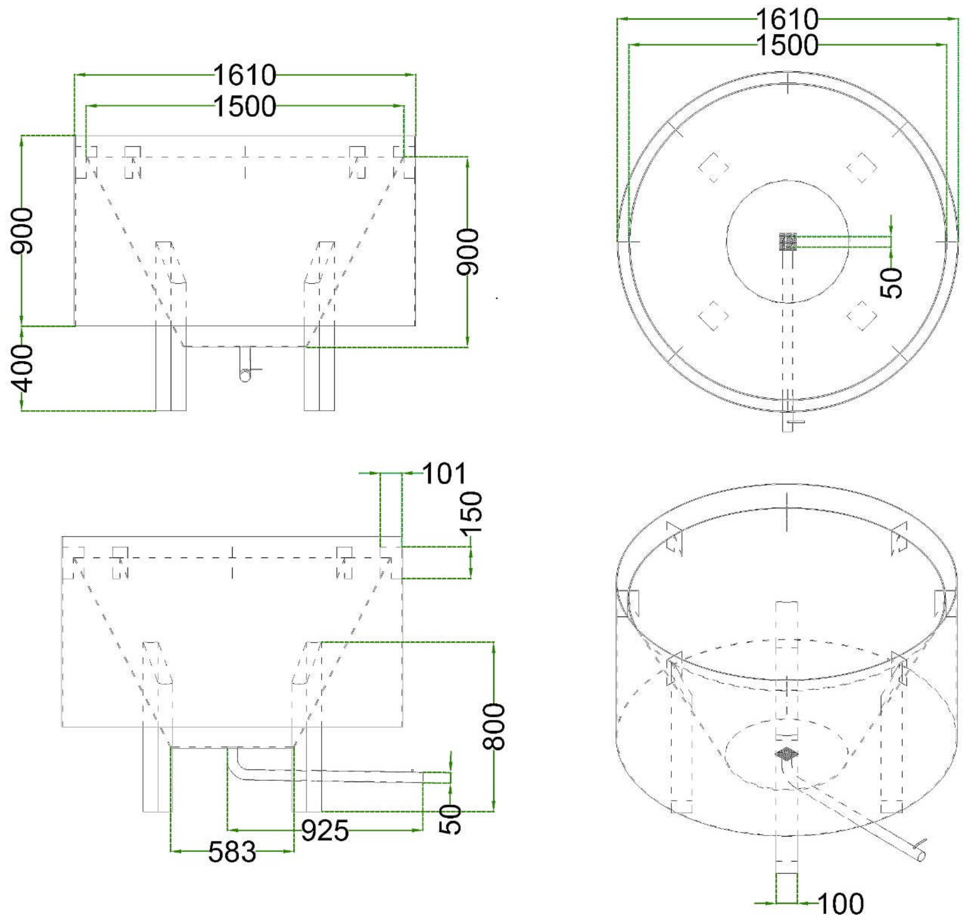


Figure S.16 - Technical drawing pyrolysis unit

# Appendix D: Material list

## 1. Pyrolysis for biochar

Table 7 - Material list pyrolysis for biochar

| Item # | Material/item | Purpose | Quantity | Cost per item (R$) | Total cost (R$) |
|---|---|---|---|---|---|
| | *Iron dome* | | | | |
| 1 | Steel sheet minimal 2200x1200mm (2 mm) | Cone main pyrolysis chamber | 2 | 310.24 | 620.48 |
| 2 | Steel sheet minimal 600x600 mm (2mm) | Bottom of the cone | 1 | 176.54 | 176.54 |
| 3 | Steel sheet minimal 2500x1000mm (0.7 mm) | Screen around the cone for wind management | 2 | 113.05 | 226.1 |
| 4 | Steel connectors | Attach cone to the screen | Waste pieces from item #01 | | |
| 5 | Steel mesh 70x70mm | Prevent biochar from draining away | 1 | | 0 |
| 6 | Steel bar 100x100x3200mm | Legs to hold reactor above the ground | 3 | 100 | 300 |
| | *Drain pipe* | | | | |
| 7 | Pipe 90cm (50mm) | Drain for flush water | 1 | 23.9 | 23.9 |
| 8 | Tap | To open and close the drain when | 1 | 34.9 | 34.9 |

| | | | | | |
|---|---|---|---|---|---|
| | | flushing | | | |
| | **Total** | | | | **1381.92** |

## 2. Hydroponic for wastewater treatment

Table 8 - Material list hydroponic unit for wastewater treatment

| **Item #** | **Material/item** | **Purpose** | **Quantity** | **Cost per item (R$)** | **Total cost (R$)** |
|---|---|---|---|---|---|
| **Hydroponic system** | | | | | |
| | *Bottom reservoir* | | | | |
| 1 | Water tank (500 L) | Reservoir | 1 | 159.9 | 159.9 |
| 2 | Wooden plate 1.4x1.4x.03 m (lxwxh) | Lid of reservoir | 1 | 100 | 100 |
| 3 | Flange adaptor (50 mm) | Openings for topping up and water level measuring | 2 | 12 | 24 |
| 4 | Float valve | For water level measuring | 1 | 15 | 15 |
| 5 | Wooden plate 0.9x0.9x.03 m (lxwxh) | Bottom anchor for towers | Included in item #02 | | |
| | *1 Tower* | | | | |
| 6 | PVC pipe 7m (40mm) | Back pipe, connectors between wyes and tees | 1.17 | 22.8 | 26.6 |
| 7 | PVC wye (40mm) | Plant holders | 30 | 2 | 60 |

| | | | | | |
|---|---|---|---|---|---|
| 8 | PVC pipe .15 m (150mm) | Main top reservoir | 1 | 9.5 | 9.5 |
| 9 | Pipe lid (150mm) | Close top reservoir bottom and top | 2 | 18.8 | 37.6 |
| 10 | Flange adaptor (40 mm) | Watertight openings in top reservoir for four openings | 4 | 10 | 40 |
| | *Total* | | | | 173.7 |
| | *3 complete towers* | | | | 532.5 |
| | *Top connection* | | | | |
| 11 | PVC 90-degree elbow (40mm) | Connectors for the top connection | 4 | 2 | 8 |
| 12 | PVC tees | Connecting top reservoirs with top connection | 3 | 2 | 6 |
| | *Pump system* | | | | |
| 13 | Pump | To pump the water upwards | 1 | 220 | 220 |
| 14 | Flexible tube | To pump the water through | 4 | 2.5 | 10 |
| | *Miscellaneous* | | | | |
| 15 | Coco coir | As substrate for the plants | 1 | 9.5 | 9.5 |
| 16 | Silicon glue | To use in case of leakages | 1 | 14 | 14 |
| 17 | Tie wrap | To reinforce the towers if necessary | 0.3 | 100 | 30 |
| | **Total** | | | | **1117.5** |

## 3. Vermifilter

Table 9 - Material list vermifilter

| Item # | Material/item | Purpose | Quantity | Cost per item (R$) | Total cost (R$) |
|---|---|---|---|---|---|
| **Vermifilter** | | | | | |
| 1 | Water tank (500 L) | Filter reservoir and water receptor | 2 | 159.9 | 319.8 |
| 2 | Concrete brick | To place one reservoir higher than the other | 6 | 2.6 | 15.6 |
| 3 | Gravel | Filter medium | 14 | 4.09 | 57.26 |
| 4 | Finer gravel (2 layers) | Filter medium | 28 | 4.09 | 114.52 |
| 5 | Topsoil | Filter medium | Partly comes with item #06 and can be collected in situ | | |
| 6 | Earthworms | To put in the topsoil | 8 | 89 | 712 |
| 7 | Wire mesh 1.25x1.25m | To keep the worms from going into lower layers | 2 | 39 | 78 |
| 8 | Pump | To pump the water upwards | 1 | 220 | 220 |
| 9 | Flexible tube | To pump the water through and distribute it over the surface | 4 | 2.5 | 10 |
| | **Total** | | | | **1297.18** |

## 4. Combined hydroponic and vermifilter system

Table 10 - Material list combined hydroponic and vermifilter system

| Item # | Material/item | Purpose | Quantity | Cost per item (R$) | Total cost (R$) |
|---|---|---|---|---|---|
| **Combined hydroponic and vermifilter system** | | | | | |
| | *Bottom vermifilter* | | | | |
| 1 | Water tank (500 L) | Reservoir | 2 | 159.9 | 319.8 |
| 2 | Concrete brick | To place one reservoir higher than the other | 6 | 2.6 | 15.6 |
| 3 | Gravel | Filter medium | 14 | 4.86 | 68.04 |
| 4 | Finer gravel (2 layers) | Filter medium | 28 | 4.09 | 114.52 |
| 5 | Topsoil | Filter medium | | | 0 |
| 6 | Earthworms | To put in the topsoil | 8 | 89 | 712 |
| 7 | Wire mesh 1.25x1.25m | To keep the worms from going into lower layers | 2 | 39 | 78 |
| | *1 Tower* | | | | |
| 8 | PVC pipe 8m (40mm) | Back pipe, connectors between wyes and tees | 1.3 | 22.8 | 30.4 |
| 9 | PVC wye (40mm) | Plant holders | 30 | 2 | 60 |
| 10 | PVC pipe .15 m (150mm) | Main top reservoir | 1 | 9.5 | 9.5 |

| | | | | | |
|---|---|---|---|---|---|
| 11 | Pipe lid (150mm) | Close top reservoir bottom and top | 2 | 18.8 | 37.6 |
| 12 | Flange adaptor (40 mm) | Watertight openings in top reservoir for four openings | 4 | 10 | 40 |
| | *Total* | | | | 177.5 |
| | *3 complete towers* | | | | 543.9 |
| | *Top connection* | | | | |
| 13 | PVC 90-degree elbow (40mm) | Connectors for the top connection | 4 | 2 | 8 |
| 14 | PVC tee (40mm) | Connecting top reservoirs with top connection | 3 | 2 | 6 |
| | *Vermifilter spreading tubes* | | | | |
| 15 | PVC pipe (40mm) | Form network for water distribution over vermifilter | 1 | Included in item #08 | |
| 16 | PVC tee (40mm) | | 9 | 2 | 18 |
| 17 | PVC 45-degree elbow (40mm) | | 6 | 2 | 12 |
| 18 | PVC 90-degree elbow (40mm) | | 9 | 2 | 18 |
| 19 | PVC wye (40mm) | | 6 | 2 | 12 |
| 20 | PVC tap switch (40mm) | To switch the water from going to the vermifilter or straight to the bottom reservoir | 3 | 19.45 | 58.35 |
| | *Pump system* | | | | |
| 21 | Pump | To pump the water upwards | 1 | 220 | 220 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 22 | | Flexible tube | To pump the water through | 4 | 2.5 | 10 |
| | *Miscellaneous* | | | | | |
| 23 | | Coco coir | As substrate for the plants | 1 | 9.5 | 9.5 |
| 24 | | Silicon glue | To use in case of leakages | 1 | 14 | 14 |
| 25 | | Tie wrap | To reinforce the towers if necessary | 0.3 | 100 | 30 |
| | **Total** | | | | | **2256.31** |