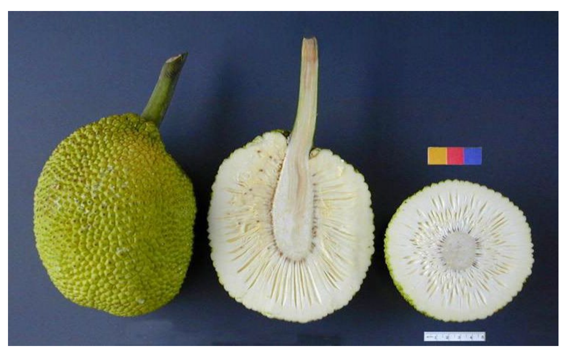
Swette Center for Sustainable Food Systems
Arizona State University

Is Breadfruit a Climate-Smart Choice?

Assessing the carbon footprint of breadfruit and value-added breadfruit products



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Swette Center for Sustainable Food Systems, Arizona State University
January 2025

This publication is a Capstone Report produced by Leanne Kami, completing the Master of Science in Sustainable Food Systems at Arizona State University.

Suggested Citation:
Kami, L. *Is Breadfruit a Climate-Smart Choice*? January, 2025. (Kami, 2025)

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Executive Summary

Breadfruit cultivation aligns with sustainable agricultural practices, such as agroforestry, which enhance climate resilience and overall sustainability. Like those traditionally used in Hawai'i and across the Pacific, agroforestry systems provide multiple ecosystem services and are gaining attention as a solution to food production challenges.

Rich in complex carbohydrates, vitamins, and minerals, breadfruit is a nutritious alternative staple crop. It is naturally gluten-free, high in fiber, and has a low glycemic index, making it suitable for people with dietary restrictions.

Breadfruit's short shelf life and high processing energy requirements pose challenges for commercial production. Modern processing for commercial-scale breadfruit production requires high energy consumption for refrigeration, cooking, freezing, and dehydration to extend its shelf life.

Despite these processing challenges, breadfruit has a lower carbon footprint than staples like potatoes and rice, especially considering its carbon sequestration potential. The study used two methods to assess greenhouse gas emissions: a simplified energy use method and a life cycle analysis (LCA) approach. When considering the potential for carbon sequestration, the LCA showed that breadfruit has a net negative carbon footprint.

Breadfruit presents a promising option for sustainable agriculture and climate change mitigation. Its cultivation can enhance food security, support sustainable agricultural practices, and contribute to climate resilience. However, further research and development are needed to optimize its processing and better understand production emissions to overcome challenges related to its short shelf life and high processing energy requirements.

Introduction

Breadfruit (Artocarpus artilis), also known as ʻulu in the Hawaiian language, originated in Papua New Guinea (Letman, 2019) and was traditionally cultivated through a holistic ecosystem approach called **agroforestry**. This method, practiced by cultures worldwide for centuries, is not just a tradition but a proven forest management strategy to increase production, resilience, and sustainability (Lincoln, Haensel, & Lee, 2023).

The challenge of feeding a growing human population while minimizing the impact on ecosystems and aiding in their regeneration is a pressing issue. The early inhabitants of the Pacific Islands faced similar challenges, where the increase in human populations necessitated sustainable food production methods that would not lead to ecosystem collapse (Lincoln, Haensel, & Lee, 2023). They employed various agroecological strategies, with forest management and arboriculture playing a significant role in maintaining ecosystem integrity (Lincoln, Haensel, & Lee, 2023). The breadfruit tree, which produces large, starchy fruits, was a key element in these strategies and spread throughout Polynesia as one of 24 "canoe crops," which collectively provided for all of life's vital needs (Letman, 2019).

Breadfruit production has declined in Hawaiʻi over the past century due to changing land uses and food preferences. Today, ʻulu is undergoing a "revʻulution" as sustainable agriculture practices such as agroforestry, crop rotation, cover crops, permaculture, organic farming, and integrated pest management are employed to address food security challenges on a global scale. These practices aim to protect soil, manage water wisely, minimize pollution, and promote biodiversity, aligning with the principles of environmental sustainability. In particular, breadfruit cultivation is recognized for its potential to contribute to climate-resilient food systems in low-latitude regions (Yang, Zerega, Montgomery, & Horton, 2022). Its cultivation alongside other food crops in agroforestry plots increases food security and bolsters these systems' resilience to climate change (Lincoln, Haensel, & Lee, 2023). Furthermore, breadfruit trees offer significant benefits to climate-smart agriculture, especially in carbon sequestration (Livingston & Lincoln, 2023).

Incorporating sustainable practices and crops like breadfruit into modern agriculture can play a vital role in addressing the dual challenges of ensuring food security and preserving ecosystem functions. These approaches mirror the wisdom of ancient Pacific Islander agricultural methods, demonstrating that traditional knowledge can inform and enhance contemporary efforts toward a more sustainable future.

There are many positive impacts associated with breadfruit production. However, breadfruit is seasonal and has a short shelf life, with fruit quickly ripening 1-3 days after harvest (National Tropical Botanical Garden, 2019). Traditionally, breadfruit was fermented and buried in underground pits as a way of preservation for food storage (Atchley & Cox, 1985) and was a preferred method of preparation for consumption (Pollock, 1984). Modern processing for commercial-scale breadfruit production requires high energy consumption through refrigeration, cooking, freezing, and dehydration to extend its shelf-life and season of availability.

Given its high processing requirements, this study aimed to identify the carbon footprint of fresh breadfruit and value-added products made from breadfruit in Hawaiʻi. The study also looked at Hawaiʻi grown breadfruit compared to similar imported staple starches.

Research Questions:

1. What is the carbon footprint of raw breadfruit and breadfruit value-added products?
2. How does the carbon footprint of fresh and frozen breadfruit compare to imported staples such as fresh and frozen potatoes and white rice?
3. Is breadfruit a climate-smart crop choice to address global food security?

Background

According to Livingston & Lincoln, “Breadfruit, and breadfruit agroforestry, remain vastly understudied despite significant international recognition of its potential roles in developing climate-smart agriculture in terms of mitigation, adaptation, and resilience.” (2023)

Breadfruit not only has the potential to sequester carbon in its biomass, but its cultivation often accompanies farming practices that are less intrusive and more regenerative (Livingston & Lincoln, 2023). Breadfruit holds the potential to be a significant part of the solution to the global hunger crisis, offering a ray of hope in the face of this pressing issue. It is an orchard crop that grows year-round, and as such, it requires less energy input, including water and fertilizer, than crops that need to be replanted yearly (Yang, Zerega, Montgomery, & Horton, 2022).

Like other trees, breadfruit sequesters carbon dioxide from the atmosphere over its lifetime (Yang, Zerega, Montgomery, & Horton, 2022). This means that breadfruit absorbs more carbon dioxide, a greenhouse gas, than it releases, helping to reduce its overall carbon footprint. Despite the challenges of climate change, breadfruit has shown remarkable resilience and is predicted to be relatively unaffected by shifting climates (Yang, Zerega, Montgomery, & Horton, 2022). This makes breadfruit a reliable and potentially essential crop for future food security and climate change mitigation strategies.

Multi-story cropping or Forest Farms, the traditional agroforestry system utilized in Hawaiʻi, holds immense potential and is gaining attention as a multifaceted solution to various agricultural challenges. In addition to providing ecosystem services, these forest farming systems offer a promising solution to food production challenges.

Methods Analysis

This research was conducted by a graduate student researcher under the supervision of Professor Kathleen Merrigan at the Swette Center for Sustainable Food Systems of Arizona State University. The research process included exploring the topic and questions, followed by a literature review and interviews with staff from the Hawai‘i ‘Ulu Cooperative. Data collection, analysis, and interpretation of the findings followed.

This study was reviewed by the Arizona State University Institutional Review Board (IRB). It was deemed exempt from review and approval by Arizona State University as the proposed activity is not research involving human subjects as defined by DHHS and FDA regulations. The IRB number is STUDY00020290.

Research Design, Scope and Limitations

Quantitative research methods used data from interviews with the Hawai‘i ‘Ulu Cooperative (HUC) staff. Secondary data referenced by the staff and found through desk research were also evaluated for inclusion in the study. The field production data is based on HUC’s agroforestry pilot with OK Farms and production models created in Overyield – an online tool designed to plan, evaluate, and monitor regenerative agriculture transitions. Qualitative information was also collected to understand field production practices, harvesting methods, and processing flows.

The scope of the carbon analysis starts with receiving raw produce at the processing facility and ends with the finished product. The analysis does not include carbon emissions associated with packaging and final-mile transportation to distributors, retailers, and consumers. The researcher did not include specific carbon emissions related to breadfruit farm production in the analysis due to inconsistent data on production practices used in the agroforestry pilot. Challenges arose in disaggregating and allocating inputs and fuel use amongst the diversified crops included in the pilot (see Figure 1).

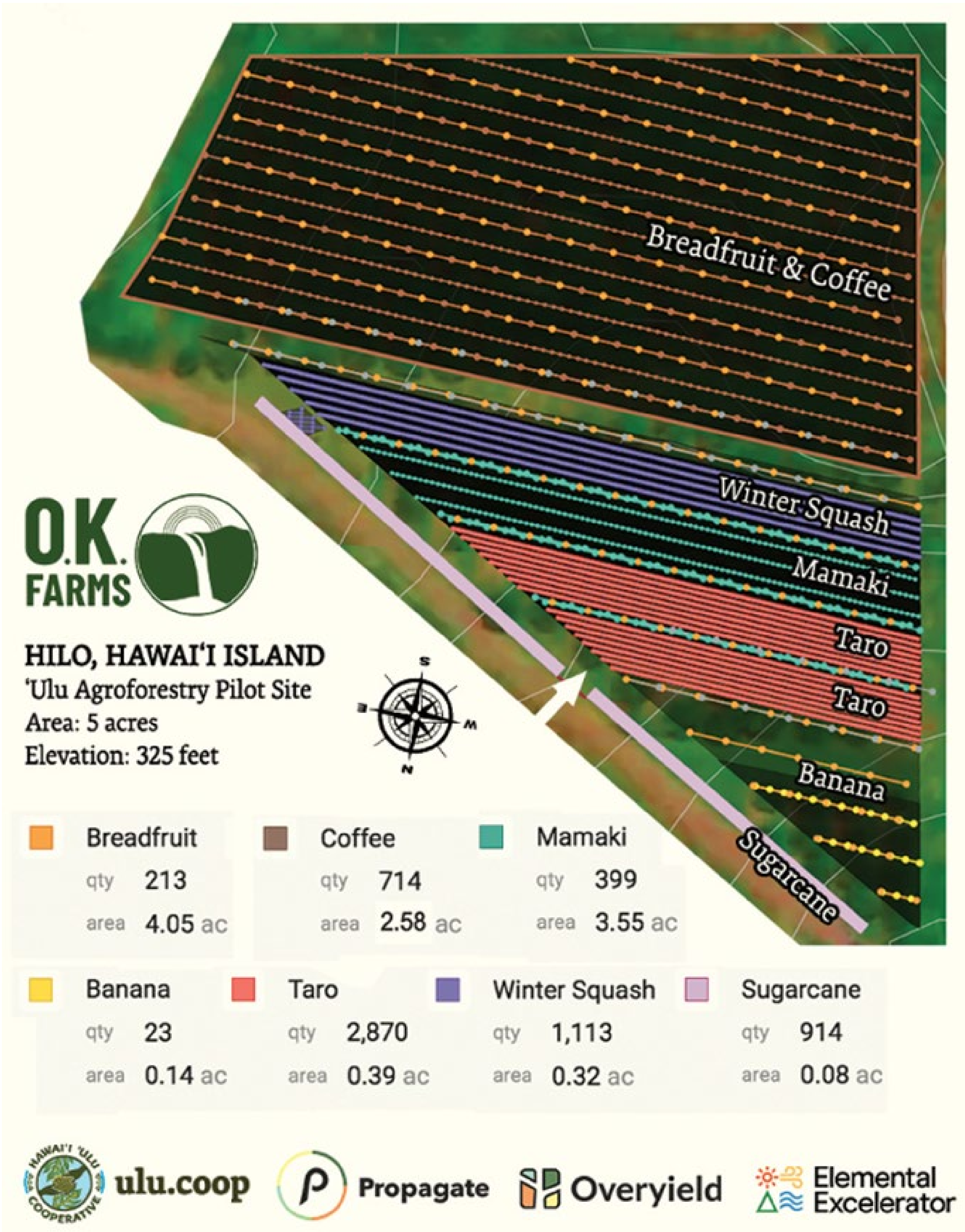

Figure 1: OK Farms Agroforestry Pilot (source: HUC 2022)

Assessment Methods and Assumptions

Two methods assessed the greenhouse gas emissions associated with breadfruit processing. The first is a simplified method incorporating overhead and sunk costs to look at total energy use at HUC's processing facility in Honalo. This facility processes steamed frozen breadfruit products. In addition to breadfruit, HUC processes taro, sweet potato, and winter squash at this facility. These crops go through similar processing steps and share the use of cold storage, and other shared overhead costs. For this simplified method, crop data has been consolidated. Therefore, the calculations estimate the total carbon footprint of peeled, cut, steamed, and frozen breadfruit, taro, sweet potato, and winter squash, with breadfruit accounting for 11% of the total finished product.

The second method to assess greenhouse gas emissions is based on a life cycle analysis approach, focusing on the direct energy used to process steamed frozen breadfruit and breadfruit flour. Research interviews identified equipment used at each processing step, equipment run times, and product throughput. The researcher then used this information to calculate the estimated kilowatt-hours (kWh) of energy consumption. The calculations represent a high estimate using the equipment manufacturer's label information, which assumes the equipment is used at maximum capacity. Based on HUC staff estimations, energy usage varies from 25-50% of capacity. Power monitoring equipment is needed to observe specific usage over time to refine the energy consumption calculations further.

The calculated energy consumption from both methods was then used to estimate greenhouse gas emissions using the Greenhouse Gas Equivalencies Calculator available from the U.S. Environmental Protection Agency (EPA) (United States Environmental Protection Agency, 2024). The Greenhouse Gas Equivalencies Calculator is a tool for understanding and communicating the impact of various activities on greenhouse gas emissions. It translates complex emission data into more relatable terms, such as the equivalent gallons of gasoline consumed or the number of gasoline-powered passenger vehicles per year.

The calculator employs the Global Warming Potentials (GWPs) from the Intergovernmental Panel on Climate Change's Fifth Assessment Report (AR5) to compute CO2 equivalents (CO2e) (United States Environmental Protection Agency, 2024), providing a standardized measure for comparing the potential climate impact of different gases over a specified period.

The calculator uses the AVoided Emissions and geneRation Tool (AVERT) to determine the CO2e emissions avoided by reducing kilowatt-hour consumption. This is particularly relevant for energy efficiency (EE) and renewable energy (RE) initiatives.

Literature Review

Carbon “Foodprint” in a Global Food System

Food’s carbon footprint or “Foodprint” refers to the greenhouse gas emissions produced by the entire life cycle of food from the farm to your plate (Green Eatz, 2022). According to the Food and Agriculture Organization of the United Nations (FAO), agrifood systems contribute about one-third of human-caused greenhouse gas emissions. These emissions come from activities within farms, land-use changes like deforestation, and processes before and after production, including food manufacturing, retail, household consumption, and disposal.

FAOSTAT provides detailed statistics on these emissions for over 200 countries from 1961 to 2022. In 2022, global agrifood systems emissions were 16.2 billion tonnes of CO_2, equivalent to a 10% increase since 2000 (Food and Agriculture Organization of the United Nations, 2024).

An article from Our World in Data addresses the common belief that eating locally is the most effective way to reduce the carbon footprint of one's diet. However, it argues that what we eat is significantly more important than where our food is grown. The research presented by Roser, Ritchie, and Rosado uses a comprehensive meta-analysis of global food systems, which includes data from over 38,000 farms across 119 countries (2023). It highlights that transportation contributes only a fraction of food's greenhouse gas emissions. Instead, the type of food produced has a much more significant impact.

The environmental impact of different crops is a complex and multifaceted issue, deeply intertwined with the global ecosystem and human practices. Agriculture is a significant human activity that profoundly affects the environment. It is a major consumer of freshwater, accounting for about 70% of global freshwater withdrawals (Roser, Ritchie, & Rosado, 2023), which can lead to water stress in various regions.

Half of the world's habitable land is utilized for agriculture (Roser, Ritchie, & Rosado, 2023), which has led to the loss of natural habitats, a primary factor in global biodiversity decline (Roser, Ritchie, & Rosado, 2023). The conversion of forests and wildlands into agricultural areas reduces the number of species and affects the carbon storage capacity of these ecosystems. According to Livingston and Lincoln, agricultural practices and their associated deforestation contribute to almost one-quarter of the world's greenhouse gas emissions (2023).

The type of crop grown also has varying environmental impacts. For instance, meat and dairy products generally have a higher carbon footprint than plant-based foods due to the additional resources required for raising livestock, such as feed, water, and land, as well as the methane emissions from ruminant digestion (Roser, Ritchie, & Rosado, 2023). Crop rotation, a practice where different crops are planted in succession to improve soil health and reduce pests, can mitigate some of these impacts by promoting a healthier ecosystem and reducing the need for chemical inputs.

Climate change itself influences agricultural practices and crop yields. Changes in temperature, precipitation, and extreme weather events can alter growing seasons, introduce new pests and diseases, and affect the nutritional quality of the food produced. Some crops may benefit from higher carbon dioxide concentrations, which can enhance growth and water efficiency, while others may suffer from increased heat and variability in water availability (Roser, Ritchie, & Rosado, 2023).

Addressing the environmental impact of crops involves a holistic approach that considers not only the type of crops grown but also the methods of cultivation and the broader food system.

Reducing Food's Environmental Impact

The environmental impact of food production is a complex issue due to the vast diversity of producers worldwide. A comprehensive study involving data from 38,700 farms has revealed significant variability in environmental impact, even among producers of the same product (Poore & Nemecek, 2018), suggesting considerable mitigation opportunities exist. However, achieving lower impacts is not straightforward due to trade-offs, various methods available to producers, and the interconnected nature of the supply chain.

The findings advocate for a strategy where producers actively monitor and report their environmental impacts, aim to meet environmental targets through a selection of practices, and transparently communicate their impacts to consumers. This approach is nascent as current dietary and production practices contribute to ecosystem degradation and water resource depletion (Poore & Nemecek, 2018).

The sheer scale and diversity of the agricultural sector exacerbate the challenge of mitigating environmental impacts. With over 570 million farms operating under various conditions and employing different farming techniques (Poore & Nemecek, 2018), finding universally effective solutions is daunting. The study suggests that addressing this issue requires a nuanced understanding of the agricultural landscape, including the recognition that food products undergo varying degrees of processing and international transport, further complicating the environmental footprint of our global food system.

The construction of a multi-indicator global database involved a comprehensive meta-analysis of 1,530 studies, encompassing 119 countries and 40 products that account for about 90% of global protein and calorie intake (Poore & Nemecek, 2018). The database measures five key environmental impact indicators: land use, freshwater withdrawals (adjusted for local water scarcity), greenhouse gas emissions, acidifying emissions, and eutrophying emissions. Although the database does not include breadfruit, it provides a roadmap for assessing carbon emissions.

Regarding agricultural productivity, the database considers factors such as yield, multi-cropping, fallow periods, and crop co-product allocation like straw. This comprehensive approach provides a more robust indicator of farm productivity and food security than yield alone. The assessment system spans from the initial inputs at the producer level to the point of retail. The collected data includes detailed inventories of outputs and inputs, such as fertilizer use, irrigation, soil, and climate conditions.

Environmental impacts are recorded at each stage of the supply chain, with greenhouse gas emissions further broken down into 20 different sources at the farm stage (Poore & Nemecek, 2018). New models were developed specifically to address gaps in data, particularly for nitrate leaching and aquaculture. Additionally, the studies provided around 1,050 estimates for post-farm processes (Poore & Nemecek, 2018). Where there were gaps in data on processing, packaging, or retail stages, further meta-analyses were conducted to provide a comprehensive view of the environmental impacts of food production (Poore & Nemecek, 2018).

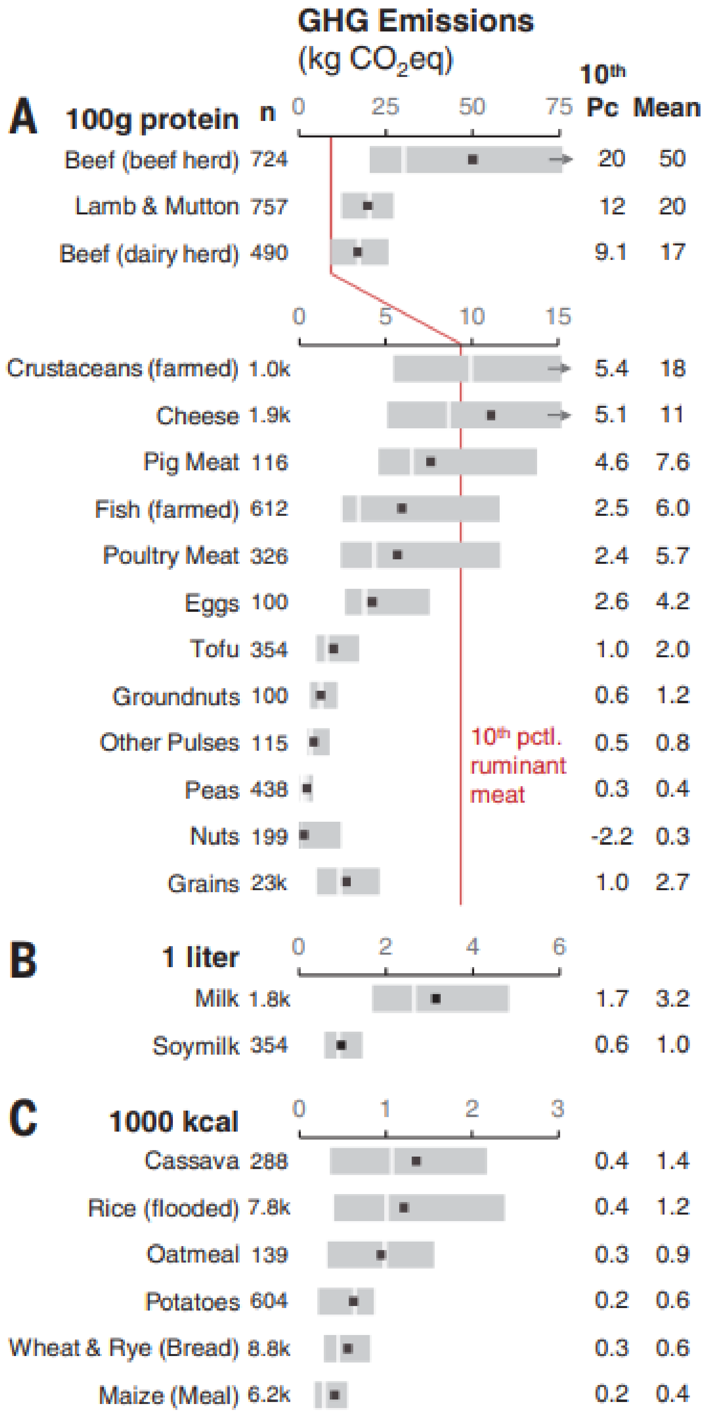

Figure 2. "Reducing Food's Environmental Impacts Through Producers and Consumers" - Estimated global GHG emissions variation within and between 40 major foods. (A) Protein-rich products including grains (which contribute 41% of global protein intake, despite lower protein content.) (B) Milks. (C) Starch-rich products. (Poore & Nemecek, 2018)

Carbon Sequestration Potential of Breadfruit

As a tropical tree that produces large, carbohydrate-rich fruit (Ragone, 2014), breadfruit has been pushed forward by advocates as a climate solution and a way to strengthen food security (Livingston & Lincoln, 2023) (Yang et al., 2022). According to Yang et al., increased breadfruit cultivation can enhance climate resilience and the sustainability of low-latitude agricultural systems (2022).

However, researchers from the University of Hawaiʻi at Mānoa found that breadfruit's carbon storage abilities in orchards are relatively low compared with other broadleaf trees in wet environments (Livingston & Lincoln, 2023). The study used allometric equations to predict tree volume and carbon sequestration based on tree diameter at breast height. Livingston and Lincoln calculated that over 20 years, breadfruit orchards can sequester approximately 69.1 tons of carbon per hectare (2023).

If planted at the recommended density of 100 trees/ha (approx. 48/acre) (Hawaiʻi ʻUlu Cooperative, 2024), this equates to approximately 0.03 tons (30 kg) of carbon per tree each year. Based on the OK Farms pilot, the Overyield software estimates on the low end that each breadfruit tree will yield an average of 250 lbs (113 kg) of fruit/tree/year, equating to approximately 0.26kg of CO_2 sequestered for each kilogram of fruit produced.

Despite its low carbon storage, breadfruit compensates for this with a fast growth rate of up to four feet per year (Livingston & Lincoln, 2023), potentially allowing it to put away carbon much faster than other slow-growing trees. Breadfruit also requires less energy input, including water and fertilizer, than crops that must be replanted annually (Livingston & Lincoln, 2023).

Although production emissions are not part of the scope of this study analysis, they are estimated to be very low. Emissions for breadfruit management in the OK Farms agroforestry pilot mainly came from applying fertilizer and mulch annually, occasional mowing, and pruning once a year using hand-held power tools. The pilot trees are not mature, but harvesting is typically performed manually. In addition to carbon sequestration, breadfruit provides shade, stabilizes the soil, benefits watersheds, and provides many invaluable environmental benefits. Production in an agroforestry model also increases overall carbon sequestration potential and spreads the carbon emissions associated with inputs and maintenance across multiple crops, further reducing Breadfruit's contribution.

Nutritional Potential of Breadfruit

Breadfruit is a rich source of complex carbohydrates, vitamins, and minerals and contains essential amino acids, making it a substantial food source that can aid in combating global hunger (Liu, Brown, Ragone, Gibson, & Murch, 2020). Protein deficiency is a significant cause of global malnutrition; although inequalities between countries are shrinking, protein-energy deficiencies in Asian and African countries may continue to increase (Jiang et al., 2023).

A study by Liu, Ragone, and Murch evaluated the protein quality of 49 breadfruit cultivars, finding that all varieties were rich in phenylalanine, isoleucine, and valine (2015). Although the U.S. Department of Agriculture's National Nutrient Database lists 100g of cooked breadfruit as having 1.1 g of protein per 100g serving, three breadfruit varieties Ragone evaluated (Ma'afala, Hawaiian 'Ulu, and Meinpadahk) contained an average of 4g of protein per 100 g (2014). According to Golden and Williams, breadfruit contains all the essential amino acids (2001). The Ma'afala cultivar, in particular, had the highest total essential amino acid content and an average of 7.6% protein by dry weight that was superior in quality compared to everyday staples like corn, wheat, rice, soybean, potato, and pea (Liu, Ragone, Murch, 2015). Breadfruit is also rich in essential nutrients like potassium, magnesium, phosphorus, and vitamins such as vitamin C, thiamine (B1), and niacin (B3) (Frey, 2022). Ragone's research found that breadfruit contains carotenoids like β-carotene and lutein, absent in white rice and potatoes (2014).

A low to moderate glycemic index makes breadfruit a good option for managing blood sugar levels (Frey, 2022) (Ragone, 2014). By providing 25% of the recommended daily allowance of dietary fiber per 100g serving, breadfruit aids in digestion and helps regulate blood sugar levels (Frey, 2022) (Ragone, 2014). Compared with data from the U.S. Department of Agriculture's National Nutrient Database, per 100g serving, breadfruit delivers twice the amount of fiber found in white potatoes and 16 times the fiber found in white rice (2025).

Like potatoes, Breadfruit can be used in various culinary applications and processed into gluten-free flour, making it an ideal starch for people with allergies, celiac disease, and irritable bowel syndrome (Hawai'i 'Ulu Cooperative, 2024). Research on breadfruit starch demonstrates its advantages over wheat flour in water and oil holding capacity, swelling power, and viscosity. Cooking with breadfruit flour also does not seem to alter the bioactive compounds it contains. (Liu, Brown, Ragone, Gibson, & Murch, 2020)

Table 1: Nutritional Comparison of Breadfruit, Potatoes, and White Rice (per 100g serving) (USDA FoodData Central, 2025)

Nutrient	Breadfruit	Potatoes	Rice (white, cooked)
Calories	103	77	130
Protein	1.1 g	2 g	2.4 g
Carbohydrates	27.1 g	17.5 g	28.6 g
Fiber	4.9 g	2.4 g	0.3 g
Fat	0.2 g	0.1 g	0.3 g
Potassium	490 mg	407 mg	35 mg
Vitamin C	29 mg	19.7 mg	0 mg
Calcium	17 mg	9 mg	10 mg
Iron	0.5 mg	0.8 mg	1.2 mg
Magnesium	25 mg	23 mg	13 mg

Analysis of Key Findings

Simplified Analysis

Using the simplified analysis method based on total energy consumption at HUC's Honalo facility between July 2023 and June 2024, the total kWh usage was 56,719 kWh. This calculation includes credits received by the utility company as part of HUC's renewable energy Net Energy Metering system (Hawaiian Electric, n.d.). Using the U.S. Environmental Protection Agencies Greenhouse Gas Equivalencies Calculator, the annual energy usage at the Honalo facility equates to 31,334kg of Carbon Dioxide equivalent (CO2e), which is equivalent to the greenhouse gas emissions from 7.3 gasoline-powered passenger vehicles driven for one year or the energy use of three homes for one year (United States Environmental Protection Agency, 2024).

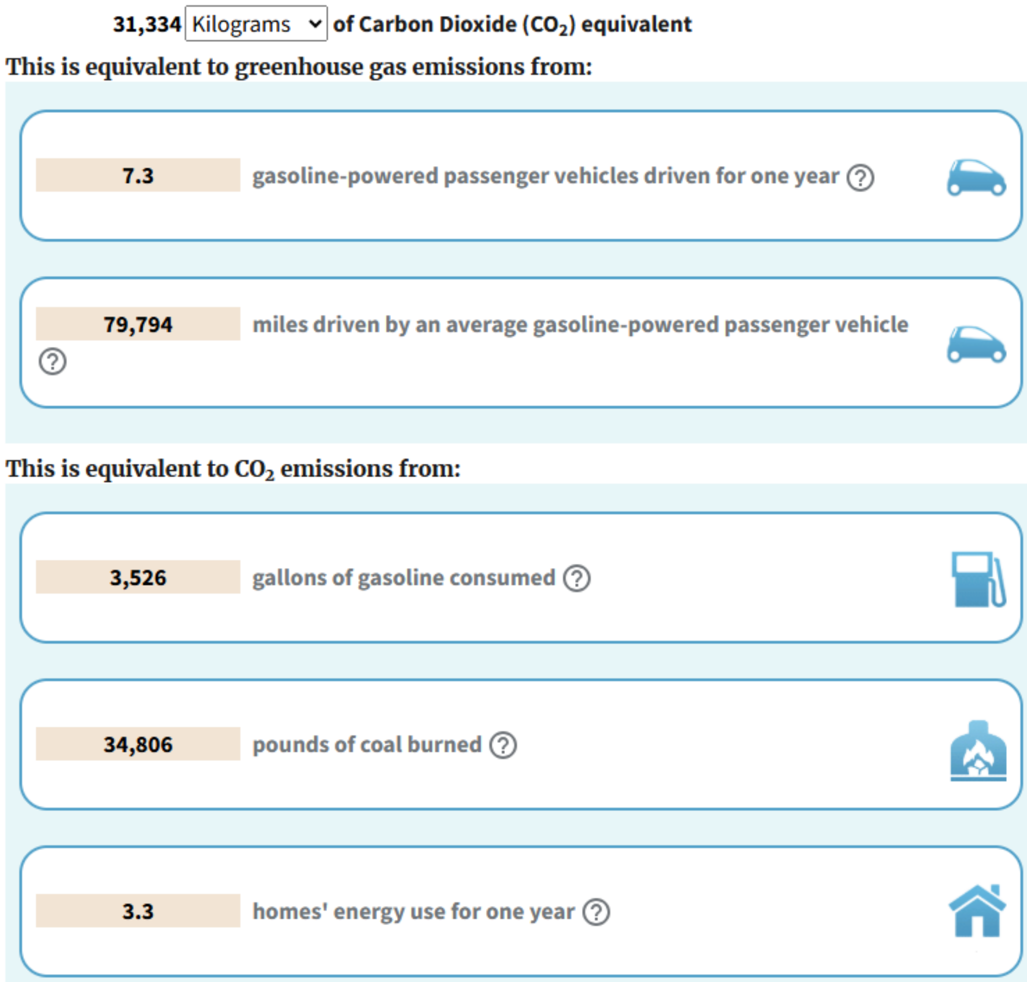

Figure 3: U.S. Environmental Protection Agencies Greenhouse Gas Equivalencies Calculator

Processing throughput data, averaging 7,580kg (16,713 lbs) of finished product in May and June 2024, show that the two-month average of 5,222kg of CO2e used to operate the facility equates to approximately 0.69kg of CO2e for every kilogram of steamed frozen product.

Life Cycle Analysis

Using the Life Cycle Analysis (LCA) method, process flowcharts obtained from HUC were examined to determine energy consumption points during the life cycle of breadfruit value-added processes. The specific equipment used at each processing stage was identified, and kilowatt information was calculated based on the equipment manufacturing label. The calculations in Table 2 and Table 3 below show the CO2 equivalent emissions for each processing stage and the total grams of CO2e emitted per pound of raw breadfruit, steamed frozen breadfruit, and breadfruit flour. The calculations and run times are based on processing 227kg (500 lbs) of raw fruit.

Table 2: CO2 equivalent calculations for life cycle analysis of steamed frozen breadfruit based on processing 227kg (500 lbs).

Equipment/ Process	Make/ Model	kW	Estimated run time (hours)	Total kWh usage	CO2e(kg)	CO2e (kg)/kg of fruit
Tumble wash	Vanmark Peeler	2.685	0.10	0.4	0.2	0.001
Industrial peeler	Unknown	1	1	1	0.6	0.003
Industrial Slicer	Urschel G-A 3721	1.5	6.6	0.6	0.3	0.001
Steamer	Accutemp 240 D6	11	6.6	73.3	41	0.181
Blast freezer	Heatcraft	5.35	.5	2.6	1	0.004
Weigh & bag	Fairbanks	0.01	2.5	0.02	0	0*
Freezer Storage	Hoshizaki 13506	0.26	24	6.2	3	0.013
Total				**84 kWh**	**46kg**	**0.2kg**

* The amount of energy used to weigh, and bag was too low to calculate CO2e/lb

Table 3: CO2 equivalent calculations for life cycle analysis of breadfruit flour based on processing 227kg (500 lbs).

Equipment/ Process	Make/ Model	kW	Estimated time (hours)	Total kWh usage	CO2e(kg)	CO2e (kg)/kg of fruit
Dehydrator (fan + heater)	Harvest Saver Pro/HS-R-SS-1-E	9.2	40	368	203	0.89
Milling (Hammer mill + filter)	Colorado Hammer Mill /HMS-VB-HT-3 & Cyclone filter/5018ES3E5 6CFL-S	3.7	1.6	6.2	3	0.013
Bagging/sealing	Impak/ VakRapid 2.5	0.7	5	3.6	2	0.009
Fan x 2	Commercial Electric Drum Fan	0.4 x 2	6	5.3	2	0.009
Air Filtration	JET AFS - 1000B	0.4	6	2.2	1	0.004
Total				**385 kWh**	**211kg**	**0.93kg**

Discussion

Based on estimated yields and allometric calculations by Livingston & Lincoln (2023), we can estimate that with a target yield of 250 lbs (113 kg) of fruit/tree/year through sequestration over 20 years, breadfruit offsets its carbon footprint by an estimated 0.26kg of CO2e per kilogram of fruit. Creating a net negative carbon footprint of (-0.26kg) CO2e per kilogram of fresh/raw breadfruit and (-0.06kg) CO2e per kilogram of steamed/frozen breadfruit (based on LCA method).

Table 4: Comparison of CO2e in kilograms per kilogram of product. Includes CO2e when factoring carbon sequestration potential.

	Simple Method	Life Cycle Analysis (LCA)	Including Carbon Sequestration
Fresh/Raw (whole)	-	0.001kg CO2e	(-0.26kg) CO2e (LCA)
Steamed Frozen	0.69kg CO2e	0.2kg CO2e	0.43 CO2e (Simple) (-0.06kg) CO2e (LCA)
Flour	-	211kg CO2e	0.16kg CO2e (LCA)

Breadfruit in Comparison to Other Staple Crops

Rice has the highest greenhouse gas emissions from the staple starches at 4.5kg CO2e, with maize, wheat, and rye in the midrange at 1.6-1.7 kg (Our World in Data, 2024). Potatoes' average greenhouse gas emissions are the lowest at 0.46kg CO2e per kilogram (Our World in Data, 2024). However, not accounting for carbon sequestration potential, potato emissions are still 460 times higher than the estimated 0.001kg CO2e for raw breadfruit and over two times higher than steamed frozen breadfruit.

Although farm practices, transport, retail, packaging, and loss emissions for breadfruit are not included in the scope of this study, according to Our World in Data, transportation accounts for a minimal portion of a food's carbon footprint (Roser, Ritchie, & Rosado, 2023). Farm practices contributed the most emissions for rice and potatoes (Our World in Data, 2024). In comparison, production via agroforestry methods tends to require fewer inputs (Livingston & Lincoln, 2023) and less farm equipment use than crops that require annual planting

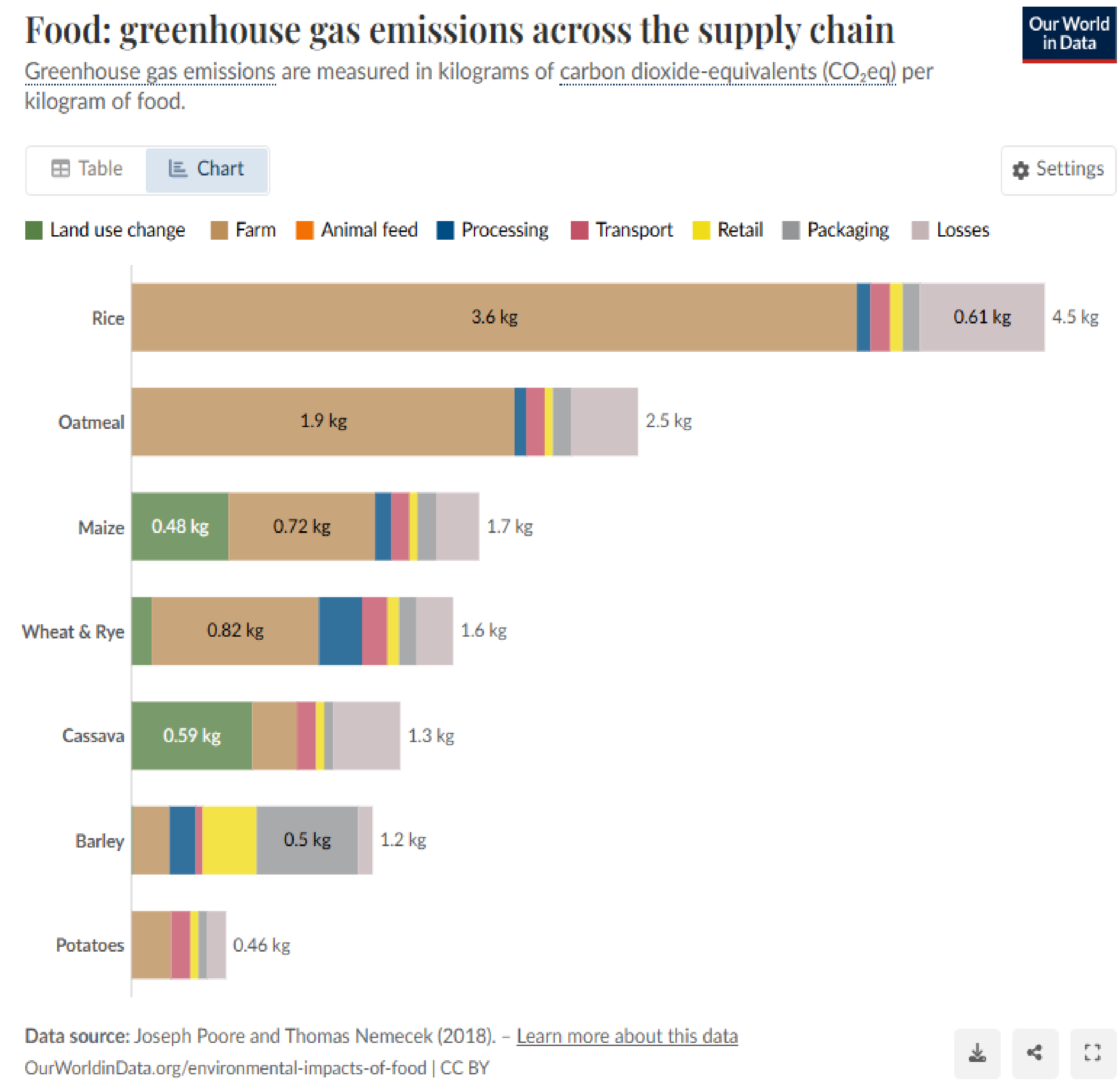

Figure 4: Greenhouse gas emissions across the supply chain for staple starches (Our World in Data, 2024)(Poore and Nemecek, 2018) .

Although this data shows promise for processed breadfruit compared to other staple starches, further research is needed to identify specific emissions associated with the remaining supply chain gaps to make an accurate comparison.

Case Study for Collaboration

The Hawai‘i ‘Ulu Cooperative (HUC) is an agroforestry advocate and pioneer in commercial breadfruit production in Hawai‘i. It is a farmer-owned business that aims to improve Hawai‘i’s food security by revitalizing traditional Hawaiian staple starches such as ‘ulu (breadfruit), ‘uala (sweet potato), and Kalo (taro). These crops were once part of the daily Hawaiian diet and are significant for their health benefits and cultural value.

In 2021, HUC won Elemental Excelerator’s ‘Ohana Award in partnership with Propagate, an agroforestry startup at the forefront of the agroforestry movement (Watson, 2024). In partnership with OK Farms, the collaboration addresses a critical need in Hawai‘i’s food security efforts by demonstrating breadfruit agroforestry's long-term economic and environmental benefits.

Propagate’s mission is to overcome the three primary obstacles hindering the widespread adoption of agroforestry: awareness, technical knowledge, and capital (Watson, 2024). By providing an innovative IT platform called Overyield, Propagate assists farmers in planning and implementing tree-planting strategies tailored to their land's unique characteristics. This platform estimates costs, labor, and suitability, offering a comprehensive tool for decision-making.

Propagate collaborates with Agroforestry Partners to address the financial barrier and leverages funding from the USDA's Climate Smart Commodities initiative, facilitating access to the necessary resources for farmers to initiate agroforestry projects. Despite these efforts, agroforestry remains underutilized in the United States, with less than 1.5% of farmland employing this method (Watson, 2024). The reasons are multifaceted, but HUC and Propagate's work is a significant step towards changing this statistic by demonstrating that agroforestry can be a viable and beneficial practice for farmers nationwide with the proper support and resources.

Recommendations

The environmental impact of specific crop production is an issue that requires attention from various stakeholders, including farmers, policymakers, researchers, and consumers. To advance breadfruit as a carbon-smart crop, a wide range of needs need to be addressed. By understanding the complexities and taking collaborative action to promote sustainable and regenerative practices, producing food that respects and preserves the natural environment is possible.

The recommendations below outline steps that Hawai'i can take to enhance the sustainability and viability of breadfruit as a key crop for carbon-smart agriculture, contributing to global food security and environmental resilience.

Improve Agricultural Practices

Agroforestry Expansion: Promote the expansion of agroforestry systems that integrate breadfruit with other crops and trees to enhance biodiversity and ecosystem services.
Farming Techniques: Encourage the adoption of farming techniques, such as traditional Polynesian methods, organic farming, and permaculture, to reduce the environmental impact of breadfruit cultivation.

Optimize Processing and Storage

Energy-Efficient Technologies: Invest in renewable energy and research and development of energy-efficient technologies for processing and storing breadfruit to reduce its high energy consumption.
Shelf-Life Extension: Develop innovative methods to extend the shelf life of breadfruit, such as improved refrigeration techniques and natural preservatives.

Policy Development

Incentives for Sustainable Practices: Implement policies incentivizing farmers and processors to adopt sustainable practices, such as subsidies or reduced taxes for processing breadfruit and installing agroforests.

Research and Development: Increase funding for research and development focused on breadfruit cultivation, processing, and storage to address existing challenges and unlock its full potential.
Carbon Markets: Establish regulatory frameworks and policies for carbon markets that can accurately represent the carbon sequestration potential of breadfruit and similar crops.
Public Awareness Campaigns: Launch public awareness campaigns to educate consumers about the benefits of breadfruit and encourage its consumption as a sustainable alternative to imported staple crops.

Collaboration and Partnerships

Stakeholder Engagement: Foster collaboration between farmers, researchers, policymakers, and industry stakeholders to share knowledge and best practices for breadfruit cultivation and processing.
International Cooperation: Engage in international cooperation to learn from successful breadfruit initiatives in other regions and share best practices adapted to the local context in Hawai'i.
Collaborative Investment & Public/Private Partnerships: Expand public/private partnerships and leverage investments to expand breadfruit production and processing. See the Case Study above.

Data Collection and Analysis

Expand Data Sources: Incorporate data from a broader range of breadfruit farms and processing facilities to comprehensively analyze its carbon footprint and sustainability.
Longitudinal Studies: Conduct long-term studies to monitor the carbon sequestration potential of breadfruit trees over their entire lifecycle, including sequestration data for commonly used agroforestry co-crops.
Advanced LCA Methods: Utilize more advanced life cycle analysis (LCA) methods to capture the full environmental impact of breadfruit production, including indirect emissions from packaging, product distribution, and land-use changes.

Conclusion

Breadfruit is gaining attention as a valuable component of climate-smart agriculture due to its ability to adapt to and mitigate the impacts of climate change (Livingston & Lincoln, 2023) (Yang, Zerega, Montgomery, & Horton, 2022). As a long-lived tropical tree, it offers significant potential for carbon sequestration in its biomass, enhanced by sustainable farming practices like reduced tillage and co-cropping (Livingston & Lincoln, 2023). These methods increase carbon storage and contribute to soil health and biodiversity.

The study highlights the significant potential of breadfruit as a sustainable agricultural crop in Hawai'i. Breadfruit's lower carbon footprint compared to imported staple starches, combined with its ability to sequester carbon, positions it as a valuable crop for climate-smart agriculture. The cultivation of breadfruit aligns with sustainable and regenerative practices, offering superior nutritional benefits to other staple starches, further contributing to food security. Despite challenges such as its short shelf life and high processing energy requirements, Breadfruit is a carbon-negative crop.

Despite its potential, breadfruit agroforestry and its role in carbon market projects are still emerging fields. Current carbon accounting protocols are yet to fully incorporate crops like breadfruit (Livingston & Lincoln, 2023). This gap highlights the need for further research and development of methodologies that can accurately represent the carbon sequestration potential of breadfruit and similar crops in carbon market frameworks. As the science progresses, breadfruit is a promising candidate for future climate-resilient food systems and carbon offset projects.

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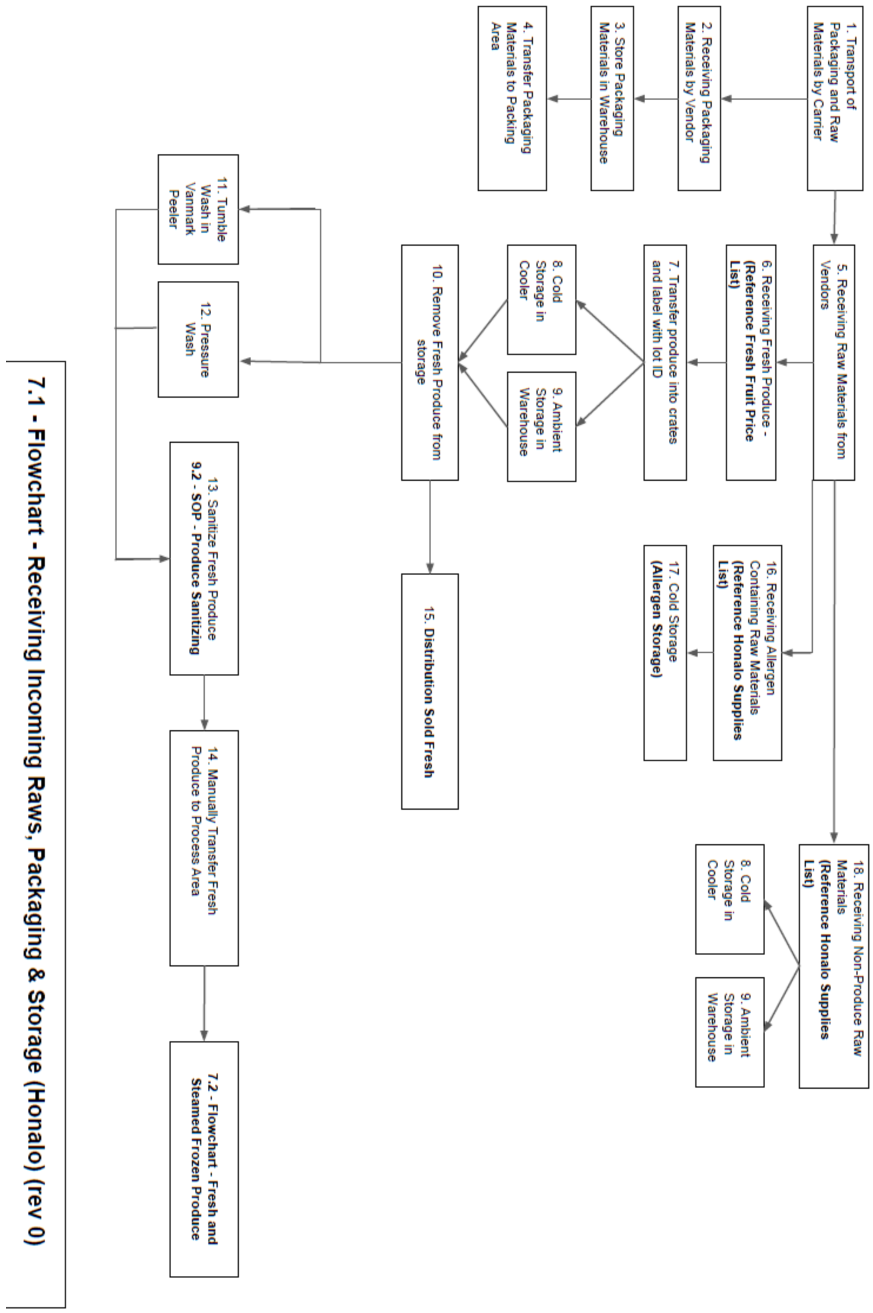
Appendix

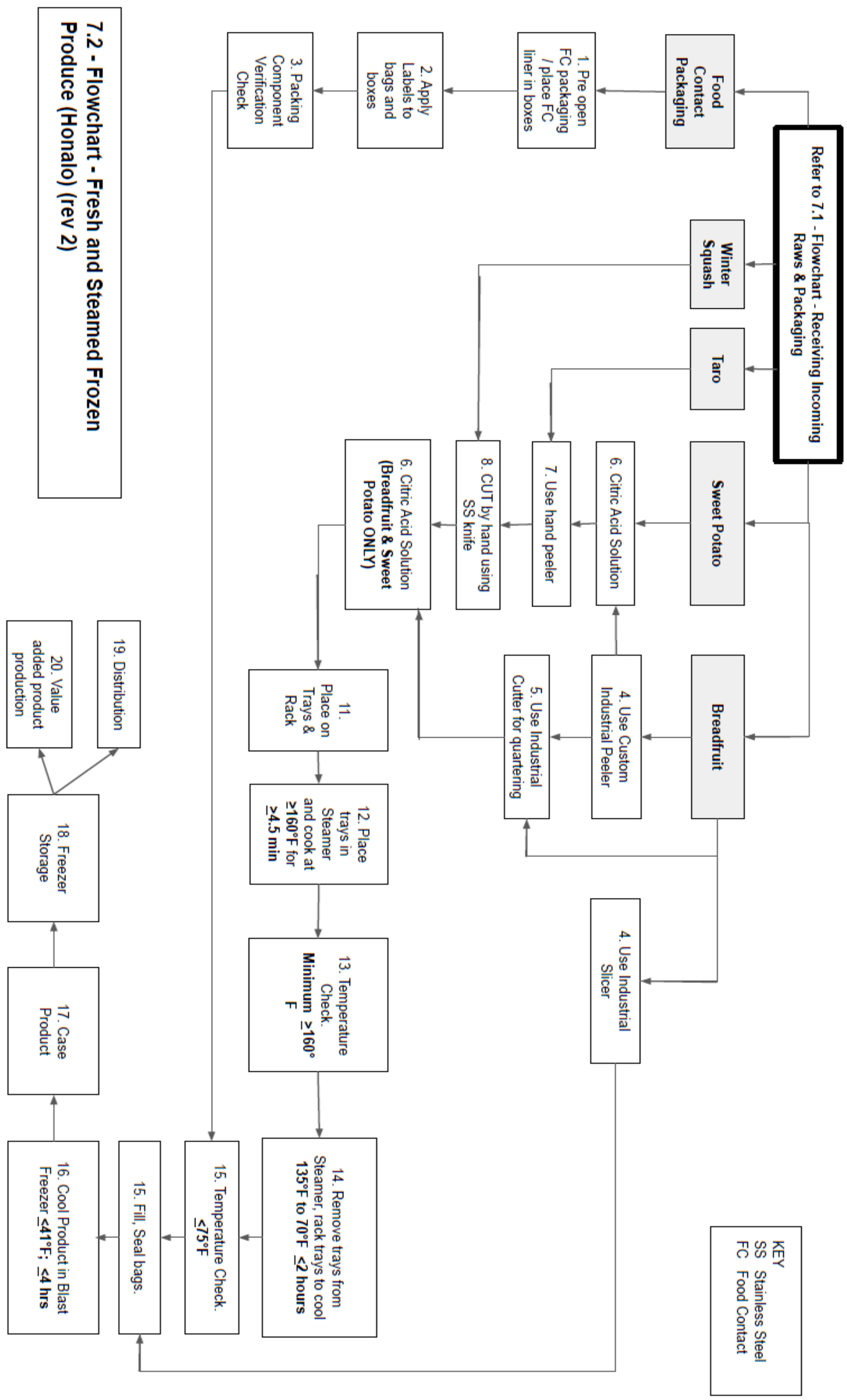
Appendix A

Process Flow Chart for Receiving Incoming Raws, Packaging & Storage
(Chart Source: HUC, Direct Communications, July 2024)



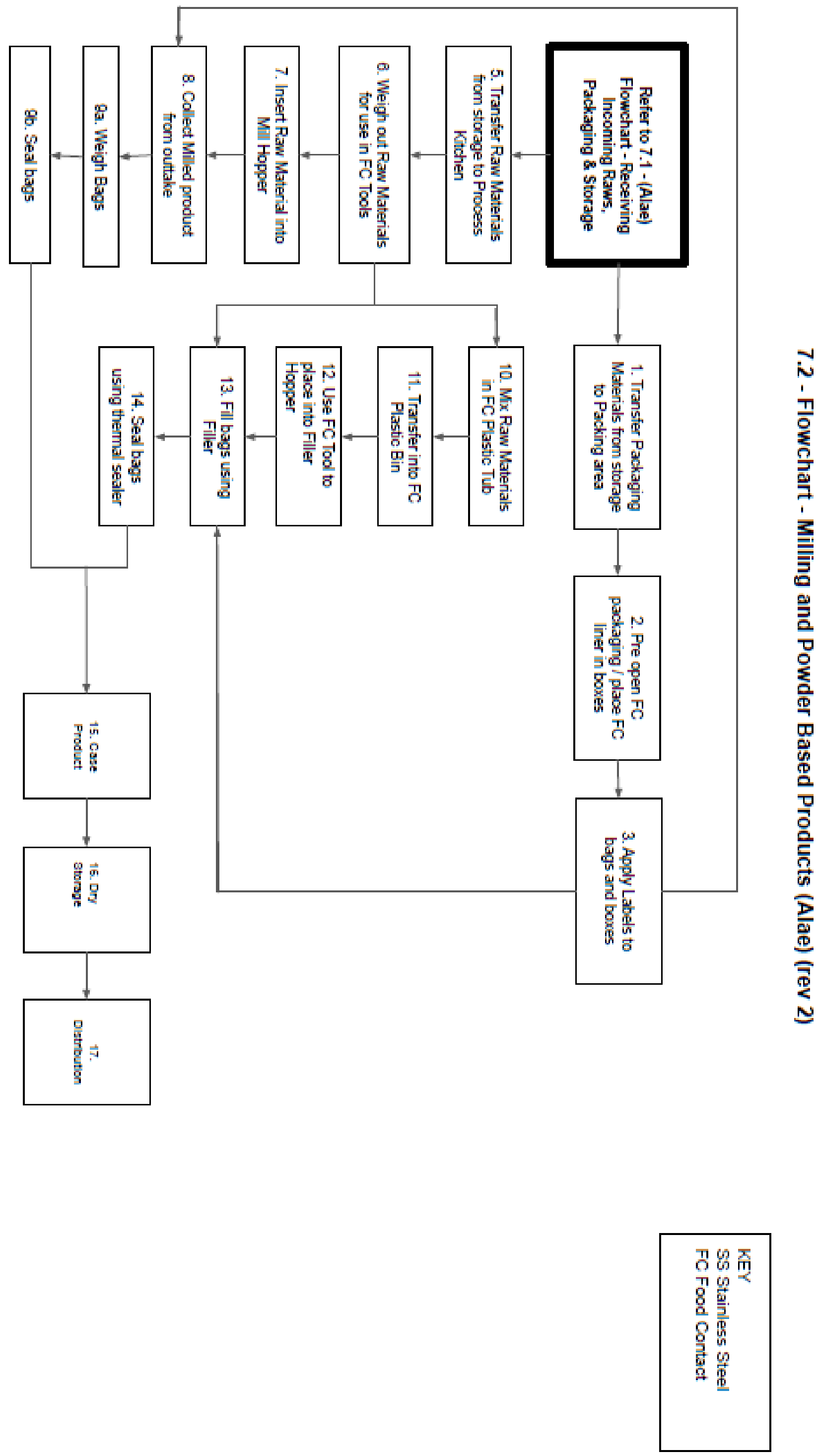
Appendix B

Process Flow Chart for Fresh and Steamed Frozen Breadfruit
(Chart Source: HUC, Direct Communications, July 2024)



Appendix C

Process Flowchart Milling and Powder Based Products
(Chart Source: HUC, Direct Communications, July 2024)



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Leanne was born and raised in Puna on Hawaiʻi island and resides in Panaʻewa with her husband and two sons. She holds a B.A. in Communication from the University of Hawaiʻi at Hilo and an M.S. in Sustainable Food Systems from Arizona State University. As a Strategy Consultant at Kamehameha Schools, Leanne focuses on strengthening local food systems and increasing agriculture production in Hawaiʻi. As a Native Hawaiian business owner and principal of Kohana Family Farms and Lelehua Consulting, LLC, Leanne also has a working knowledge of agriculture. She has spent her career helping non-profits, advocating for farmers, and educating communities using indigenous and regenerative ag practices.

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