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Creating Sustainable Biofuels Using Essential Oil Distillery Leaf Waste Near Vohimana Reserve

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Abstract

Like most of Madagasacar’s population, people around Vohimana Reserve rely on traditional fuels like firewood and charcoal for cooking and heating. As a result, the region is facing deforestation, which poses a threat to biodiversity and the livelihoods of local populations. A local essential oil distillery was created by the NGO L’Homme et L’Environnement as a sustainable income generator to combat deforestation and protect biodiversity. The distillery produces leaf biomass that can be mixed with binding agent(s) and transformed into biofuel as a sustainable alternative to traditional fuels. 14 biofuels were created by combining distillery leaf biomass and various percent ratios of locally available binding agents (potato starch, clay, and cassava). The fuels were tested for durability, and a rice-cooking test was conducted to determine the most effective biofuel. A biofuel with a 25% potato starch to leaf biomass ratio was the most effective with an average durability of 16.18 ± 1.54 minutes, and successfully cooked a pot of rice within 0.3 minutes of the time taken by traditional charcoal. Distillery leaf biomass can be paired with local binding agents to produce biofuel and potentially replace traditional fuels in the area.

Key words: Vohimana; biofuels; biomass; binding agent; potato starch; distillery

Résumé

Comme la plupart de la population de Madagascar, les habitants de la réserve de dépendent des combustibles traditionnels comme le bois de chauffage et le charbon de bois. En conséquence, la région est confrontée à la déforestation, qui constitue une menace pour la biodiversité et les moyens de subsistance des populations locales. Une distillerie locale d’huiles essentielles a été créée par l’ONG L’Homme et L’Environnement comme activité génératrice de revenus durables pour lutter contre la déforestation et protéger la biodiversité. La distillerie produit de la biomasse foliaire qui peut être mélangée à un ou plusieurs liants et transformée en biocarburant comme alternative durable aux carburants traditionnels. 14 biocarburants ont été créés en combinant la biomasse des feuilles de distillerie et divers pourcentages d'agents liants disponibles localement (fécule de pomme de terre, argile et manioc). Les carburants ont été testés pour leur durabilité et un test de cuisson du riz a été effectué pour déterminer le biocarburant le plus efficace. Un biocarburant avec un ratio de 25 % de fécule de pomme de terre sur la biomasse foliaire était le plus efficace avec une durabilité moyenne de 16,18 ± 1,54 minutes, et a réussi à cuire une marmite de riz en 0,3 minute de charbon de bois traditionnel. La biomasse des feuilles de distillerie peut être associée à des liants locaux pour produire du biocarburant et potentiellement remplacer les carburants traditionnels dans la région.

Mots clés : Vohimana ; biocarburants ; biomasse ; agent de liaison ; fécule de pomme de terre ; distillerie

Introduction

Madagascar is facing an energy crisis. As of 2020, only 33.7% of Madagascar's total population and less than 10% of the rural population has access to electricity. (Amsalu et al., 2022: The World Bank, 2020). Most households rely on traditional sources of energy for cooking and heating, and 95% of households use firewood and charcoal as their basic energy source (Amsalu et al., 2022; Andrianaivo et al., 2011). Although not native to the island, *Eucalyptus robusta* now covers about 140 thousand hectares around the capital Antananarivo, and its timber has become the main source of fuel for urban and rural households in Madagascar. However, the availability of this resource is threatened due to market deficit and rural poverty, which is causing forest owners to shorten their coppicing cycles (cutting trees at their base and creating a stool where new shoots will grow) to sometimes as little as 2 years (Verhaegen et al, 2014). Over-exploitation of forest resources for fuel is one of the primary causes of deforestation in Madagascar, and the rate of deforestation was 72.9 kha/year from 2014-2020 (Ralimanana et al., 2022). The destruction of forest for firewood and charcoal is a direct source of carbon emissions, endangers rain patterns that are regulated by forest systems, and leads to loss of topsoil (David, 2022). Over-exploitation depletes soil minerals, and continued reliance on new eucalyptus wood as well as other types of wood presents a challenge to Madagascar's biodiversity and reforestation goals.

Biofuels (biomass derived fuels) as an alternative to traditional fuels have emerged as a more environmentally friendly form of energy. As of 2020, biofuels provided 11% of the total global primary energy supply (Pan et al., 2022). Biofuels have the potential to help satisfy energy needs, reduce dependence on fossil fuels, decrease pollutant emissions, and provide energy in solid, liquid, or gas forms (Pan et al., 2022; Abd El-Malek et al., 2022). In Madagascar, biofuels can combat deforestation by replacing traditional fuels like charcoal, decrease greenhouses gas emissions, reduce energy poverty, and contribute to rural development. Previous efforts to create biofuels have evaluated the potential of agricultural residues from crops (carbon-rich) and animal production (nitrogen-rich) as good sources of bioenergy that can contribute significantly to bioenergy generation. (Amsalu et al., 2022). To form solid biofuel, this biomass is combined with a binding agent that holds the material together. Cassava and clay are common binding agents for environmentally friendly fuel projects in Madagascar and in other parts of Africa due to their availability (Abayomi, 2021; Romaric 2018). In 2019, a paper by RAKOTONIAINA

Jean Romaric from the University of Antananarivo was published describing how to pair sawdust and charcoal biomass with clay, laterite, and cassava flour to create biofuel balls (Romaric, 2019). The result was effective and used only local materials to create biofuel. However, the question remains whether a similar biofuel can remain effective if charcoal biomass is eliminated.

The Vohimana Reserve and the neighboring village of Ambavaniasy, located on the RN2 between Moramanga and Tamatave in Eastern Madagascar (Figure 1), is 2082 acres in size and has a population of approximately 1500 peopled (L'Homme et L'Environnement, 2020). Deep in the forest, charcoal is produced by cutting eucalyptus and other trees and placing them into a makeshift *four de charbon* (charcoal oven) created by layers of long sticks and soil. The timber remains in the *four de charbon* for approximately a week for carbonization, then is packaged as charcoal. Every morning, men run massive bags of charcoal as far as 15km from these production sites to town, where it can be sold. Firewood and charcoal are the primary sources of energy, and charcoal is valued for its intense heat and durability. Many people in this area make a living from the production and sale of charcoal, and sometimes the charcoal itself is used as currency. Such is the case around all of Madagascar, including Ambovombe, a provincial capital in the south, where, despite its illegality, people make a living by burning trees and openly selling charcoal on the roadside. As a result, the lack of trees contributes to vicious dust storms in the region known as *tiomena*, and the soil has largely deteriorated (David, 2022). The forest around Vohimana is threatened by deforestation, and much has already deteriorated due to charcoal production (Figure 2). Although deforestation poses both direct and indirect threats to the health of Madagascar's land and its people, the important role that charcoal plays in local economies and

Figure 1: Map of Vohimana within the District Moramanga
Source: L'Homme et L'Environnment

in peoples' livelihoods presents a challenge to disrupting this destructive cycle in favor of producing a different, more environmentally friendly fuel.

Figure 2: Deforestation next to Vohimana Reserve

Due to Vohimana's richness in biodiversity, L'Homme et L'Environnement, an NGO based in Antananarivo, Madagascar, has been working with the local community for the past 20 years to support sustainable development in the area. One strategy the NGO has implemented to achieve development goals is creating more sustainable income-generating activities, including ecotourism, essential oil distillery, tree nursery, and handicraft, that improve living conditions as well as preserve the surrounding environment. The local essential oil distillery or *Ambodikýy*, just a ten-minute walk from the main road, exemplifies this strategy. The distillery uses steam-distillation to produce a range of essential oils, including Ravensara and ginger, that is then sold at a local shop on the RN2 alongside other crafts. However, after the essential oil is made, the cooked plant leaves are treated as a waste product (Figure 3). These leaves are carbon rich and a potential source of biomass the community can use to produce biofuel.

Figure 3: Distillery leaf waste

The aim of this study is to determine if the leaves cooked for essential oil production at the distillery near Vohimana Reserve can be transformed into effective biofuel using only local resources. Prioritizing the transformation of distillery leaf waste into biofuel would reduce deforestation and preserve biodiversity in the area. 14 types of biofuels were created using

Angustifolium zingiberaceae and *Hedychium flavescens* leaves from the distillery (types of ginger), which were cooked for three hours to extract essential oil before being discarded. The leaves were then mixed with different percent ratios of cassava, clay, and/or potato starch to determine what binding agent(s) at what percent ratio to leaf waste produce the most effective biofuel. Each biofuel was tested for durability (minutes burned until ash), then a rice-cooking test was conducted between a potato starch-based biofuel and a cassava-based biofuel to identify the most effective fuel alternative for the local community.

Materials and Methods

Preparing Materials

Previous biofuel projects in Madagascar have successfully used clay and cassava as binding agents (Romaric, 2019). The biofuel recipe used in the Romaric paper describes how to mix sawdust biomass with a variety of binding agents to create biofuel balls. The directions to make this fuel include combining 1kg of sawdust, 1.5kg of charcoal powder, 1kg of clay, 0.5kg of laterite, and 1.5kg of cassava powder. Upon arrival in Vohimana, there was a lack of cassava and clay available for collection or purchase. However, people were growing potatoes nearby, which have similar starchy properties to cassava. While waiting for cassava and clay to become available, potato starch was made as a possible binding agent, given it was the most readily available product in the community.

Biomass materials for fuel production were made and collected over the course of multiple days as determined by availability around Vohimana and Ambavaniasy. One large bag of leaf waste was transported in a large bag from the distillery to Vohimana Reserve, then was spread over a tarp and left to dry outside for four days. Clay was collected using a shovel from the Ranomena riverbed next to Ambavaniasy, spread on a tarp, and left to dry outside for four days. 1 kilogram of cassava was bought from Ambavaniasy for 3000 Ariary ($0.68), peeled, sliced into thin discs, and spread on a tarp to dry outside for three days. To make potato starch, seven kilograms of potatoes were bought from Ambavaniasy at a price of 2000 Ar/kilo ($0.45). The potatoes were washed, peeled, then shred with a grater into a bucket. Every half kilo of potatoes was transferred to another pot and mixed with four cups of warm water, then the mixture was drained using a colander lined with thin cloth over a second bucket, separating the potatoes and conserving the water. The drained potatoes were returned to the pot and this process was repeated two more times. After all potatoes had undergone this process, the water was left to sit in the bucket for an hour, allowing the starch to settle on the bottom of the bucket. Afterwards, the warm water was dumped out and the bucket filled with cold water, which was left to sit for another hour. The water was then discarded, and the clean starch scooped off the bottom of the bucket into a thin tray. The starch was left to dry outside for two days. One kilogram of charcoal was taken from the kitchen supply in Vohimana Reserve. All materials were brought under the canopy of the Vohimana office upon anticipation of rainfall and stored inside the office from 6:00pm—7:30am. All dry materials were ground into a powder using a mortar and pestle, then separated into different containers. The ground leaves were also sifted using a colander to create a uniform powder. Length of drying time was based on material type and weather conditions; most days had intermittent sun with some rain. Observational data was collected regarding the availability of materials.

Creating Biofuel

An electronic scale was used to measure the mass of all required materials needed to create each biofuel. Water was added to a pot on a heated charcoal stove at 5 times the quantity of the binding material(s), including starch, cassava powder, or clay. The binding materials were then added into the pot. For biofuels using starch as a binding material, starch was added first and cooked down until the formation of a sticky substance. For biofuels using clay alongside another binding material, clay was always added last to ensure consistency. The pot was removed from heat once the desired binding consistency was achieved. The combustion material, including leaf powder and charcoal powder, was then added to the pot and incorporated using a spoon. The final mixture was then either a) pressed with a briquette press or b) hand pressed into half-palm sized balls. Each biofuel was placed in an open pot or a tray and left in the sun to dry for several days (Figure 4). Due to laterite and cassava being initially unavailable and wanting to test the effectiveness of the Romaric recipe, a similar biofuel was made by identifying the percent of binding agents and combustion materials in his recipe and mimicking it using the materials at hand: leaves, charcoal powder, starch, and clay. This is the only biofuel created using charcoal powder.

Figure 4: Biofuel balls drying the sun

To determine if a ball or briquette was ready for testing, they were cut in half and the middle visually assessed as dry or needing more time. Observational data was collected on both the processes necessary to create biofuel tests using different biomasses, and the most effective percent ratios of each binding agent in forming biofuel.

Durability Test

Once a biofuel test was determined to be dry, it was transported to the kitchen and tested for durability in a brick stove (Figure 5). Wood was chopped into thin long pieces and arranged in a pyramid in the middle of the stove, then lit by transferring a flame from an active stove using a piece of wood. An electronic scale was used to measure 15 grams of the biofuel. To achieve this mass, a mix of complete and halved balls were used, and the briquettes were broken into large pieces. The fuel was then added to the flame. A chronometer was started once the biofuel began to burn and turn dark in color. The biofuel was fanned throughout the test to aggravate the flame. The chronometer was stopped once all the biofuel turned into ash. This process was repeated three times for each biofuel test based on material availability. The average durability and standard deviation of each biofuel was calculated. Using Microsoft Excel, a correlation test was conducted between total binding agent percent ratio and average durability.

Figure 5: Clay stove used for Durability and Rice Cooking tests

Rice Cooking Test

Three members of the community were asked to fill a brick stove with charcoal as if they were about to cook a pot of rice. This quantity of charcoal was removed from the stove and measured using an electronic scale to determine the appropriate quantity of biofuel to make for the rice cooking test. The quantity of charcoal was massed at around 500g each time. Based on this observation and community interest in further comparing the effectiveness of potato starch and cassava as a binding agent, half a kilogram of 25% ratio starch biofuel and of 25% ratio cassava biofuel were produced using the methods described in “Creating Biofuel.” The stove was started using the methods as described in “Durability Test.” 500g of each biofuel was measured using an electronic scale, then placed in the stove. 400g of water was added to a pot, and initial water temperature taken in the middle of the pot with a thermometer. The pot was transferred to the stove, and a chronometer started. The tip of the thermometer remained in the middle of the pot throughout the duration of the study, and temperature measurements were taken each minute. Once the temperature of the pot reached 60ºC, 120g of rice was added to the pot. When the rice was deemed ready to eat by a community member, the chronometer was stopped. Rice cooking time and the heating rate from 0-60°C for each biofuel was calculated, and the effectiveness of each fuel compared.

Results

Experience and Observations

Table 1: Ingredients of Biofuels Effectively Created for Testing

Biofuel Test	Ingredients (g)				
	Leaf Waste	Charcoal Powder	Potato Starch	Cassava Powder	Clay
1	50		10		
2	40		10		
3	50		15		
4	40			10	
5	25			25	
6	50				10
7	25				25
8	167		25		8
9	50		25		25
10	67.5		40.5		40.5
11*	33	50	50		50
12	50			25	25
13	38		6	6	
14	25		12.5	12.5	

*****Jean Romaric recipe using local materials

Different quantities of binding agents are mixed with distillery biomass to achieve "biofuel tests" with varying percent ratios of binding agent(s) to leaf waste.

The first attempt at creating a biofuel followed the Romaric recipe in terms of percent of combustion material (≈50%) to binding agents (≈50%) using only leaves, starch, and clay (Test 10). Combining these ingredients with cold water and pressing it in the briquette maker was unsuccessful, and the product fell apart easily. However, upon further experimentation, when potato starch is added to warm water and boiled down it forms a thick, sticky substance that effectively holds leaves together (Figure 6). Another attempt to mimic this recipe using hot water proved more successful and a briquette, Test 10, could be formed.

Figure 6: Potato starch after being boiled down

Around Vohimana, the only area where clay was available was along the Ranomena riverbed, an hour walk from the reserve. Shoveling clay from the side of the river altered the landscape and introduced silt to the water. The transportation of clay proved difficult, and two men were needed to carry a small bag of clay from the river back to the reserve due to its weight. Additionally, using only clay as a binding agent produced a substance that lacked viscosity, and producing biofuel balls and briquettes was difficult. Therefore, to avoid the use of clay, I created multiple biofuels using only potato starch as a binding agent. The result was too sticky to use in a briquette press but could easily be molded into balls at a ratio of 30% starch to total leaf waste mass. Higher ratios of starch to leaves formed a substance that was too runny to form balls.

Cassava powder had thicker grains than potato starch, but similar properties. Attempting to make biofuel using cassava powder, leaves, and cold water was unsuccessful at both small and large binding agent ratios, and the ingredients did not stick to form a ball or briquette. However, cooking cassava powder in warm water using the same process as potato starch produced a similar thick substance that could be used to form biofuel balls, although the result was less sticky. Unlike potato starch, combining a higher percent ratio of cassava to leaf waste produced a sturdier biofuel ball. A biofuel ball with a 100% ratio of cassava powder to leaves had similar properties to a biofuel ball with a 25% ratio of potato starch to leaves. Attempting to create a biofuel ball using a less than 25% ratio of cassava powder to leaves did not form a substance sticky enough to form biofuel balls or sturdy briquettes.

When cassava and starch were used tangentially as binding agents in the same biofuel, the combined 100% binding agent ratio produced a soft substance that was difficult to mold into a ball, whereas the combined 30% ratio created a sturdier substance. Biofuels that used both cassava and clay as binding agents were easily moldable, as were biofuels that paired starch and clay.

The two biofuel briquettes tested for durability each needed about five days to completely dry in the sun, whereas biofuel balls needed only two days to dry. The efficiency of creating biofuel balls was more appealing due to project time constraints, therefore balls were preferred over briquettes for testing different mixtures of biomass.

Durability Test

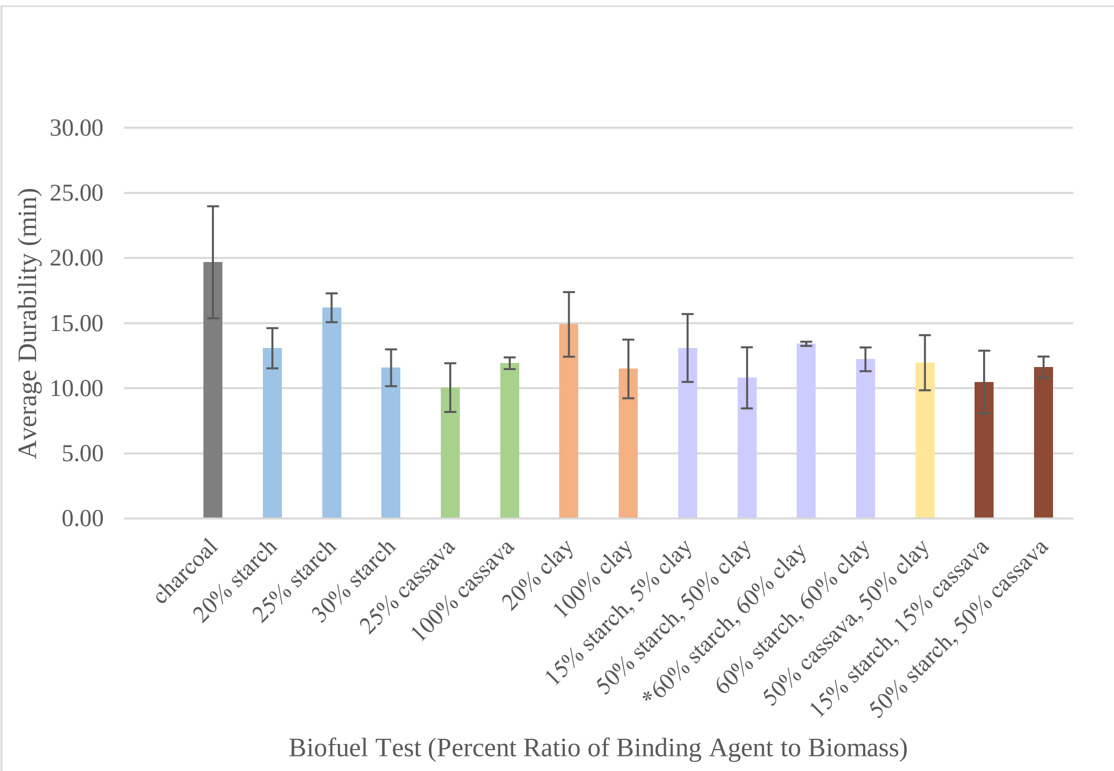

Figure 7: Average durability of biofuel tests. Charcoal had the highest average durability and turned to ash in 19.96 ± 4.30 minutes. The 25% starch biofuel had the second highest average durability at 16.18 ± 1.54 minutes, followed by 20% clay at 14.90 ± 0.45 minutes. The 25% cassava had the lowest average durability at 10.05 ± 1.41 minutes. A one-way ANOVA demonstrated that biofuel ingredients were significant for biofuel durability, $F(14,30)=4.43$, $p < .001$. Error bars represent the standard deviation for each biofuel test.

Biofuel Test 2, created from a 25% ratio of potato starch to leaf waste, was the most durable biofuel created with an average durability of 16.18 ± 1.54 minutes. Test 2 burned for an average of 1.28 minutes longer than the most effective clay-based biofuel (Test 6) and 4.26 minutes longer than the most effective cassava-based biofuel (Test 5). Test 2 also burned 2.77 minutes longer than Jean Romaric's 'mimic' recipe (Test 11), which contains charcoal powder. However, charcoal was still the most durable, and burned an average of 3.78 minutes longer than Test 2. Within the tests that used only starch as a binding material, Test 1 had a percent ratio of starch that was 10% less than Test 3 and burned for 1.50 minutes longer. Clay produced a similar result: Test 6 had a percent ratio of 80% less than Test 7 and burned 3.42 minutes longer. The opposite was observed for cassava-based tests; Test 4 had a percent ratio of 75% less than Test 5 and burned 1.87 minutes shorter.

Rice-Cooking Test

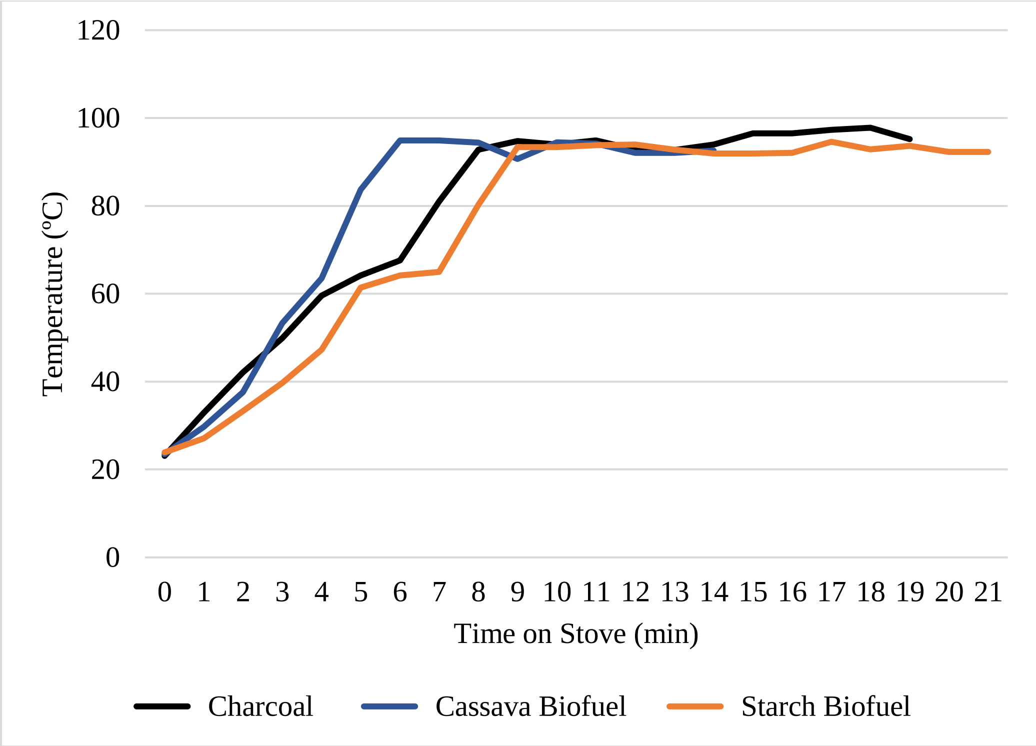

Figure 8: Temperature of rice pot throughout duration of rice-cooking time using charcoal, cassava biofuel, and starch biofuel. The pot using the cassava-based biofuel reached the rice addition point of 60ºC in 3.55 minutes at a rate of 9.66 ºC/min, then burnt too low after 14.0 minutes before the rice was completely cooked. The pot using the charcoal reached 60ºC in 4.17 minutes at a rate of 7.78 ºC/min and the rice was fully cooked in 19.4 minutes. The pot using the

starch biofuel reached 60 ºC in 4.80 minutes at a rate of 7.07 ºC/min and the rice was fully cooked in 20.3 minutes.

The Test 2 replicate (25% starch to leaf ratio) effectively cooked 120g of rice in 15.5 minutes, only 0.3 minutes slower than traditional charcoal, which cooked the rice in 15.2 minutes. Test 2 and traditional charcoal also had similar heating rates, with Test 2 heating the rice pot at a rate of 0.71 ºC/min slower than traditional charcoal. The Test 4 replicate (25% cassava to leaf ratio) initially heated the pot the fastest at a rate of 9.66 ºC/min but lacked the durability to fully cook the rice. As seen in Figure 9, after 14 minutes, the quantity of Test 4 was too low to continue cooking the rice. After the Test 2 Rice-Cooking Test, additional fuel remained that could continue being used in the stove. Charcoal had the greatest remaining fuel after testing.

Figure 9: Cassava-based biofuel (left) and starch-based biofuel (right) after completion of Rice-Cooking Test. A large quantity of the cassava biofuel has turned to ash, whereas the starch biofuel can continue to be used for cooking.

Discussion

Durability Test

Biofuel Test 2, created from a 25% ratio of potato starch to leaf waste, burned longer than the most durable clay-based biofuel and the most durable cassava-based biofuel, making it the most effective biofuel created at an average durability of 16.18 ± 1.54 minutes. The higher durability of Test 2 in comparison to Jean Romaric's 'mimic' Test 11 indicates that it is a viable alternative to other biofuels that contain charcoal. Although Test 2 was not as durable as traditional charcoal, its relatively high durability reveals that leaf waste from the local distillery can be used to create an effective biofuel.

In comparing the effectiveness of different binding agents when mixed with leaf biomass, biofuel made from a low percent ratio of clay or starch has a higher durability than biofuel with a greater percent ratio of cassava. Because a lower percent ratio of clay and starch are needed to produce a durable biofuel, the resulting fuel is cheaper, making starch and clay preferable binding agents. A greater percent ratio of cassava is required to produce a biofuel with the same durability as a biofuel with a low percent ratio of starch or clay, and the resulting fuel still has a lower burn time. Additionally, pairing cassava with clay or starch (Tests 12, 13, and 14) did not improve the durability of biofuel. Therefore, cassava is not an effective binding agent for distillery leaf waste because a greater quantity of it is needed to produce durable biofuel.

A weak correlation was found between total binding agent percent ratio and average durability, r (27) = 0.252, $p < .001$, suggesting that there is not an association between the quantity of binding agent(s) used and biofuel durability. Due to limited materials and project time constraints, only 3 durability trials could be conducted for each biofuel, and each biofuel varies greatly in the type and quantity of binding agent(s) used. This variation within the data makes it unsuitable for further statistical analysis. Additional trials of these biofuels would allow for more robust statistical analysis. One of these analyses can evaluate if there is a relation between durability and binding agent material, which would further reveal which binding agent produces the most durable biofuel when paired with distillery leaf waste.

Rice-Cooking Test

A biofuel made using a 25% starch to leaf-waste ratio can effectively cook rice at approximately the same efficiency as traditional charcoal, but a greater quantity of it is needed to contest its durability. In contrast, the 25% cassava to leaf-waste biofuel caused the quickest rise in temperature in the rice pot but lacked the durability to fully cook the rice. The 25% starch and 25% cassava biofuels were chosen for comparison due to community interest in evaluating the difference between cassava, which is a more traditional binding agent, and the less traditional potato starch. The greater success of starch-based biofuel suggests that fuel made by pairing leaf biomass with potato starch is more applicable to use in the kitchen than fuel made using cassava. However, due to limited materials and time constraints, only one rice-cook test was performed for two of the biofuel tests, and the small amount of rice cooked did not reveal how the fuels would perform if used to cook rice in a home. Conducting more rice-cooking trials for Test 2 and creating larger batches of the other high durability biofuels (Tests 6, 8, and 10) for comparison would further reveal which biofuels are effective for use in the kitchen. Repeating this test with a larger volume of rice would evaluate if these biofuels can be used to meet the cooking demands of a household in Madagascar. The high durability and cooking capability of Test 2 suggests that local distillery leaf waste can be transformed into an effective biofuel using only local resources as binding agents.

Improvements

Carbonizing the leaf waste from the distillery can potentially increase the durability of the fuel and enhance the speed of the fuel making process. A biofuel experiment by Abayomi et al. out of Abeokuta, Nigeria was conducted in 2021 comparing the performance of carbonized Neem leaf briquettes and uncarbonized Neem leaf briquettes mixed with cassava as a binder. 1000g of carbonized and uncarbonized briquettes were tested to boil one liter of water. The uncarbonized briquette effectively boiled water in 5.17 ± 0.03 minutes, suggesting that either a) cassava when paired with distillery leaf waste is not as effective a binder as it is for other biomasses or b) the distillery leaf waste needs to undergo another process before it can combine with a wider variety of binding materials to create an effective biofuel. The carbonized briquette boiled the water 0.88 minutes faster than the uncarbonized briquette, indicating that biofuel efficiency is improved by carbonizing the biomass. Additionally, the study found the calorific value of carbonized leaves to be 31.64 ± 0.08 MJ/Kg and uncarbonized leaves to be 24.22 ± 0.06 MJ/Kg respectively, revealing that carbonization also improved the quality of the biofuel (Abayomi, 2021).

To further improve the performance of Test 2 and other biofuel tests, leaf waste from the distillery can be carbonized before being mixed with a binding agent. Carbonization decomposes biomass at a high temperature in an oxygen free environment, which decreases the volatile matter and moisture content of the raw material and increases its carbon content, thereby improving the quality (Haykiri-Acma et al., 2013). There is a facility to carbonize material in Ambavaniasy, making this experiment practical for the local community.

Limitations

Due to a lack of expected materials available at my study site and the need to develop other options, preparing materials took a greater amount of time than anticipated and limited the number of biofuel tests that could be conducted. However, the initial lack of cassava and clay as a resource allowed me to utilize potato starch, which ended up producing the most effective biofuel. Additionally, after the starch was extracted from the potatoes, food remained that could be used in the kitchen and eaten. This versatile quality of the potato starch differed from cassava powder and clay, which were completely utilized in the production of biofuel. Additionally, using clay as a binding agent does not seem to be a viable option for the community due to its heavy weight and transportation difficulties, and instead poses a threat to the environment by eroding and introducing silt to the river. Conducting an economic analysis of the costs and benefits of each binding agent is another way to evaluate the potential of each material to create biofuel.

It took multiple days and physical labor to create and dry the materials, then additional work to manually form the biofuel and even more time to dry them in the sun. The onset of rainy season further complicated the time needed to dry materials. However, the energy taken to create the biofuel may still be less than time and effort needed to create traditional charcoal, which involves cutting trees, creating a *four de charbon,* and waiting for the wood to carbonize. Further examination needs to be completed to compare the efficiency of creating biofuel and charcoal. Using available machinery, such as the grinder at the distillery, and prioritizing biofuel production during the dry season can accelerate the production of materials.

Another limitation is the indeterminate quantity of biomass available at the distillery at a given time. The local distillery is in operation only several days a week based on essential oil demand, and the types of leaves cooked at the distillery also change based on demand. The distillery may not produce enough biomass to create fuel for everyone in the community, and tests have not been done to evaluate the effectiveness of other leaf wastes in the production of biofuel. However, even if there is not enough biomass to produce biofuel for everyone in the community, incorporating some biofuel into total fuel use would continue to combat deforestation.

Incorporating biofuel made from distillery biomass and local materials into everyday kitchen use can combat deforestation around Vohimana and preserve the biodiversity of the area. As more forests are cleared for fuel and farming, and fuel alternatives like gas remain expensive, local people search farther for sources of traditional fuel. Continued reliance on firewood and charcoal puts a strain on the community and on the environment. Finding a local, cheap solution to fuel consumption is essential for the health of the area and allows the local community to remain self-sufficient. Using biomass from the distillery presents no extra cost, and the distillery is located much closer to larger villages around Vohimana and Ambavaniasy than charcoal production sites, making biofuel easier to transport than traditional fuel. Additionally, pairing the leaf biomass with a binding agent like starch will continue supporting the local agricultural economy.

Conclusion

An effective biofuel was successfully created using leaf waste from the essential oil distillery and local ingredients around Vohimana. Test 2, made from a 25% ratio of potato starch to leaf biomass, was the most durable and reliable biofuel. It burned for an average of 16.18 minutes and cooked a small pot of rice in 15.5 minutes, only 0.3 minutes slower than traditional charcoal. The success of Test 2 suggests that potato starch is an effective binding agent and can be used in relatively small amounts to create a reliable biofuel when paired with leaf biomass. Leaf biomass compatibility with other binding agents like cassava may be improved by initial carbonization of leaf waste, a process which may also improve overall durability. Using biofuel made from distillery biomass and local materials as opposed to traditional charcoal and firewood can combat deforestation around Vohimana, preserve the biodiversity of the area, and allow the local community to remain self-sufficient.

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Appendix

Table A1: Biofuel durability based on percent ratio of binding agent to biomass; raw data, average, and standard deviation calculations

Fuel Type in Percent Ratio of Binding Agent to Biomass (15g)	Durability (min)				
	Trial 1	Trial 2	Trial 3	Average	Standard Deviation
charcoal	19.67	23.97	15.37	19.67	4.300
20% starch	13.20	14.55	11.47	13.07	1.544
25% starch	17.45	15.42	15.67	16.18	1.107
30% starch	10.00	12.75	11.95	11.57	1.415
25% cassava	11.30	10.95	7.90	10.05	1.870
100% cassava	12.17	11.40	12.18	11.92	0.447
20% clay	13.23	13.72	17.75	14.90	2.480
100% clay	10.18	14.08	10.18	11.48	2.252
15% starch, 5% clay	11.68	16.10	11.50	13.09	2.605
50% starch, 50% clay	13.48	9.78	9.13	10.80	2.346
60% starch, 60% clay	13.60	13.32	13.32	13.41	0.162
60% starch, 60% clay	13.27	11.73	11.65	12.22	0.913
50% cassava, 50% clay	10.12	11.48	14.27	11.96	2.116
15% starch, 15% cassava	12.35	11.32	7.77	10.48	2.403
50% starch, 50% cassava	12.07	10.68	12.10	11.62	0.811

Table A2: Total binding agent percent ratio for each biofuel test and its average durability

Biofuel Test	Total Binding Agent Percent Ratio	Average Durability (min)
1	20%	13.07
2	25%	16.18
3	30%	11.57
4	25%	10.05
5	100%	11.92
6	20%	14.90
7	100%	11.48
8	20%	13.09
9	100%	10.80
10	120%	13.41
11	120%	12.22
12	100%	11.96
13	30%	10.48
14	100%	11.62

Table A3: Temperature of rice pot each minute spent on stove for charcoal, cassava biofuel and starch biofuel raw data

	Temperature of Rice Pot°C		
Time on Stove (min)	Charcoal	Cassava Biofuel	Starch Biofuel
0	23.1	23.5	23.9
1	32.9	29.7	27.1
2	42.1	37.6	33.3
3	49.9	53.3	39.7
4	59.6	63.5	47.3
5	64.2	83.7	61.4
6	67.6	94.9	64.2
7	81.0	94.9	65.0
8	92.8	94.4	80.3
9	94.8	90.7	93.4
10	94.0	94.5	93.4
11	94.9	94.2	93.8
12	92.8	92.1	94.0
13	92.7	92.1	92.8
14	94.0	92.6	91.9
15	96.5		91.9
16	96.5		92.1
17	97.3		94.6
18	97.8		92.9
19	95.2		93.7
20			92.3
21			92.3

Table A4: One way ANOVA results for the effect of biofuel type on durability

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	261.032	14	18.6452	4.43364	0.00031	2.03742
Within Groups	126.162	30	4.20539			
Total	387.194	44				

Table A5: Correlation between average durability and total binding agent percent ratio

	Total Binding Agent Percent Ratio	*Average Durability (min)*
Total Binding Agent Percent Ratio	1	
Average Durability (min)	-0.25238883	1