Pineapple residues for high quality fiber and other applications

With a case study from Costa Rica

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This report describes pineapple residues as potential feedstock for new carbon-based materials, especially the use of pineapple leaf fiber (PALF) in textiles. Using Costa Rica as a case study, five application domains of residues are identified. Cascading of different valorization options has the potential to increase resource use efficiencies and to reinforce the economic viability of individual valorization options. Various bottlenecks hampering a biomaterial transition in Costa Rica are identified, and a R&D agenda to address these bottlenecks.

Keywords: bioeconomy, biomaterial, PALF, bio-based economy, materials transition

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Preface

This report is written within the WUR investment theme ‘Transformative Bioeconomics: Towards a materials transition that phases out fossil feedstock’. Although WUR has worked on supporting systems transitions for some time already, this investment theme connects different scientific fields in WUR that so far operated largely independent of each other. In this way the investment theme Transformative Bioeconomics builds upon and strengthens the broad experience available within WUR on systems transitions.

The project call in 2022 of the investment theme Transformative Bioeconomics specifically focused on innovative, ground-breaking and high-risk ideas with an explorative character in the field of textiles. Globally, approximately 100 Mton textile of fibers are produced annually. After plastics (over 360 Mton per year) it is the second largest domain of carbon-based materials. Currently, 60% of all textiles are fossil based (mainly polyester), and the 40% biobased part is mainly cotton, which has a large ecological footprint. New resources or revisited resources that can be used in textiles are presently under development.

The idea of the topic of this report was already borne in 2018 when Wageningen Plant Research and Wageningen Food and Biobased Research carried out a diagnostic study related to problems of the Costa Rican pineapple industry dealing with the sustainable discharge of crop residues. Findings of that study suggested possible win-wins by using the residues in the bioeconomy. The WUR investment theme Transformative Bioeconomics provided an opportunity to study in-depth the possibilities to use the fibers of and other components of the pineapple leaves in the bioeconomy. This report is the result of that study.

Summary

This report describes the case of pineapple residues as potential feedstock for new carbon-based materials, especially the use of pineapple leaf fiber (PALF) in textiles. Currently, pineapple crop residues are an environmental burden and their discharge an important cost for the pineapple industry in many tropical countries. The use of pineapple residues as feedstock for biomaterials could create potentially a win-win situation: The pineapple industry can add value to crop residues that are currently a costly waste, while the residues provide a valuable feedstock for various biomaterials contributing to the bioeconomy.

Using Costa Rica as a case study, the objectives of this study were to:
1. Identify pineapple residue valorization options with a focus on the characteristics of PALF for textiles.
2. Estimate the amount of pineapple residues potentially available for PALF.
3. Better understand the agronomic, technical, economic, social-institutional bottlenecks hampering the transition towards a biomaterial transition.
4. Identify follow-up R&D tracks to deal with the identified bottlenecks with focus on the total use of pineapple residues.

This study identifies five major application domains for pineapple residues, i.e., fibers (including PALF for textile), chemical compounds, animal feed, substrate, and energy. Because only 10-20% of the dry matter of the pineapple leaves consists of PALF the remaining residual biomass will also have to find an application (in the bioeconomy) for enhancing the economic viability and optimizing the sustainable use of PALF in the textile and apparel industry. Cascading of different valorization options may increase the resource use efficiency and the economic value of the pineapple residues.

Current management costs of pineapple residues in Costa Rica varies between 32 and 81 USD/ton dry matter. The amounts of crop residues and PALF that each year come available after the second harvest of pineapples in Costa Rica are large enough for scalable solutions. We estimate that annually ≈ 620,000 t dry matter of crop residues is available for valorization options, which contains about 45,800 and 91,600 t PALF per year. At the same time, biogas (LPG) can be generated from the crop residues in an amount sufficient to meet about 13% of the national LPG requirements per year, which is currently based for 100% on imports.

Despite the large amount of biomass available and the need for more environmental-friendly ways to dispose pineapple residues up to date there are no large-scale initiatives to bring any of the identified valorization options to scale in Costa Rica. There is even less attention for the cascading of different valorization options, which have the potential to reinforce the economic viability of individual valorization options. Four interrelated bottlenecks are identified that hinder valorization developments in Costa Rica: i) The failure to account for the true costs of current residue management, which slows down the industry’s response to develop alternative ways to dispose the residues; ii) Lack of basic knowledge and information about material properties needed to assess the technical feasibilities, market potential, etc. of valorization options; iii) related, is the lack of sound business models; and iv) the role of the Government and institutions hampering the energy production from pineapple residues as an important valorization option to increase their economic value.

Potential follow-up R&D tracks to use of pineapple residues as feedstock for biomaterials are:
- Development of topical knowledge and technologies to increase innovation readiness of pineapple valorization options.
- Development of models to assess and quantify resource use efficiencies and economic benefits of cascading different valorization options for pineapple residues.
- A public-private partnership to develop a joint strategy (roadmap) towards the valorization of pineapple residues. Such a strategy is needed to mobilize private and public funding for large-scale investments, and to change current legislation and institutions facilitating the valorization of pineapple residues for a biomaterial transformation.

1 Introduction

One of the biggest challenges that our society faces nowadays is to phase out fossil fuels. This means a transition towards renewable energy systems, but also a transition towards renewable carbon-based materials. Currently, many materials used in textile, packaging, car and construction industries are made from fossil energy sources. Therefore, the energy transition also means a search for sufficient feedstock with the required qualities for new fossil-free biomaterials to be used in various industries and contributing to the bio-economics and transition of society. Fortunately, large amounts of agri-residues are produced which are considered a nuisance and for which added value applications are needed.

This report describes the case of pineapple residues as potential feedstock for new carbon-based materials. Pineapple crop residues are an environmental burden and their discharge an important cost factors for the pineapple industry in many tropical countries. Currently, pineapple residues are burned in the field or incorporated in the soil after frequent shredding operations, which is a time-consuming process because of the large volume of residues and the slow decomposition of the fibrous crop biomass. In the process herbicides are used to speed up the biomass decomposition and pesticides to control the larvae of the bloodsucking stable fly (*Stomoxys calcitrans*) that feeds on the decomposing residues. This stable fly is a risk for nearby cattle farms as it can infect their animals. The current way of residue disposal is expensive, time-consuming, damaging the environment and a risk for neighbouring cattle farms. More sustainable alternatives need to be developed.

The use of pineapple residues as feedstock for biomaterials could create potentially a win-win situation: The pineapple industry can add value to crop residues that are currently a costly waste, while the residues provide a valuable feedstock for various biomaterials contributing to the bioeconomy. Pineapple crop residues contain many components that have a potential application in the bioeconomy. This study focusses specifically on the pineapple leaf fibres (PALF) as potential feedstock to be used in the textile and apparel industry. Yet, we address the use of PALF for other biomaterials and other components of the residues because only 10-20% of the dry matter of the pineapple leaves consists of PALF. The remaining residual biomass will also have to find an application (in the bioeconomy) for enhancing the economic viability and optimizing the sustainable use of PALF in the textile and apparel industry. We will introduce a methodological framework, that uses a hierarchical approach to use resources, i.e., pineapple crop residues in this case, as efficiently as possible (Elbersen et al., 2022; Sirkin & Houten, 1994). We will use this framework to illustrate the use of different components of pineapple residues and subsequently zoom in on the characteristics and use of PALF for textiles and the leather industry. The technical, economic and social-institutional and economic barriers are identified that hamper the value addition to the pineapple crop residues in a biobased economy. Finally, we propose various solutions to deal with the identified bottlenecks with focus on the total use of pineapple residues.

We analyse the case of pineapple residues in Costa Rica, responsible for almost 50% of the global pineapple trade of fresh pineapple, for the textile and apparel industry to better understand required system changes and pathways towards transformations needed in a bioeconomy. The pineapple case serves as an example for other cases where crop residues have the potential to be used for textile feedstocks and face similar obstacles for implementation.

1.1 Objectives of this report

The objectives of the study are to:

1. Identify pineapple residue valorization options with a focus on the characteristics of PALF for textiles.
2. Estimate the amount of pineapple residues potentially available for PALF in Costa Rica.
3. Better understand the agronomic, technical, economic, social-institutional bottlenecks hampering a biomaterial transition with pineapple crop residues in Costa Rica.
4. Identify a follow-up R&D agenda to deal with the identified bottlenecks in Costa Rica.

1.2 Readers' guide

The report is structured as follows. First, we describe the context of pineapple production and the problems with the management of pineapple residues in Costa Rica. Based on this description we estimate the amount of pineapple residues potentially available in Costa Rica each year.

In Chapter 3 we give a global overview of the different potential applications of pineapple residues in the bioeconomy. We also make a plea for the cascading of different application options as this would increase the sustainability and efficiency of any valorizing option of pineapple crop residues.

Based on a literature review, Chapter 4 characterizes PALF and describes the state of the art of the processes needed from harvesting the crop residues till the spinning of PALF. We compare the characteristics of PALF with those of other natural fibers, and we estimate the annual amount of PALF potentially available in Costa Rica.

Chapter 5 describes four major bottlenecks that hinder the valorization of pineapple residues, i.e., lacking information on the true costs of current pineapple crop residue management; ii) lacking disciplinary knowledge for further developing specific valorization options; iii) lacking sound business models allowing investors to step in the development of valorization options; and iv) lacking enabling environment to stimulate the development of valorization options.

Th last Chapter 6 draws some conclusions based on the major findings of this study and identifies three follow-up R&D tracks contributing to the use of pineapple residues as feedstock for biomaterials in the future.

2 Pineapple production in Costa Rica

2.1 Introduction

Costa Rica is the largest exporter of fresh and dried pineapple in the world[1]. The Netherlands is the largest importer in the EU of pineapples from Costa Rica. With an export value of about 1 billion USD in 2021 and providing 28.000 direct employment positions and 105.000 indirect employment the pineapple industry is of major socio-economic importance for Costa Rica [2]. About 40,000 ha pineapples were harvested in 2020, mainly in the North and Northwest of country, but about 22% of the total harvested production area is located in the Southeast, in the Pacific region (Figure 1).

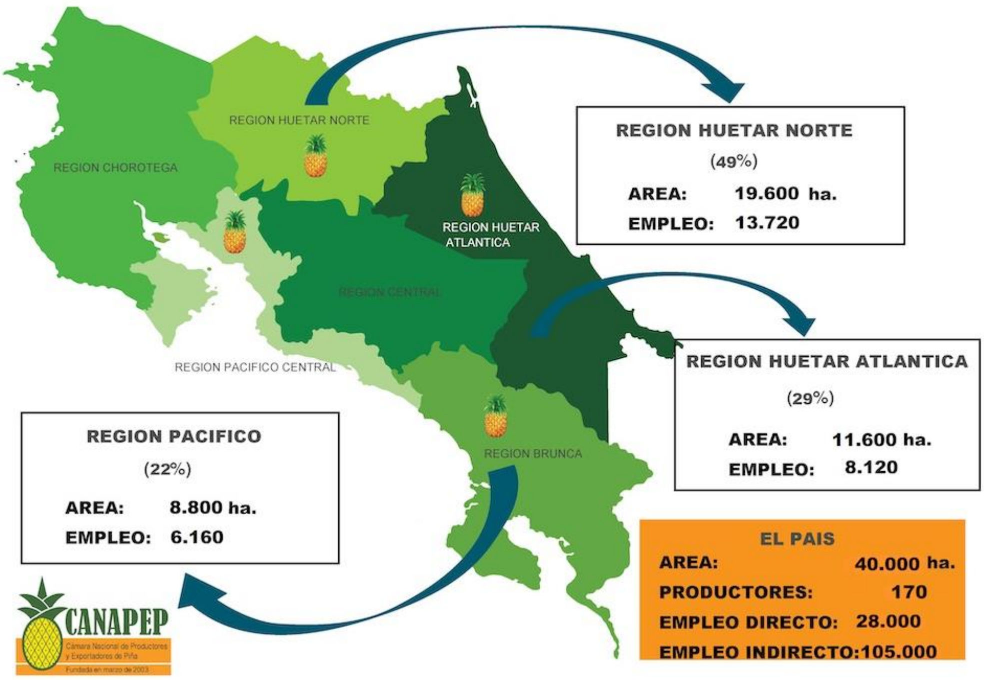

Figure 1 *Distribution of the pineapple harvested area in Costa Rica. Source: CANAPEP.*[3]

Pineapples are grown in monocultures with high levels of mechanization and inputs to satisfy international market requirements for fruit uniformity. Pineapple crops typically produce one fruit, at about 12-15 and another fruit 24-27 months after planting. Average fruit yields are about 90,000 kg/ha (first harvest) and about 65,000 kg/ha in the ratoon crop (second harvest). In addition to the high fruit yield, the crop produces a large amount of crop residues. After the second fruit harvest these crop residues, about 250 t fresh matter/ha, need to be discharged as soon as possible to enable soil preparation and crop replanting using vegetative plant material such as lateral shoots, basal suckers or fruit crowns.

1 https://oec.world/en/profile/hs/pineapples-fresh-or-dried#:~:text=In%202019%2C%20Pineapples%2C%20fresh%20or,0.013%25%20of%20total%20world%20trade. [Accessed September 21, 2022].
2 https://canapep.com/. [Accessed September 21, 2022].
3 See footnote 2.

2.2 Current crop residue management

The pineapple industry in Costa Rica has been subject of various public debates related to the compliance of labor rights, occupational health risks and environmental issues (Echeverría-Sáenz et al., 2012; Ingwersen, 2012). The industry is under continuous pressure from local communities, national authorities and international markets to implement more sustainable practices. One of the main debates focusses on the management of the crop residues. Basically, there are two methods currently used to discharge the crop residues after harvest of the ratoon crop (Figure 2):

a. Mechanized shredding of the green biomass in smaller pieces, which are subsequently incorporated in the soil with a rotor tiller or cultivator. Optionally, the shredded biomass is sprayed with microorganisms to accelerate the biomass decomposition. Yet, two to four shredding passes are required because of the large volume and firmness of the biomass. This is a costly operation associated with the machine costs (mechanical wearing of the tiller/cultivator blades [4]) and fuel costs.
b. The use of herbicides to eradicate the crop, often in combination with burning for which formally permission is needed from the Phytosanitary Service of the Ministry of Agriculture. Because of waxy and cellulose rich leaves high doses of herbicides need to be used, often herbicides that are banned in the EU such as paraquat. However, even with these harmful herbicides it takes two to three months before the crop is sufficiently decomposed to be incorporated in the soil, frequently after burning. Obviously, burning of the crop residues results in air pollution and poses a fire risk.

Independent of these two predominantly used discharge methods, the sugar-rich decomposing biomass in combination with abundant rainfall and high temperature provides a perfect substrate for the development of the larvae of the blood-sucking stable fly (*Stomoxis calcitrans*). Nearby cattle farms are invaded with swarms of these flies, which turn their cows lethargic, unwilling to eat, and affecting milk production. Furthermore, their injuries can be infected and provide entry points for viruses and bacteria. Therefore, pineapple farmers need to apply insecticides to control the larvae of the stable fly, which adds to costs and environmental concern.

Figure 2 *Different discharge methods of pineapple residues after the fruit harvest currently used in Costa Rica: Killing of the residues with herbicides followed by soil incorporation (left pane), several operations to shred the green residues followed by soil incorporation (centre pane) and landfilling as a last resort when stable fly densities are high (right pane). (Picture on right: Silvia Fernandez Gonzalez).*

Despite the use of insecticides, the control of the stable fly in pineapple residues remains difficult. The extent of stable flies nearby pineapple farms is closely monitored by the Phytosanitary Service of the Ministry of Agriculture (Figure 3). In cases that the control of stable flies fails, pineapple producers are urged by the Phytosanitary Service of the Ministry of Agriculture to bury the pineapple residues (Figure 2). This practice is costly for producers and generates methane, a 30 times more powerful GHG gas than CO_2.

[4] Commonly shredders are used that have been developed for shredding woody biomass, which indicates the difficulty to cut the pineapple biomass in small pieces.

Figure 3 *Monitoring of stable flies nearby pineapple farms using sticky white sheets.*

Current residue management poses a serious threat for the pineapple industry as it affects the environment (soil, water and air contamination) through the use of herbicides and insecticides, threatens the health of animals at nearby cattle farms, increases the production costs of pineapple farmers, and thus is a risk for the sustainability of the industry at large. Costs of current management methods have been estimated at 1,000 - 2,500 USD/ha depending on the method and local conditions (Hernández Chaverri & Prado Barragán, 2018). These costs do not include the costs associated with the wearing of the machinery for shredding the fibrous pineapple residues nor the time that the land is idle and cannot be cultivated and the damage to nearby livestock farms caused by the stable fly. In addition, environmental costs, for example, the pollution with pesticides of nearby aquifers used for drinking water and GHG emissions are not accounted for. Equally important is that still herbicides are used to eradicate the pineapple residues such as paraquat that is banned in the EU since 2007. This fuels the sustainability debate around pineapple production and may harm the export of pineapple to the EU, which is one of the major export areas of pineapples produced in Costa Rica.

2.3 Available pineapple residues and their costs

The pineapple residues are commonly named 'rastrojo' (in Spanish) which is translated as pineapple stubble. This fraction includes the leaves, stem, shoots and roots that remains in the fields after harvesting the pineapple (Alfaro, 2012). In some publications 'rastrojo' only refers to the stems, shoots and leaves (López-Herrera et al., 2009). Here, we refer to crop residues, which includes the leaves, shoots and stems of the pineapple crop.

We use the following information and assumptions to estimate the amount of crop residues available annually in Costa Rica for valorization purposes:

- The amount of residual biomass depends on the planting density and production situation, but in most of the literature it ranges between 200-300 tons fresh matter (Alfaro, 2012; Hernández Chaverri & Prado Barragán, 2018; Quesada et al., 2005; Rodríguez-Chacón et al., 2014).
- Dry matter content of the crop residues varies in the literature between 10 and 15% (López-Herrera et al., 2009)(López-Herrera et al., 2014; Moya et al., 2015; Quesada et al., 2005)(Rodríguez-Chacón et al., 2014).
- In 2019, there were 65,442 ha of pineapples in Costa Rica according to the Sistema Nacional de Informacion Teritorial (SNIT [5]). In 2020, 40,000 ha of pineapples were harvested in Costa Rica (FAOSTAT [6]). Combination of both data sources suggest that about one third of the total area was not productive (period after last harvest and before first harvest), while about half of the harvested area was

[5] https://www.snitcr.go.cr/Visor/index2019?p=cHJveWVjdG86OnBhaXNhamVzcHJvZHVjdGl2b3M= [Accessed October 25, 2022].
[6] https://www.fao.org/faostat/en/#data/QCL [Accessed September 21, 2022].

the first harvest and the other half was the ratoon harvest. This means that about 20,000 ha with crop residues is potentially available each year for valorization purposes.

- For the dry matter distribution between leaf and stem we use data from the pineapple cultivar Josapine, showing that 74% of the aboveground residues ends up in the leaves and 26% in the stem (Hanafi & Halimah, 2004). [7]

Based on the range of fresh matter yields in the literature and dry matter content of residues, dry matter yields of the pineapple residues vary between 20 and 45 t/ha, with an average yield of 31 t/ha. An area of 20,000 ha needs to be replanted each year, which implies that 620,000 t dry matter is potentially available of which approximately 458,800 t of dry matter leaves, which contain fibers for the textile industry. This estimation of the annual dry matter residue production (620,000 t) corresponds well with the 642,300-t dry matter estimated by (Hernández Chaverri & Prado Barragán, 2018a) using different data.

Pineapple is produced in the different regions of Costa Rica (Figure 1). Especially, the traditional pineapple area in the Pacific region around Perez Zeledon in the Southwest of Costa Rica, with approximately 9,000 ha of pineapple is quite far from the other major production areas in the North and North-west of the country. Transport costs of the fresh pineapple residues to a central processing unit increase with distance. On-farm (pre-)processing of the leaves may reduce transport costs and actually will be required to be able to collect and transport the leaves/fiber for further processing in an economically viable way.

Based on the average crop residue yield of 31 t/ha and current cost of crop residue management, ranging between 1,000 and 2,500 USD/ha (Hernández Chaverri & Prado Barragán, 2018), current management cost per ton dry matter crop residues is between 32 and 81 USD.

[7] In Costa Rica the most common pineapple variety cultivated is MD2.

3 Valorization options of pineapple residues

Recently, various studies based in different disciplines have investigated the valorisation of pineapple residues. Some of the studies are at laboratory scale, others at pilot scale, but none of the investigations have yet led to a scalable process to valorise pineapple residues. Without pretending to give a complete review the following gives a global overview of the major pineapple residue applications that have been studied and reported in the literature recently, i.e., fibers, chemical compounds, animal feed, substrate, and energy. In section 3.6 we address the potential effects of valorizing pineapple residues for the soil organic matter and nutrient status. In section 3.7 we introduce the concept of cascading different valorization options to increase the sustainability and efficiency of the valorization of biomass for the bioeconomy.

3.1 Fibers

Pineapple crop residues, both the leaves and stems, are fibrous. The literature has published several studies on pineapple fiber extraction and use for paper, rope and textile.

Both Moya et al. (2016a) and Sibaly & Jeetah (2017) concluded that PALF can be used for producing low quality paper, and if mixed with fillers higher quality paper can be produced.

The application of fibers from pineapple leaves into rope was aimed at substituting polypropylene rope that is commonly used in the pineapple industry. Students from the University of Costa Rica showed on a pilot scale the feasibility of producing rope from pineapple leaves [8]. Although the economic, social and environmental benefits are clear of using biodegradable rope in the pineapple industry, much more leave biomass (PALF) is available than needed by the industry.

Most developed and exploited already on commercial scale are pineapple fibers for the textile and apparel industry. The English based Ananas Anam company produces pineapple fibers from the Philippines to produce the patented Piñatex. This so called 'vegetable leather' is especially aimed at the substitution of animal leather, whose production is environmentally unfriendly [9]. Piñatex contains a corn-based polyactic acid and 5% fossil fuel resins according to an interview with the founder of Ananas Anam [10]. Through smart branding, Piñatex is put into the higher market segment as an eco-friendly alternative to animal leather. Various others have studied the use of PALF in reinforced polymeric composite materials (Kengkhetkit and Amornsakchai, 2014). In Thailand this material is being investigated as reinforcement / substitution of rubber and fossil-based plastics and it has been coined 'Zuppar' [11].

The Philippines as major pineapple producing country has experience in using the pineapple fiber for making clothing. Through an extremely labor-intensive process very fine pineapple fibers are produced to weave traditional clothing [12]. A more mechanized process, but still requiring a lot of manual labor, for extracting and using pineapple leave fibers for textile has been described recently for Indonesia (Hayu Puspasari Saputri, 2021).

Chapter 4 describes and discusses more in detail the fiber characteristics for textile purposes.

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8 https://www.ucr.ac.cr/noticias/2020/12/21/estudiantes-proponen-aprovechar-desechos-de-la-pina-para-crear-cuerda-de-uso-agricola.html [accessed September 23, 2022].
9 https://www.ananas-anam.com/about-us/ [accessed September 23, 2022].
10 https://www.youtube.com/watch?v=j9KtxgdL95U [accessed September 23, 2022].
11 https://www.youtube.com/watch?v=rJuv8KUnnrA [accessed September 23, 2022].
12 https://www.youtube.com/watch?v=yRvWiiGoOzI [accessed September 23, 2022].

3.2 Chemical compounds

Various chemical compounds in the pineapple residues have been described in the literature that potentially can be exploited and valorized. Here some of the compounds and their potential use are summarized.

One the most referenced chemical compounds is bromelain, which is an enzyme that breaks down proteins and is used in industrial processes such as meat tenderizer or clarifier in the production of craft beers (Upadhyay et al., 2010). Supposedly, bromalin also has anti-cancer properties (Chobotova et al., 2010). Highest bromelain contents are found in the fruit stem and fruit residues, not in the leaves.

Nanocellulose are materials with a dimension of 100 nm or less with extremely high specific area, lightweight, and high biodegradability. Typically, three forms of nanocellulose are identified, Cellulose Micro Fibrils (CMF), Cellulose Nano Fibrils (CNF), Cellulose Nano Crystals (CNC). Its main commercial use is in producing paper and textiles, but it has many other potential uses such as the reinforcement of plastics, thickeners, flavor carriers, and suspension stabilizers in a wide variety of food products, applications in emulsion and dispersion, cosmetics and pharmaceuticals to name a few. Current research in Costa Rica focuses on extracting nanocellulose from pineapple peels. Despite the promising technical benefit of nanoparticles in general, there are societal concerns associated with their use including the lack of accurate risk assessments and management of nanomaterials and the lack of reliable exposure and toxicity data (Calderón-Jiménez et al., 2017).

3.3 Animal feed

Pineapple leaves can be used as animal feed for ruminants. López-Herrera et al. (2009, 2014) analysed the feeding value of different parts of the pineapple plant (and in silage forms) as animal feed and concluded that the energy and nutrient content is sufficient to allow their use as part of the total daily ration in ruminant feeding, without having noticeable adverse effects on productive performance. The studies did not analyse palatability of the feed by ruminants. Pineapple forage is highly fibrous (Neutral Detergent Fiber content is 58-73% of the dry matter) with a low crude protein content (4 to 7% of the dry matter) [13]. Pineapple leaves are considered a medium-quality roughage for ruminants and pesticide residues in fresh residues (leaves) are mentioned as threat as they may end up in the cow milk (see also footnote 13). During the production of pineapple many different pesticide types are used in large quantities resulting in environmental concern (Obando, 2020).

For silage, pineapple leaves are relatively wet, and dehydration of the biomass is a difficult process under the wet conditions where pineapple is grown in Costa Rica (3,000 – 5,000 mm per year with no distinct dry season). Currently, one pineapple producer makes fresh silage from the residues and sells these in plastic bags to cattle farmers (Figure 4).

[13] https://www.feedipedia.org/node/675 [accessed September 30, 2022].

Figure 4 *Preparation of fresh silage from pineapple crop residues and the bags with silage of the pineapple producer Fruit point. (Pictures: Silvia Fernandez Gonzalez).*

A relatively new approach is the of use agricultural waste for the production of insect larvae that can serve as animal feed [14]. Currently, especially soldier fly larvae (*Hermetia illucens*) are produced using waste streams. Research is needed to assess whether pineapple residues are a suitable substrate the production of this or other insects. Current understanding is that the stable fly (*Stomoxis calcitrans*) especially is producing larvae in the stem. If the pineapple stems can be used to growth soldier fly larvae or any other insect that can be used as animal feed the leaves can still be used for other biobased applications such as fibers.

3.4 Substrate

One of the investigated areas by the Universidad Técnica Nacional in Costa Rica is the use of pineapple residues as (component of the) substrate for growing mushrooms such as oyster mushroom [15].

Xanthan Gum is a natural high molecular weight polysaccharide. Generally, Xanthan Gum is used as a hydrophilic colloid to thicken, suspend, and stabilize emulsions and other water-based systems in the food, pharmaceutical and cosmetic industry. It is industrially produced by the fermentation of pure cultures of the microorganism *Xantomonas campestris*. The gum can also be produced by using pineapple peel as substrate in the aerobic fermentation using the *Xanthomonas campestris* bacteria (TiCSO [Tecnologías de la Información y las Comunicaciones de la Orinoquia], 2014).

Pineapple leaves can be decomposed by bacteria and fungi to produce compost that is returned to the field or used in other crops. Vermicompost is a variant based on using earthworms to make compost. Main problem with this option may be the management of the black soldier fly, which may be difficult to control in decomposing biomass to produce compost.

3.5 Energy

Pineapple residues can be used in various forms to produce energy. First, as pellets as alternative of woody pellets that are used in heating systems (Valverde, 2015). Transport and processing costs will be high in this application because of the biomass volume and low dry matter content while the oxidating material in the residues may result in oxidation of the (metal) ovens to generate heat.

Another option is the production of biochar via pyrolysis (Valverde, 2015). In pyrolysis biomass is partially combusted in the absence of oxygen at relatively low temperatures (<700 °C). Biochar can be used for energy production (replacing coal) or soil improvement as it may improve aeration, Cation Exchange

[14] https://www.wur.nl/en/dossiers/file/insects-food-and-feed.htm [Accessed September 30, 2022].
[15] https://www.pinadecostarica.com/2022/01/residuos-de-pina-para-producir-hongos-ostra [Accessed September 30, 2022].

Capacity and moisture retention in tropical soils. The latter is less important in the case of Costa Rica while the pineapple residues do not seem the most efficient feedstock for the production of biochar given the high moisture content (approximately 85%).

Pineapple residues, possibly in combination with other waste streams, can be used to produce bioethanol that can be used to be blended with fossil transport fuel (Chen et al., 2020). Bioethanol produced from pineapple leaves can be combined with other valorization options, for example, after extraction of the fibers. The digestate that remains after bioethanol production can be used as a nutrient rich fertilizer and return to the pineapple fields or used as an animal feed (Valverde, 2015). Chen et al. (2020) showed that it is possible to produce 5.3 m^3 of ethanol, 3.1 tons of dry yeast, and 23.3 tons of dry fibrous fiber from 250 metric tons of pineapple leaves. The concentration of ethanol was 3.6% in the broth, which is low. Bioethanol is mostly produced from sugar- and starch-containing raw materials, while pineapple residues are low in sugar and starch content most likely resulting in high distillation costs.

Pineapple residues can probably best be used to produce biogas (methane), which can be used directly for heating purposes (e.g., in food processing industry), to generate electricity, or as transport fuel. In the latter case, the current car and fleet park and transport fuel distribution network of Costa Rica needs to be modified allowing the application of biogas as fuel. The application of biogas as fuel for the farm mechanization (i.e., tractors) potentially contributes to reducing the CO_2 emissions and circularity of pineapple farms. Biogas can also be used to generate electricity for the cool stores of pineapple farms. The digestate that remains after bioethanol or biogas production can be used as a nutrient rich fertilizer compost. As with the production of bioethanol, biogas production from pineapple leaves can be combined with some of the other application options described in the sections before.

Annex 1 shows a global calculation of how much biogas (in terms of energy content and financial benefit) can be produced on a pineapple estate of 3,000 ha on annual basis. Based on these calculations and assuming that each year pineapple residues from 20,000 ha comes available in Costa Rica (Section 2.3) the total amount of energy in equivalent of LPG produced could be as high as 23 million kg. LPG use in Costa Rica was 175 million kg in 2020 according the *Autoridad Reguladora de los Servicios Públicos* (Aresep) of which about 75% was used by consumers (for cooking) and the industry sector [16]. This means that pineapple residues could produce about 13% of the total LPG demand.

3.6 Effects on soil organic matter and nutrients

One of the consequences of valorizing pineapple residues is that the crop residues are removed from the field potentially affecting the soil organic matter and soil nutrient dynamics. Lower soil organic matter contents could negatively affect the productivity of the pineapple production in the long run. Although little information is available on the soil dynamics of pineapple fields it is useful to compare a possible future situation (i.e., residues are harvested for valorization applications) with the current management of crop residues (section 2.2). Both burning of the crop residues and potholing are some of the management strategies used in the pineapple industry. The case of potholing is comparable with harvesting the residues for valorization, in both cases the crop residues including the contained nutrients are removed from the field and in the case of potholing the crop residues/nutrients buried somewhere else. The more frequently used residue management option of crop residue burning (after eradication with herbicides) results in both organic matter and nitrogen loss to the air, while some (unburnt) organic matter and most of the potassium and phosphorus contained in the biomass will remain in the field. Only when residues are shredded in several operations and subsequently incorporated in the soil are all crop residues and nutrients returned to the soil.

In many of the valorization options described in the preceding sections only part of the crop residues is being used, for example, 10-20% of the crop residual dry matter is PALF. The remaining part comes available as a nutrient rich digestate, which can be used in other applications, directly as nutrient and organic matter source in pineapple fields or can be upgraded to a high value organic fertilizer (section 3.7). Hence, removing crop residues from the field and their application in biobased solutions not necessarily conflicts with the goal

[16] https://www.bnamericas.com/en/news/pandemic-breaks-costa-rica-lpg-growth-spurt. [visited December 8, 2022].

to maintain soil organic matter content. Moreover, timely harvesting of the pineapple residues could provide opportunities for growing a short green manure crop that could have a positive effect on soil health and the next pineapple crop.

3.7 Cascading use of pineapple residues

Sections 3.1 to 3.5 show the main potential application domains of pineapple residues described in the literature. The challenge is to use these residues sustainably and efficiently.(Sirkin & Houten (1994) developed a concept called resource cascading which basically is a generic method for optimizing resource use through a sequential re-use of the remaining resources quality from previously used resource. Figure 5 shows a graphical presentation of the concept that also can be interpreted as a method to extend the lifetime and thus the economic use of a resource. The vertical axis expresses the resource quality, which determines the capacity to perform different tasks at various degrees of difficulty. Resource quality may be characterized as a function of the amount of embodied energy, the degree of structural organization, the chemical composition of a given resource, and as a function of the effort required to produce or reproduce the quality. The higher the quality, the greater its potential to carry out more demanding tasks.

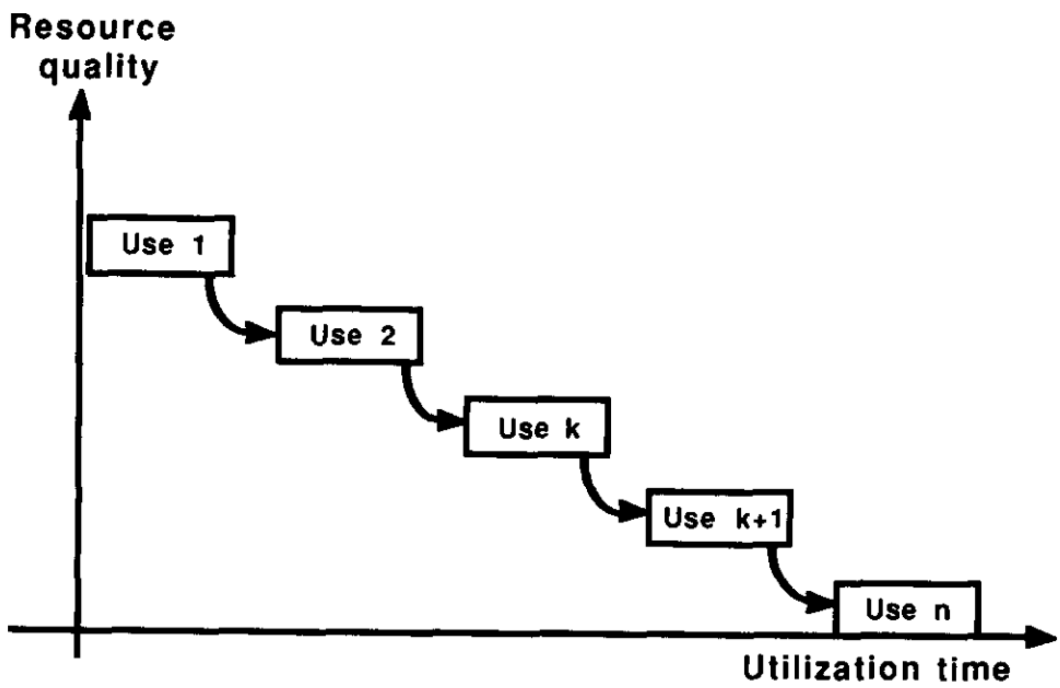

Figure 5 *The sequential use of a resource with decreasing quality properties over time. Source: (Sirkin & Houten, 1994).*

The cascading principle is to try to get the most value out of biomass by using the biomass preferentially for food over feed and materials over final uses such for energy production and returning to the soil. Depending on the application this may reduce the use of land as the biomass replaces growing a crop or may reduce the use of fossil fuel when it replaces fossil energy of fossil-based materials or crops. In the case of pineapple crop residues multiple sequential applications (cascading) may be considered as a means to improve the efficiency of the residues and to decrease environmental impacts. For example, using PALF still means that 80 to 90% of the dry matter (the non-fiber part) is not used and needs to be disposed of. An obvious next step is to use the remaining biomass for the production of 'green' energy.

The cascade concept has been successfully applied to wood and showed among others the effect of sequential use of wood in different applications may lead to large savings in primary resource use, delay the moment that carbon dioxide is emitted and other environmental indicators (Fraanje, 1997; Höglmeier et al., 2015). Model development to assess and quantify the effects of cascading the use of pineapple residues was beyond the scope of this study but may be a next step in assessing the potentials of the sequential combination of various pineapple residue valorization options in depth.

Figure 6 shows for illustrative purposes how the cascading of pineapple residues may look like with the extraction of chemical compounds such as bromelain as a first step embedding the highest resource quality, and energy production as the last step. The remaining digestate after energy production may be returned as nutrient-rich substrate to the pineapple field still containing recalcitrant biomass with a value for the soil. Similarly, but outside the considered system, animal feed can return to pineapple fields in the form of animal manure. In this way resource loops are closed as much as possible while at the same time new products from the residues are made that substitute fossil-based products: From fibers replacing fossil-based synthetics to the nutrient-rich substrate and animal manure (from pineapple fed animals) replacing fossil-based fertilizers. The cascade concept does not imply that all possible steps/cascades need to be followed to generate the largest resource savings. Moreover, some options may be difficult to combine as they may compete for the same property of the residue such as animal feed and fiber extraction. Some of the cascade options may be more positioned on the same level than actually shown in Figure 6. Therefore, Figure 6 rather serves to illustrate the many existing valorization options for pineapple residues and to inspire the use of pineapple residues in a sequential way to generate resource savings.

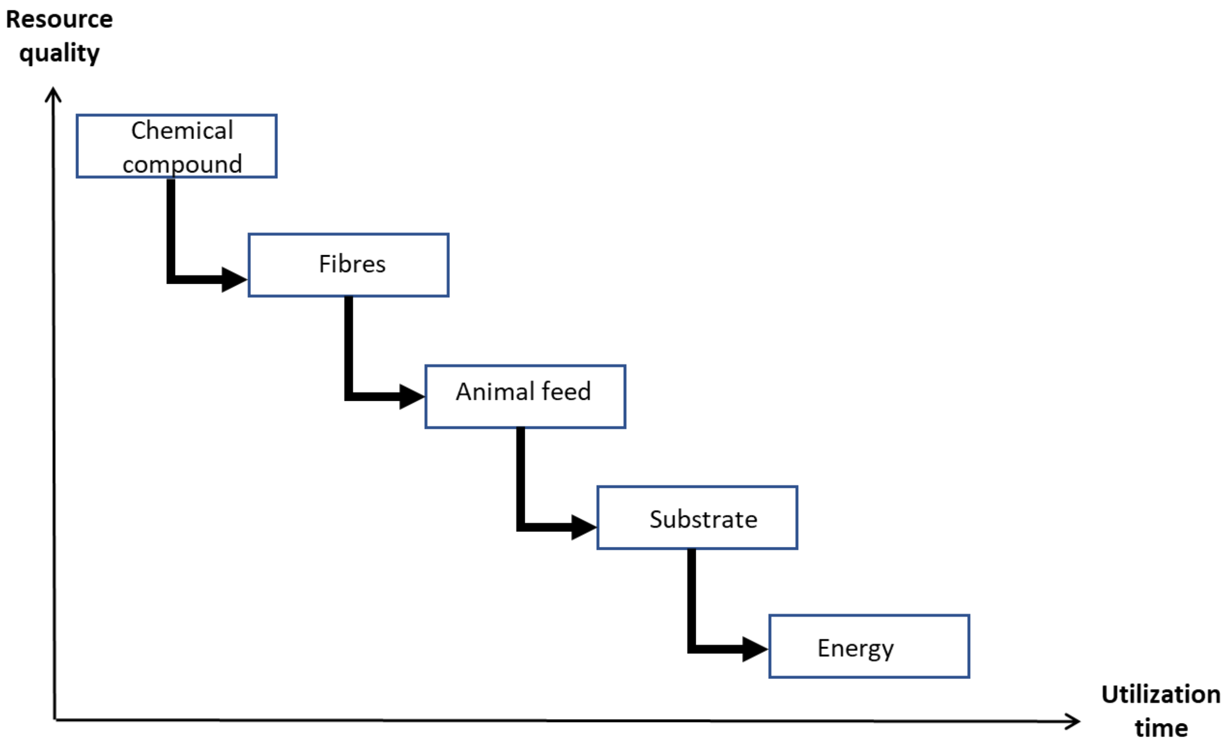

Figure 6 *Illustration of the sequential use of pineapple residues.*

4 Fiber extraction and production from pineapple leaves

4.1 Fiber characteristics and yield

4.1.1 Structure and morphology

Pineapple leaves contain two types of fibers: Large fiber bundles in the middle of the cross section of the leaf, and smaller technical fibers closer to the bottom face of each leaf (Figure 7; Mohamed et al., 2009).

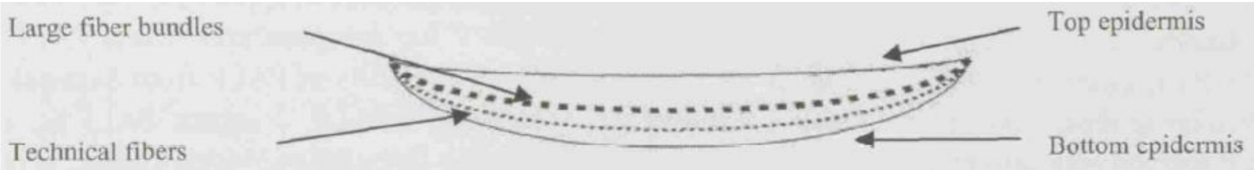

Figure 7 *Schematic longitudinal cross section of Pineapple leaf (Source: Mohamed et al., 2009).*

Pandit & Pandey (2020) call these fibers 'bastos' (course fiber) and 'liniwan' (fine fiber). Rafiqah et al. (2020) mention that 75% of the fiber weight comprises large fibers and 25% (fine) technical fibers. Figure 8a shows the location of (coarse) fiber bundles in the cross section of a leaf. Figure 8b shows that the bundles consist of finer plant cell fibers. However, the vast majority of publications does not distinguish large/coarse (*bastos*) fibers and finer fiber bundles (*liniwan*). Figure 9 shows more detail images of PALF.

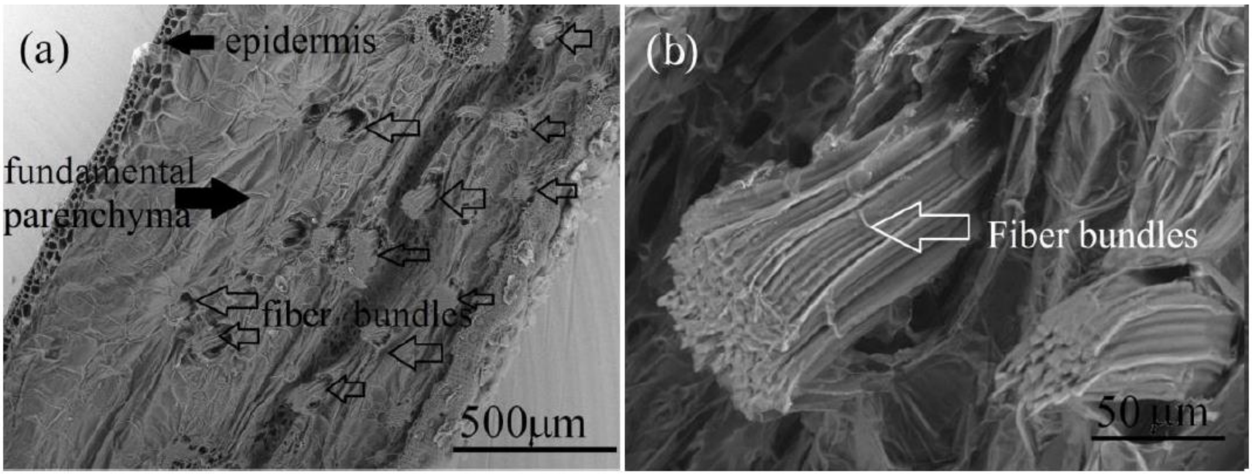

Figure 8 *SEM image of pineapple leaf cross section (a) and fiber bundle in it (b). The left side of (a) is the bottom face of the leaf. (Source: Moya et al., 2016).*

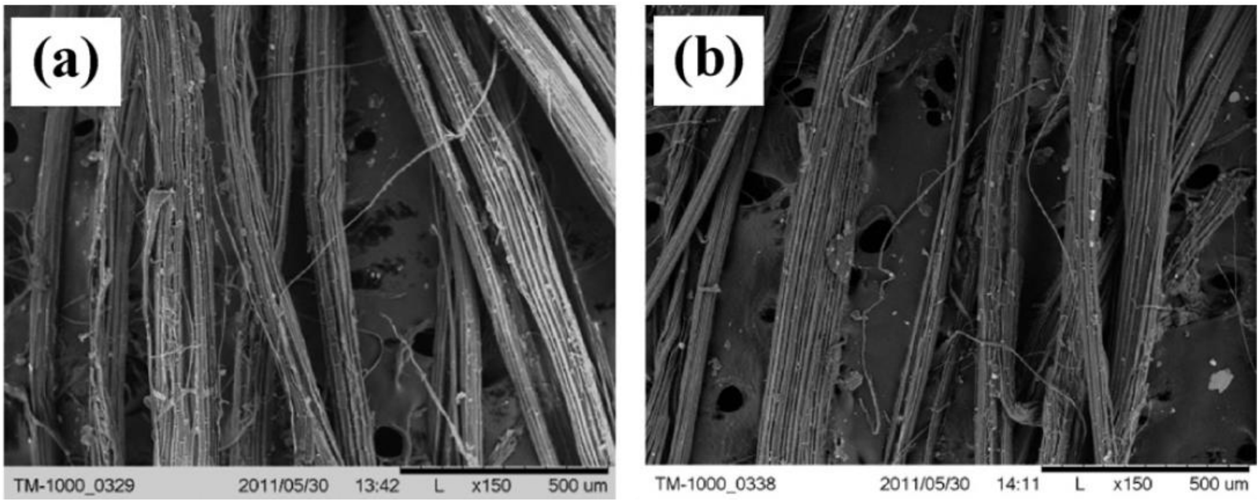

Figure 9 *SEM image of Pineapple leaf (large) fibre: green decorticated (a) and retted (b). (Source: (Kengkhetkit & Amornsakchai, 2012).*

Characteristics of pineapple leaves and PALF are presented in Table 1. Dry fiber content is reported to be in the range 1.5 – 3% on wet leaf basis, compared to about 4% for sisal. If we assume pineapple leaves have a dry matter content of 15% this translates to about 10 to 20% fiber per dry matter leaf. Based on the estimated amount of leaf dry matter available in Costa Rica per year in Section 2.3, i.e., 458,000 t, the potential available amount of fibers ranges between 45,800 and 91,600 t. As a reference, world production of sisal fibers is around 300,000 t/y;[18] world production of hemp is similar.[17]

Table 1 *Pineapple leaf characteristics presented in the literature.*

Literature	**Length (cm)**	**Width (mm)**	**Weight (g)**	**Average no. of leaves / plant**	**No. of fiber bundles per leaf**	**Fiber yield (g 'dry' fiber /g leaf wet)**
Pandit & Pandey (2020)*	55-75	3-6 (likely 'cm' is meant)	15-50			1.55-2.5 and 2.5-3.3 (extraction methods not mentioned)
Mohamed et al. (2009)	61-70	46-65		50-70	80-100	-
Kengkhetkit & Amornsakchai (2012)	**					1.4 after scraping, 1.8 after retting
Moya & Camacho (2014)	30-120		42	69		1.93 after scraping
Moya & Camacho (2014)	30-140		39	105		2.32 after scraping
Yusof et al. (2015a)	30-60	40-60				
Hazarika et al. (2017)	120-125	40-55	70-75 at 80-85% moisture			1.8-2.8 after retting
Jalil et al. (2021)						2-3 after retting
Sisal (Textile coach)[18]	100-150	100	500-700 at 90% moisture	180-240 after 7 to 12 years	1000	4

* Presents two different ranges for fiber yield in the paper.

** Mentions a moisture content of fresh leaf of about 80%. This translates into a fiber yield of 7-9% on dry matter basis.

17 https://renewable-carbon.eu/news/hemp-becomes-the-worlds-billion-dollar-business-worldwide-largest-conference-on-industrial-hemp-in-june-2019-in-cologne-germany/ [visited November 30, 2022].

18 https://www.textilecoach.net/post/sisal-fiber#:~:text=The%20leaves%20are%20dagger%2Dshaped,for%207%20to%2012%20years. [visited November 24, 2022].

4.1.2 Fiber dimensions

Dimensions of PALF bundles presented in the literature indicate a wide range of diameters (Table 2). The smallest diameters (5 micron) refer to single cells (Table 3). Largest diameters, up to 440 micron (212 tex at 1.4 g/cm^3 density), likely refer to the large coarse fibres (*Bastos*) mentioned in section 4.1.1. Intermediate fiber diameters seem to refer to technical fibres (*liniwan*). However, the publications do not explicitly refer to one or both.

Hardly any data on the length of technical fibers are presented in the literature. As the leaf lengths range from 55 to 75 cm and the coarse fibers extend from leave bottom to top, fiber lengths up to 75 cm may be expected.

Compared to, for example, flax and jute fibers, *bastos* large and coarse PALF appear to have similar length, however, a larger diameter; *liniwan* technical fibers have similar diameter but are much shorter.

Plant cell fibers (Table 3) are similar in length and diameter compared to those of sisal and jute, though shorter than flax fibers.

Table 2 *Characteristics of fiber bundles of pineapple leaf in the literature.*

Literature **	**Length (cm)**	**Diameter (micron)**	**Fineness (tex)**
Satyanarayana et al. (1986)		20 – 80	0.44 – 7 @ 1.4 g/cm^3
Mohamed et al. (2009)		105 – 440 large fibers	12 – 212 @ 1.4 g/cm^3
Mohamed et al. (2009)		30 – 80 technical	1 – 7 @ 1.4 g/cm^3
Mohamed et al. (2010)		242 (24) manual extraction	
Mohamed et al. (2010)		157 (24) bleached	
Kengkhetkit & Amornsakchai (2012)		5 – 129 (57 average)	0.03 – 18 @ 1.4 g/cm^3
Kengkhetkit & Amornsakchai (2012)		5 – 166 (59 average)	0.03 – 30 @ 1.4 g/cm^3
Hazarika et al. (2017)	3	60 retted	4.3 (1.1)
Teles et al. (2015)		100 – 280	11 – 86 @ 1.4 g/cm^3
Todkar & Patil (2019)		48 – 106	2.5 – 12 @ 1.4 g/cm^3
Pandit & Pandey (2020) *	1 – 9	45 – 68 @ 1.54 g/cm^3	2.5 - 5.5
Jalil et al. (2021)		61 (7) @ 1.4 g/cm^3 retted	4.1 (1.0)
Sisal (Textile Coach; Textile Sphere [19])	80-120	200 – 400	
Jute (Xia)		38.4 – 60.7	
Jute (Bevitori)		40 - 180	
Jute (Sfiligoj Smole)	< 300		
Flax (own data)	30 - 90	50 – 100	2.8 – 11 @ 1.4 g/cm^3

* Does not indicate whether the type of fiber bundle, i.e., large fiber bundles (*Bastos*) or technical fibers (*Liniwan*).

** Some publications present diameters in microns, others in tex; if diameter has been presented in one unit, the other has been calculated assuming a density of 1.4 g/cm^3, unless otherwise specified.

Table 3 *Characteristics of single cell of PALF presented in the literature.*

	Length (mm)	**Diameter (micron)**	**Fineness**
Pandit & Pandey (2020)	3-8	7-18	2.5-4 tex (45-58 mu at 1.54 g/cm3)
Mukherjee & Satyanarayana (1986)	3-9	4-8	
Todkar & Patil (2019)	3.14	7.66	
Sisal (Chand)[20]	0.5 – 6.0	5 – 40	
Jute (Sfiligoj Smole)	0.5 – 6.0	26 – 30	
Flax (WFBR)	20 - 50	10 – 25	

[19] https://www.textilesphere.com/2020/03/sisal-fiber-properties-applications.html#:~:text=Sisal%20fiber%20is%20derived%20from,and%20are%20lustrous%20in%20appearance. [visited November 24, 2022].

[20] https://www.sciencedirect.com/topics/engineering/sisal-fibre [visited November 24, 2022].

Single plant cell fibers in PALF are short compared to cotton and flax, rather in the range of jute. For spinning a minimum fiber length of about 20 mm would be required. This means that for spinning, PALF would have to remain bundles of fibers, which is usual, for example, for jute fiber as well.

4.1.3 Chemical composition

Chemical composition of PALF is like that of flax and jute bast fibres (Table 4). Publications basically do not explicitly refer to the type of fibers examined, *bastos* and or *liniwan*. In addition, authors tend to copy data from others (especially regarding chemical compositions and mechanical properties), listing up to five replications of the same data sets without any comment. No reference is made to the original data and checking the reliability of the data is poor. For example, chemical composition sometimes adds up to 150%, without further explanation or comment (Moya et al., 2016b).

Table 4 *Chemical compositions of PALF presented in the literature.*

	Cellulose	Hemicellulose	Pectin	Lignin	Extractives (H2O)	Fat/wax	Ash
Satyanarayana et al. (1986b)	81			12			
Saha et al. (1990)	68.5	18.8	1.1	6.0		3.2	0.9
Moya & Camacho (2014)							4.7
Hazarika et al. (2017)	71.0	15.3	3.0	4.9		1.0	1.0
Pandit & Pandey (2020)	55-68	15-20	2-4	8-12	1-3	4-7	2-3
Sisal (Textile coach)	71.5	18.1	2.3	5.9	1.7	0.5	
Jute (Sfiligoj Smole)	61-71	14-20	0.2	12-13			
Flax (own data)	73.3	9.1	2.8	3.6	4.5	2.9	1.3
Hemp (own data)	74.4	9.0	3.7	3.6	3.8	1.1	2.3

4.1.4 Mechanical properties

Strength data of PALF show large variation (Table 5), which is common for natural fibres. Strength results depend on testing conditions, and these are not always indicated in the publications. Strength data suggest that some batches of fibers have significantly higher strength than others.

Compared to flax and jute, PALF seems to have similar strength, modulus and elongation properties. The properties presented in Table 5 are indicative: Strength depends on fiber diameter (e.g., Teles, 2015; Mukherjee, 1986) and on span length and strain rate (e.g., Mukherjee, 1986), however, the majority of the research papers does not relate PALF strength properties to diameter nor testing conditions.

Table 5 *Characteristics of fiber bundles of pineapple leaf presented in the literature.*

Literature *	**Tenacity (cN/tex)**	**Tensile strength (MPa)**	**Modulus (GPa)**	**Modulus (cN/tex)**	**Elongation (%)**
Satyanarayana et al. (1986b)		413 – 1627	34.5 – 82.5		0.8 – 1.6
Mukherjee & Satyanarayana (1986)		362 (71) – 747 (99)	24.3 (3.3) – 35.7 (104)		2.00 – 2.78
Mishra et al. (2004)		575	14.9		3.9
Mohamed et al. (2009)		148, 175 & 293 as averages for 3 varieties	7.5, 10.5 & 18.9 as averages for 3 varieties		0.52, 1.05, 1.41 as averages for 3 varieties
Mohamed et al. (2010)		198 (59) manual extraction	3.5 (1.0)		7.8 (1.9)
Mohamed et al. (2010)		218 (70) – 368 (79) bleached	2.8 (0.7) – 7.8 (1.9)		4.1 (1.0) – 9.1 (1.9)
Teles et al. (2015)		50 – 327			0.75-2.5
Yusof et al. (2015b)		394 hand scraped			3.24
Yusof et al. (2015b)		614 mechanical extraction			6.67
		1089 degummed			3.79
Hazarika et al. (2017)	30				5.6
Pandit & Pandey (2020)**	30-40	462-616 at 1.54 g/cm^3	8.8-10.8 at 1.54 g/cm^3	570-700	2.4 – 3.4
Gaba et al. (2021)		630 (50)	9.0 (1.1)		7.9 (0.7)
(Jalil et al. (2021)	31.3 (9.7)	438 (136) @ 1.4 g/cm^3			4.5
Sisal (Textile Coach)		400 – 700	9 – 38		1.5 – 3.85
Jute (Asim)		393 – 800	10 – 30		1.5 – 1.8
Jute (Xia)		129 - 823			2.6 – 4.4
Jute (Bevitori)		30 - 510			
Flax (own data)		500 – 1100	40 – 70		1.5 – 3.0

* Several studies present data for several test series. Standard deviation per series is indicated between brackets when available.

** Does not indicate whether the fiber bundles are from large fiber bundles (*Bastos*) or technical fibers (*Liniwan*).

4.2 Harvesting, extraction and use of PALF in textile

The extraction processes of PALF described in the literature comprise the following steps:

- Harvesting the pineapple leaves and transport from the field.
- Green decortication to extract fibers from the leaves, mechanised or manually.
- Retting to remove ‘non-fiber’ material from the fiber.
- Degumming of the fibers to further remove impurities and improve fibre surface quality.
- Eventually bleaching to improve appearance.

These steps are discussed in more detail in the following sections.

4.2.1 Harvesting of pineapple leaves

The first step in the process to use PALF for textile is the removal of leaves from the field after the second fruit harvest. Currently, no machinery is available to harvest pineapple residues, strip the leaves and transport the entire crop residues or leaves from the field for further processing. In the past tests have been carried out with a sugarcane harvester and forestry mulcher [21] which chopped the residues in small parts for biogas production and the digestate for biofertilizer. Locally, the company Giro Industrial has been working on a crop residue harvester. In addition, some of the large pineapple companies have been working independently of each other on such type of machines for several years. Until now these efforts have not resulted in a commercially available machinery.

[21] https://www.mondomacchina.it/en/costa-rica-energy-and-fertilizers-from-pineapple-residues-c2346 [visited November 25, 2022].

One of the factors that complicates the design of machinery is the limited accessibility of pineapple fields because of year-round high rainfall (3,000 – 5,000 mm), soils that easily become smeared under wet conditions, terrain characteristics (often slightly sloping) and many ditches and drains at farm level to manage the water surplus. Consequently, harvesting machines and transport machines cannot be too large and heavy. Another factor is that the pineapples are grown on beds limiting working width of the machines (though wider machines would become possibly too heavy anyway).

A more fundamental design problem of the machinery is that the design needs to depend on the final application of residues. Sugar cane harvesters may work to chop the pineapple residues but are not suitable if PALF is the aim. In that case entire pineapple leaves need to be harvested. A targeted design for residue harvesting, collection and transport is still lacking as the final application of the crop residues is uncertain.

For PALF, the entire pineapple plant needs to be cut at soil surface or entirely removed/lifted from the soil. Leaves need to be stripped from the plant with the same machine in the field, or the entire plants are transported with rubber bands (as the fruit harvest) sideways to the field where plants are collected and. leaves are stripped from the stem, requiring another machine. In any case due attention in the machine design needs to be given to the stem (the amount that is probably small enough to be chopped and effectively incorporated into the soil) and the biomass volumes that need to be transported from the field (the leaves).

4.2.2 Green decortication

In the green decortication step PALF is separated from the parenchymal tissue. Several methods for green decortication have been reported in literature:

- Decortication machine having serrated rolers (JETIX, India) which scrap and remove the fleshly parts of the leaves from the fibers. The decorticator can process 15 kg/h of green leaves (Hazarika et al., 2017a). At the indicated dry fiber content of 2.8% on leaves as is (wet), this equals 0.42 kg/h of dry fiber.
- Decortication machine having ‘unprecedented’ blade design. The decorticator can process 5760 leaves per 8 h (5 seconds per leaf; (Yusof et al., 2015b). Assuming a fresh leaf weight of 20 – 40 g and 2% dry fiber per g wet leaf, fiber production equals 2.3 – 4.6 kg/day of 8 h.
- ‘Proposed’ decortication machine, including schematic design of the set-up, is presented by (Moya & Camacho, 2014). The machine can process 118 to 238 kg/h of 1st and 2nd crop leaves, respectively, corresponding to 3.5 to 6.4 kg/h of dry fiber.
- Manually: Patience and care are required to avoid damaging the fibres (Jalil et al., 2021).
- Pandit & Pandey (2020) mention that both long coarse fibers (*bastos*) as well as finer technical fibers (*liniwan*) can be obtained as a mixture, both via manual and mechanical extraction. The reference provided for the latter, however, is on a completely different topic.

Figure 10 shows the long coarse fibers extracted from a leaf.

Figure 10 *Large coarse fibers (left) extracted from pineapple leaves (right).*
(Source: Silvia Fernandez Gonzalez).

4.2.3 Retting

After green decortication, some leafy components are still attached to the fibers (Hazarika et al., 2017a). These can be removed by soaking the fibers in water for some days, commonly called retting. Conditions for retting presented in literature:

- Decorticated fibers are dipped in a water tank at fiber:water ratio of 1:10 at 28 °C for several days. Optimal retting is obtained after 7 days (Hazarika et al., 2017a).
- Scraped leaves are immersed in a retting tank. Urea was added for retting at 27 °C for 7 days (Jalil et al., 2021).

4.2.4 Degumming

Degumming is performed to further optimise fiber quality for textile grade yarn (Hazarika et al., 2017a):

- Retted fibers are treated in 1% w/v NaOH solution at 85 °C for 1 h (Hazarika et al., 2017a). After degumming, fibers are neutralised with 1% acetic acid and water, prior to drying.
- Retted fibers are treated with 5% w/v NaOH solution at 90 °C for 2h (Jalil et al., 2021). After treatment, fibers are neutralized with 'mild acid' and washed with soft water.
- Decorticated fibers are treated in 3% Na2CO3 solution at 100 °C for 1 h (Yusof et al., 2015b). After degumming, fibers are washed with water and sun dried.
- Padzil et al. (2020) mention that cellulases can be used to remove fibrils on the fiber surface, resulting in smoother and softer fabric (referring to a study on hemp).

4.3 Final fiber preparation and spinning

After extraction of fibers from the leaves, they can be used for further processing into a range of products, e.g., non-wovens for composites or 'plant leather'; or the fibers can be spun to yarn for weaving or knitting.

4.3.1 Bleaching

Bleaching may be performed to further enhance fiber quality. This can be done by treating fibers at 30% w/v hydrogen peroxide at 85 °C and pH 10-11 for 1 h (Hazarika et al., 2017a). After bleaching, fibers are neutralised with 1% acetic acid and water, prior to drying.

4.3.2 Fiber softening and sliver preparation

Prior to spinning, Jalil et al (2021) have softened degummed PALF in a jute softening machine (Douglas Fraser & Sons) using 25% emulsion on fiber weight for 48 h. The emulsion consisted of 79% water, 19.5% jute batching oil and 1.5% emulsifier (Nonidet P-40). Next the softened fibers were processed in a conventional jute spinning system, i.e., through a breaker card, a finisher card, and 1^{st}, 2^{nd} and 3^{rd} draw frame machines (Jalil, 2021, section 2.2.5).

Mohamed et al. (2010) used abrasive paper (grade #100) to refine fiber bundles into finer fibers.

4.3.3 Spinning

Jalil et al. (2021) have spun PALF sliver resulting from the 3^{rd} drawing-frame into yarns using 2 spinning techniques: a modified apron draft ring-spinning frame and a jute flyer-spinning frame, resulting in yarns of 121 and 138 tex, and having twist factors from 6-12. They also present fiber, yarn diameter (tex) and strength (cN/tex) and their limitations.

Hazarika et al. (2017b) have spun PALF yarn at 90 tex subsequently using machines for jute softening, flax carding, jute drawing and apron-draft spinning. As a reference, linen (flax) yarn can be as fine as 15 tex, hemp eventually 25 tex (Westerhuis, 2016).

5 Bottlenecks to valorization options

Despite the large amount of biomass available and the need for more environmental-friendly ways to dispose pineapple residues up to date there are no large-scale initiatives to bring any of the identified valorization options described in Chapter 3 to scale. There is even less attention for the cascading of different valorization options, which has the potential to reinforce the economic viability of individual valorization options. In this Chapter we identify and discuss four interrelated bottlenecks that hinder valorization developments with a focus on the situation in Costa Rica.

5.1 True costs of current residue disposal

Little is known about the true costs of current ways of pineapple residue disposal because i) the operational costs are unclear and ii) environmental costs are not considered. The pineapple sector is dominated by large farms (the majority of farms > 100 ha) that only become larger because smaller farms cannot compete on the demanding export markets. The residue management is part of the business model of large farms. Sharing of technical and financial information is not common, current estimates of the current residue management in the literature range from 1,000 to 2,500 US$ per hectare, but not clear is, for example, whether these costs also include the time (= costs) that a field remains fallow, depreciation and maintenance costs of machinery, etc. Equally important, these estimates do not include environmental costs and occupational health costs associated with the current residue management: costs related to the potential pollution of soil, water and air by the pesticides used in current residue management, losses of nutrient contained in the residues, the costs borne by nearby livestock farms affected by the stable fly, or the occupational health costs of field laborers working with the pesticides. In the past, when the pesticide bromacil was still allowed in pineapple production in Costa Rica drinking water supplies of some nearby communities were that much polluted that water-trucks needed to supply clean drinking water to these communities with. Costs during 15 years of truck supply with drinking water has been estimated at US$ 3 million [22]. Therefore, more insight in the true costs of current disposal could urge the Government of Costa Rica to request other pineapple residue management. This would stimulate residue valorization as option for improved residue management.

5.2 Lack of knowledge

Recent attention for the potential applications of pineapple residues in a biobased economy has sparked various R&D tracks to explore valorization options for pineapple residues (Chapter 3). Yet, insights in the availability, properties of pineapple residues, residue processing needs, and final products (including their properties) for various valorization options is still limited. This report contributes to some of the required insights to bring valorization options one step further. However, we were not able to assess the fiber characteristics of pineapple residues in Costa Rica that are relevant for using pineapple residues by the textile industry. Instead, we relied on the literature for describing the fiber characteristics, mostly sources from South-East Asia. Many of these literature sources appeared inconsistent, provided partial information, and were based on secondary data copying and adapting already earlier published primary data. Therefore, still important research questions remain, for example, related to a more accurate assessment of the PALF content in the pineapple variety used in Costa Rica (MD2); Which share of the PALF can go to yarns for textile, to composites, and, for example, to paper for packaging? How can the remaining part of the residues be converted into valuable products? Which share of the pineapple residue may remain on the land, and to which size would it need to be chopped, to be ploughed under the soil without the need to use pesticides? This type of basic information including product properties is needed to assess the technical feasibilities, market potential and scalability of valorization options of pineapple residues produced in Costa Rica.

[22] https://slothconservation.org/real-cost-of-pineapples-from-costa-rica/ [visited November 25, 2022].

5.3 Lack of clear business models

Related to the previous point are the lack of business models, i.e., the potential costs and financial benefits of the various valorization options is still largely unknown. Partly this has to deal with the stagnation in development of machinery to harvest, transport and process residues for a targeted valorization option (e.g., section 4.2.1): A targeted design for residue harvesting, collection and transport is still lacking as the final application of the crop residues is uncertain. This can be considered the 'chicken or the egg' problem: For example, if nobody invests upstream in the required machinery for harvesting of the crop residues no downstream investments will take place in the requirements for processing, marketing, etc. But also *vice versa*: If nobody invests downstream in product development, its distribution and marketing no upstream investments in machinery for harvesting and collection will happen. As a consequence, financial costs but also the financial gains of valorization options are yet largely unknown hampering the development of solid business models.

5.4 Enabling environment

In this study, we plea for the cascading of different valorization options to use the available feedstock resources (i.e., pineapple residues) as efficiently as possible and to increase the economic value of the pineapple residues. In general, 'green' energy production, bioethanol but especially biogas are important valorization options to be combined with other valorization options. In technical terms, energy production from residues can be combined relatively easy with other valorization options that only use part of the pineapple residues, such as fibers. Energy production and its use by private entities is allowed in Costa Rica, but not its supply and distribution to the grid, which is a state monopoly. For example, pineapple farms may use own produced biogas-based electricity for cool stores or biogas as LPG fuel for the own machine park, but they may not deliver the surplus biogas-based electricity to the grid or sell biogas as transport fuel. Hence, new legislation is needed that allows and guarantees LPG producers to be able to supply to the national energy market. Although the market price of electricity is relatively high in Costa Rica, production of 'green' biogas-based electricity may not be the most obvious option as Costa Rica is self-sufficient in the production of renewable hydropower-based electricity. Hence, a focus on improving LPG availability is more logical in the case of Costa Rica. Biogas can be used to produce LPG as transport fuel or can be used directly by the local industry and consumers (for cooking purposes). Currently 100% of the LPG used in Costa Rica is imported, and we estimate that about 13% of this import could be substituted by biogas produced from pineapple residues. The energy demand for electricity and LPG is expected to continue to growth in Costa Rica which may increase the need to open up the state monopoly on LPG (and electricity) for other suppliers. This could also mean an important incentive for the development of other pineapple valorization options. Public private partnerships are needed in which the Government of Costa Rica, including its energy parastatals, and the private sector, including the pineapple industry as one of the backbones of the national economy, could further develop economically viable valorization options.

6 Conclusions

Currently, pineapple residues are a problem for the pineapple sector, while their amount and continuous supply throughout the year offer great potentials in the biobased economy creating yet unrealized win-win solutions, for both the pineapple sector and society.

This study identifies five major application domains for pineapple residues of which PALF for textiles is one. Cascading of different valorization options may increase the resource use efficiency of the available pineapple residues and the economic value of the pineapple residues. The amounts of crop residues and PALF that each year come available after the second harvest of pineapples are large enough for scalable solutions. See the Box with 'Facts on pineapple residues in Costa Rica' as developed in this study. The amount of biogas that potentially can be produced as part of PALF valorization is considerable and contributes to Costa Rica's goal of net-zero emissions by 2050 (Groves et al., 2020).

Facts on pineapple residues in Costa Rica

- Current management costs of pineapple residues varies between 32 and 81 USD/ton dry matter.
- We estimate that annually ≈ 620,000 t dry matter of crop residues is available for valorization options.
- The potential available amount of PALF ranges between 45,800 and 91,600 t per year. As reference, global sisal and hemp production is around 300,000 t per year.
- Energy production from pineapple residues could supply about 13% of the national LPG demand, which currently is based for 100% on imports.

Despite the potentials that pineapple residues offer for the transition of a fossil-based economy towards a bioeconomy there are currently no scalable solutions to valorize these residues in Costa Rica. We identify four major interrelated bottlenecks. First, the failure to account for the true costs of current residue management, which slows down the industry's response to develop alternative ways to dispose the residues, including the exploration of valorization options. Second, lack of basic knowledge and information, for example, about material properties needed to assess the technical feasibilities, market potential and scalability of valorization options. In this study, we were not able to assess the fiber characteristics of pineapple varieties used in Costa Rica. Instead, we described fiber characteristics from other varieties based on the literature, which appeared to be inconsistent and giving conflicting information in some cases. Third, strongly related to the previous bottleneck is the lack of sound business models. This seems a chicken an egg dilemma: the required upstream and downstream investments do not take place as information on the real costs and benefits of valorization options is lacking. Only a more coordinated approach to develop solid business models can trigger such investments. Fourth, the role of the Government and especially the energy parastatals hamper the energy production from pineapple residues as an important valorization option to increase their economic value.

Potential follow-up R&D tracks to use pineapple residues as feedstock for biomaterials are:

- Development of topical knowledge and technologies to move from innovation readiness levels 3/4 to 6 (Sartas et al., 2020). For example, this includes but not limited to technology development for the mechanization of residue harvesting, knowledge on PALF characteristics and extraction methods, and technologies for further large-scale PALF processing steps to spinning (for textiles).
- Development of models to assess and quantify resource use efficiencies and economic benefits of cascading different valorization options for pineapple residues.
- A public-private partnership to develop a joint strategy (roadmap) towards the valorization of pineapple residues. Such a strategy is needed to mobilize private and public funding for large-scale investments, and to change current legislation and institutions facilitating the valorization of pineapple residues for a biomaterial transformation.

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Annex 1 Simple biogas to energy calculations and benefits for large pineapple estate

Assumptions	Value	Unit	References/comments
Farm area	3,000	ha	
Cycle duration 2 harvests	36	Months	Including two harvests, time to growth *hijos* (planting material for the next crop), kill/bury crop residues, field preparation and planting of the next crop.
Area replanted per year	1,000	ha	one third of the farm area is replanted each year with a crop cycle of 36 months
Residue yield	250	ton FW/ha	own estimate
Total biomass input	250,000	tons FW/farm	
Biogas yield per ton FW	25	Nm3/ ton FW	Range between 25 to 50 (Evilio Chaves, Valle del Tarso farm, pers. Com.)
Nm3 to kWh energy LHV	6.5	kWh / Nm3 biogas	http://www.sgc.se/ckfinder/userfiles/files/BasicDataonBiogas2012.pdf
Nm3 to MJ energy LHV	23	MJ/ Nm3 biogas	http://www.sgc.se/ckfinder/userfiles/files/BasicDataonBiogas2012.pdf
efficiency conversion biogas to electricity	40%		assumption
Operational hours electricity generation	8,000	hours per year	assumption
Selling price electricity	$100	$ per MWh	Assumption: 2/3 of buying price (= $150 per MWh)
Capital expenditure per ton at 2 MW	$41	$/ton input	IFC 2017. p 131 rest of the world
Capital expenditure per ton at 4 MW	$35	$/ton input	IFC 2017. p 131 rest of the world
Heat available	40%		
Heat available	57,500,000	MJ per year	
LPG (propane) energy content	49	MJ/kg	https://www.elgas.com.au/blog/389-lpg-conversions-kg-litres-mj-kwh-and-m3
LPG (propane) energy content	25	MJ/liter	https://www.elgas.com.au/blog/389-lpg-conversions-kg-litres-mj-kwh-and-m3
Calculations per year:			
Biogas from biogas 3000 ha farm	6,250,000	Nm3 biogas LHV	
Energy from biogas 3000 ha farm	40,625,000	kWh biogas LHV	
Energy from biogas 3000 ha farm	143,750,000	MJ biogas LHV	
Electricity per year produced	16,250,000	kWh electricity	
Electricity per year produced	16,250	MWh electricity	
Generator needed in kW	2,031	kW	
Generator needed in MW	2.03	MW	
Value of electricity produced	1,625,000	USD per year	
Investment Capex	10,250,000	USD	
Simple break-even:	6.3	years	
We assume the benefit of removing residue and nutrient recycling cancels OPEX.			
Residual heat 40% can also be used for drying or for cooling (heat to cold.) at the biogas installation			
Equivalent amount of LPG	1,173,469	Kg LPG	
Equivalent amount of LPG	2,214,469	Liter LPG	1 kg LPG = 1.89 l LPG: https://www.cbs.nl/en-gb/onze-diensten/methods/definitions/weight-units-energy
LPG price	0.40	USD / liter	Assumed
LPG savings value of Biogas heat	$920,000	Requires drying at biogas plant and requires investment	

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Report WPR-1212

The mission of Wageningen University & Research is “To explore the potential of nature to improve the quality of life”. Under the banner Wageningen University & Research, Wageningen University and the specialised research institutes of the Wageningen Research Foundation have joined forces in contributing to finding solutions to important questions in the domain of healthy food and living environment. With its roughly 30 branches, 7,200 employees (6,400 fte) and 13,200 students and over 150,000 participants to WUR’s Life Long Learning, Wageningen University & Research is one of the leading organisations in its domain. The unique Wageningen approach lies in its integrated approach to issues and the collaboration between different disciplines.

To explore the potential of nature to improve the quality of life

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