Closing Agricultural Nutrient Gaps with Human Waste Streams: Case Study of Tongatapu

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ENVS3016: Special Research Topic

4 June, 2021

Abstract

Global soil quality is declining with the depletion of nitrogen, phosphorus and potassium (NPK) macronutrients and soil organic carbon (SOC) as a result of human activity. Reduced soil health has stagnated farming productivity in Pacific Island Countries (PICs) such as Tonga, forcing high importation of expensive chemical fertilisers (~$500,000 per annum). This study uses Tonga's largest island, Tongatapu, as a case study for modeling human waste repurposing for agriculture. Human waste streams present an alternative to chemical fertilisers as a cheaper, domestic nutrient source and have associated environmental, social and economic benefits for the people and soils of Tonga. This research takes a literature review methodology to determine the nutrient breakdown on human waste streams, existing conversion methods and crop rotation recommendations. Perennial crops have been found to assist in NPK and SOC storage and final estimates suggest 100-200 ha of taro, legumes and coconut crops can be sustainably farmed with biosolid fertilisers on Tongatapu. This is a 1.2% reduction in chemically fertilised land. Additional benefits are identified in the environmental sphere, including diminished disease risk and lagoon pollution from human waste. Further research is required to gage social uptake and consider whether this intervention is economically feasible in a Tongan context.

Introduction

Problem Statement

Declining global soil fertility is one of the most serious problems the world faces, resulting in stagnated growth in agricultural sectors (Hartemink, 2003). Soil degradation here is defined as processes which reduce soil quality and macronutrient content, making it less fit for crop production (Bindraban et al, 2012). At present, approximately 75% of global soils are “degraded” or “very degraded” due to human activity, meaning they lack sufficient macronutrient stocks. Macronutrients, such as nitrogen, phosphorus and potassium (NPK), are the primary elements needed by plants in large amounts (GRDC, 2018). NPK deficiencies impact the well-being of 3.2 billion people and costs more than 10% of annual global gross product in lost ecosystem services and biodiversity (Global Education Project, 2021). This issue threatens current and future food security for a growing global population (Bindraban et al., 2012).

Case study of Tongatapu

Pacific Islands Countries (PICs) are feeling the effects of poor soil quality in their agricultural and economic sectors. Tonga’s economic reliance on small scale family plots for subsistence farming and some commercial agriculture leave them particularly vulnerable (FAO, 2014). This report focuses on Tongatapu (latitude -21.14, longitude -175.20) as a specific case study. Tongatapu is Tonga’s largest island and home to its capital, Nuku’alofa (population = 23,221 people) (Tonga Statistics Department, 2016). The island is geologically constructed of coral limestone with a thick layer of fertile volcanic ash, historically rich in NPK macronutrients and soil organic carbon (SOC) (Kennedy, 2016).

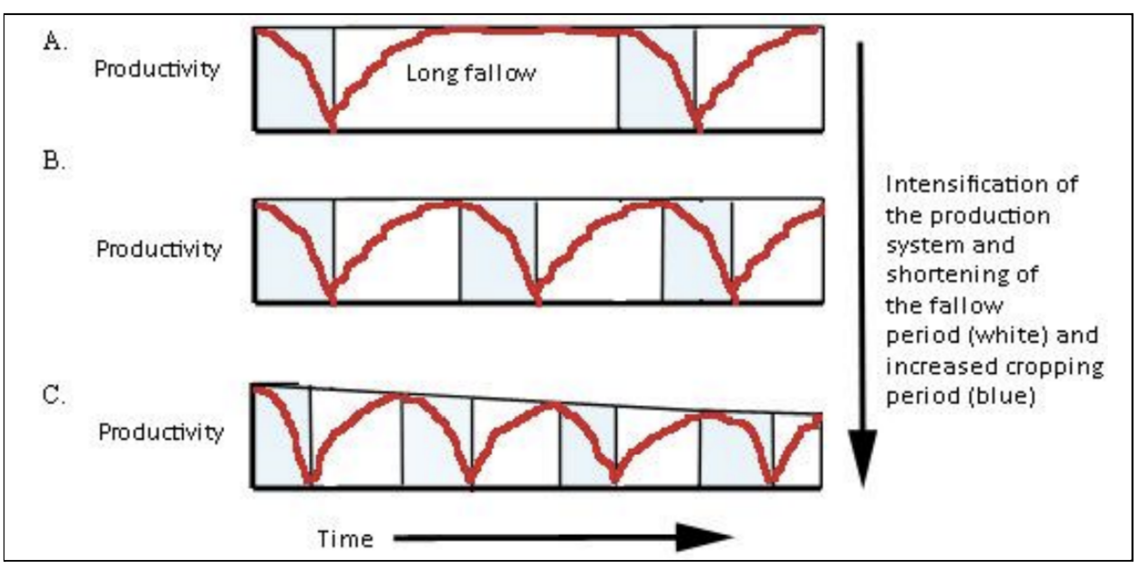
There is a known nutrient gap in NPK and SOC on Tongatapu as a result of three factors: increased farming intensity, decrease crop variation and a changing climate (ACIAR, 2019). Increasing development in Tonga has led to greater commercial agriculture (Rennie, 1991). These industries use continuous cropping systems, leaving less time for fallow. *Figure 1* below illustrates how decreased fallow leads to lower productivity (yield). Decreased crop variation is just as detrimental to the soil system. The endpoint of this monoculture continuum is continuous cultivation of the same piece of land which leads to nutrient loss (via crop harvest, erosion and oxidation of organic matter) and major yield decline (ACIAR, 2019). In conjunction with decreased fallow, less variation leads to nutrient leaching and long-term soil degradation (ACIAR, 2019). As the middle of the 21st century approaches, climate change is beginning to leave its mark on Pacific ecosystems. Increasing rainfall events continue to leach alkaline elements (i.e. potassium) from soils, resulting in increased pH (acidic). This runoff impoverishes agricultural soils for subsequent cropping seasons (Bertol et al, 2007).

Importance of NPK and SOC

Rejuvenating NPK and SOC stocks is vital for increasing productivity of agricultural land on Tongatapu, allowing healthy soils to produce nutrient-rich foods for human consumption. Robust macronutrient stocks support higher yield and quality. Nitrogen (N) is found in all plant cells, helping to form its structure and drive metabolic processes such as photosynthesis (Leghari et al, 2016). Plants can either access nitrogen through the atmosphere or the soil. Phosphorus (P) is essential for plant growth throughout its life cycle, especially in root, stem and stalk development, and flower and seed production. Potassium (K) has a number of different roles in plant growth including activation of growth-related enzymes. This in turn affects the shape, size, colour and even taste of the food produced. K also plays a vital role in a plant's water management, regulating water uptake through roots and losses through transpiration. This assists plant tolerance to fluctuating weather conditions (NSW DPI, 2021).

SOC is also a key indicator of soil health and existing NPK levels in the soil bank. Increasing SOC leads to healthy nutrient supply and exchange to plants, water storage, and pH buffering (Australian State of the Environment Report, 2016). These attributes culminate for productive agricultural land. The addition of plant residues and compost is one way of increasing SOC stocks. Current agriculture on Tongatapu, however, sees SOC levels dropping with crop removal and monoculture. Findings from *Sub-research question 3* below explore how sustainable farming systems can promote SOC levels.

Figure 1: Generalised decline in productivity of Pacific island farming-systems. Increasing intensification without appropriate nutrient management leads to declining productivity (ACIAR, 2019)



Tongatapu was chosen as the case study of this research for a number of reasons. Firstly, the island system has easily-definable physical bounds due to island geography. This allows for straightforward nutrient budgeting. Furthermore, while using human waste is ruled out in many developed countries due to a range of health risks, Tongatapu's clean waste stream (due limited pharmaceutical and industry pollutants) earn it further research merit. Tongatapu also presents a unique opportunity of limited land area (257 km^2), meaning that increased agricultural productivity must stem from increasing efficiency rather than area. Finally, this analysis could act as a model to other PICs, highlighting how low-effort, high-yield solutions have potentially wide-reaching implications working towards sustainable agriculture in the Pacific.

Human waste solution

In the past, deteriorating soil nutrient stocks have been restored through chemical fertiliser application. These fertilisers offer the iconic macronutrient trio NPK in plant-available form. These products, however, are expensive and require importation to locations such as Tonga. The growing concern about fertiliser availability and depleting nutrients in soils has re-emphasised the need for better nutrient management (Harder et al, 2019).

In recent decades, human waste streams have been investigated as a potential nutrient source to revitalise degraded soils. This research proposes that biosolids can recycle nutrient sinks into sources. Human excreta is rich in NPK and carbon due to humans' rich, omnivorous diets, offering all the elements necessary for crop growth. At present, human waste is the largest and most underutilised waste stream in existence (Strauss & Blumenthal, 1990). Underuse in Tonga stems largely from cultural stigmas, taboos (Jewitt, 2011) and inadequate knowledge of treatment before use (Phuc et al, 2006). While chemically and biologically it is a waste stream not dissimilar from pigs, chickens and cattle which are used frequently in Tonga, human source creates new challenges. In recent years, however, significant research funding has focused on the opportunities human waste could deliver to the agricultural sector. This paper aims to comprehensively understand how human waste fertilisers could build agricultural productivity in a Pacific island context.

Research relevance

Investigations into the potential benefits of human waste fertiliser are paramount to growing the sustainable agriculture sector worldwide. In the 21st century, humankind faces challenges including a booming population (55% of which live in urban centres), degrading soil health, increased frequency of natural disasters (higher rainfall/tsunami events for PICs), and biodiversity loss (UN, 2018). Successful sustainable agriculture practices are critical for overcoming these challenges. At present, rigorous Pacific island specific research is lacking. That said, there are a number of Australian and international research agencies such as the Australia Centre for International Agricultural Research (ACIAR) and the Commonwealth Scientific and Industrial Research Organisation (CSIRO) playing a pivotal role in closing that gap.

Identifying research questions

The field of fertiliser alternatives for sustainable agriculture is vast. A structured approach was adopted to keep the research scope bounded. The main research question and three sub-research questions shown below reflect this structure. The methods and findings sections also adopt these sub-research questions to maintain consistency and clarity across sections.

<u>Overarching research question</u>

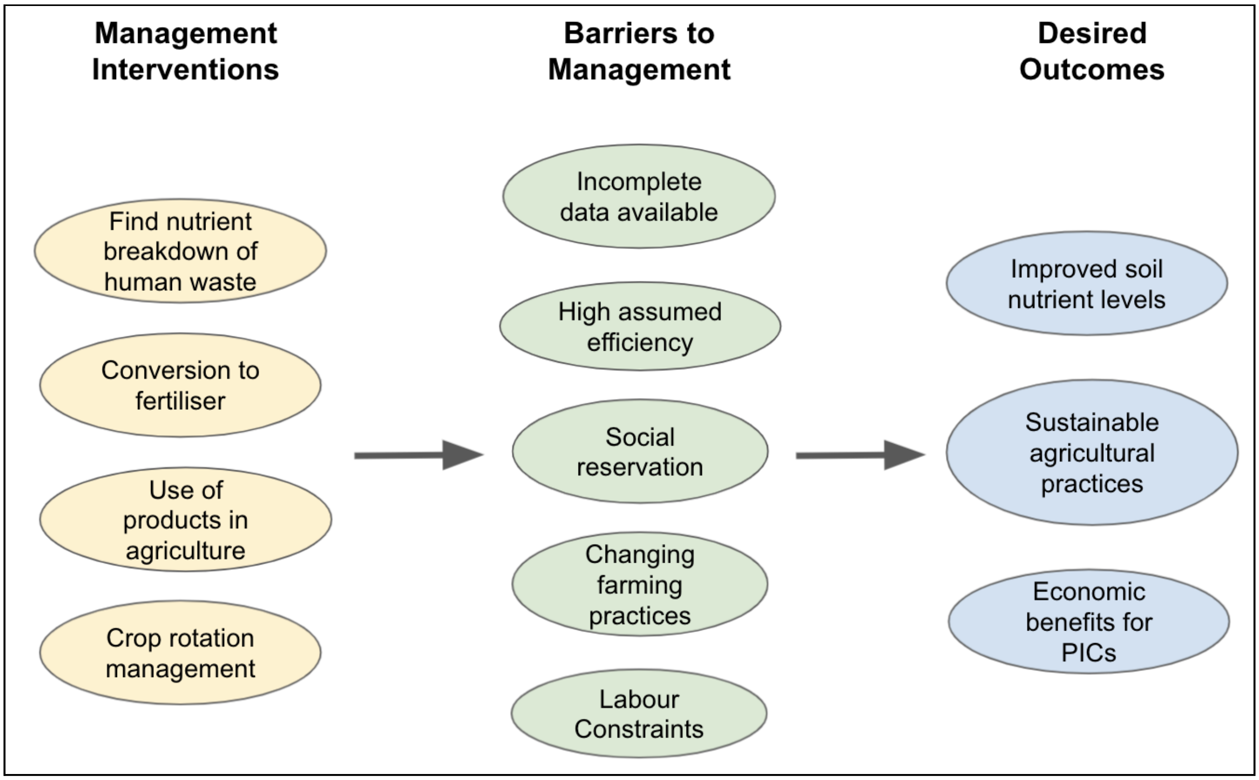
1) How can human waste be used to close agricultural nutrient loops in Tongatapu?

<u>Sub-research questions</u>

1) What is the nutrient breakdown of human waste streams?
2) What waste conversion processes exist?
3) What cropping rotation recommendations can improve nutrient retention?

Diagram 1 visually illustrates the pathway taken by this research. The “Management Interventions” reflect each of the three sub-research questions, while the “Barriers to Management” mirror the limits and assumptions of this report. These include acknowledging the social reservation to using human waste products, changing current farming practices, working with an incomplete dataset, assuming an efficiency factor, and labour constraints of working overseas in a developing nation. Finally the “Desired Outcomes” show the overarching goals of this research: to improve soil nutrient levels, to promote sustainable agriculture practices and to provide economic benefits to Tonga through this model.

Diagram 1: Identified barriers impairing research intervention. Modified from the 2019 ACIAR Final Report diagram on Soil Management in Pacific Islands (ACIAR, 2019).



Methods

This section details the approach underpinning the study, including decisions on the methodology. The systematic research procedures adopted for the literature review are also outlined here. A literature review was chosen to offer a comprehensive summary of current research into human waste use in agriculture. Due to COVID-19 travel restrictions, limited time and resources resulting from university studies, a literature review was deemed the most appropriate methodology. Conducting an initial literature review considers the feasibility of such projects before in-country field work is coordinated.

For each sub-research question and the acknowledgement of barriers/risks, a series of pertinent keywords/phases were identified. *Table 1* below outlines the final list of terms. These keywords/phrases were used as search terms in peer-reviewed, scientific databases such as ANU Scopus, Web of Science, JSTOR, AGRICOLA, and Google Scholar. Results were then narrowed using search boundaries including time (post-2000), requiring citations, and peer-review status. The time range was set quite large relative to most modern research due to limited data for Tonga and the Pacific. Relevant articles were chosen from the list of resulting papers.

Table 1: Key words and phrases used as search terms in scientific databases for sub-research questions and barriers/risks acknowledgement

Sub-research question	**Search terms**
#1: Nutrient breakdown of waste	Biosolids, sustainable agriculture, nutrient in human waste, pacific island diets, NPK content of excreta, nitrogen mineralisation, retention of micronutrients from food after digestion, organic/inorganic carbon in waste, mass of biosolids produced by humans (Tonga specific)
#2: Waste conversion processes	Human waste conversion processes, hydrothermal carbonisation, pyrolysis, solar-drying waste, waste processing, pathogen dieoff, composting waste, sand drying beds, pellet waste, waste to fertiliser
#3: Crop rotation recommendations	Sustainable crop rotations, agriculture in Tonga, nutrient requires of taro/cassava/legumes/coffee/cocoa, impact of diverse crop sequences on soils, cover crops, crop storage of NPK, importance of soil carbon, agricultural practices on soil nutrients, preparation of fields, application of biosolid fertilisers , nutrient requirements of taro/legumes/maize
Barriers/risks of using human waste	Contamination in human waste streams, pharmaceutical use in Tonga, cultural/religious barriers to human waste use in the Pacific, efficiency of waste conversion, risks of human waste as fertiliser, pathogens in human waste

Findings

This research revealed a long list of findings, most importantly the glaring knowledge gap that surrounds human waste use in the Pacific. Findings are separated by sub-research questions below.

#1: Nutrient breakdown

Sub-research question 1 identifies the nutrient breakdown of human waste streams in Nuku'alofa. *Table 2* below displays final values for overall wet waste, dry waste after processes, and available masses of NPK macronutrients. All values were measured in kilograms (kg) for consistency. Values for average excreta per capita per day (kg/cap/day) for phosphorus and potassium were derived from Rose et al's (2014) study on the characterisation of feces and urine designed to inform treatment technology. These stem from the "developed countries" mean value of 0.149 kg/cap/day wet waste and 0.030 kg/cap/day dry waste (i.e. after waste treatment, see *Sub-research question #2*). Mean phosphorus content was 0.000575 kg/cap/day (2% of dry weight) while potassium was slightly higher at 0.00075 kg/cap/day (2.5% of dry weight). Values for nitrogen in the waste stream stem from Binder et al's (2002) review on nitrogen potential of biosolids in the United States (Nebraska). This paper derived a mean value of 0.0012 kg/cap/day (4% of dry weight) using Rose et al's (2014) mass production rate. Harder et al's (2019) recent study suggested feces hold the majority of carbon content in human waste, opposed to urine. Up to 30% of dry waste is carbon, while wet waste is only 10% carbon. This equates to 0.009 kg/cap/day of non-degradable carbon.

After the NPK content per capita was identified, each value was multiplied by 365 to reflect available nutrients per annum, then by Nuku'alofa's population of 23,221 people. Finally, values were multiplied by this 80% efficiency factor to reflect inefficiencies in collection and processing. This report used the population of Nuku'alofa, opposed to the entire population of Tongatapu (~75,000 people), to utilise the higher population density and existing sanitation networks. This will aid in collection efficiency per unit effort, justifying the efficiency factor of 80%. This factor may easily be scaled back to 100% for use in systems with greater or less efficiency from start to end.

Table 2: Available macronutrient mass (kg) available per annum from the population of Nuku'alofa

	Nitrogen (N)	**Phosphorus (P)**	**Potassium (K)**	**Carbon (C)**
% of dry weight	4%	2%	2.5%	30%
Wet waste mass (kg/cap/day)	0.00596	0.00298	0.00373	0.0447
Dry waste mass (kg/cap/day)	0.0012	0.000575	0.00075	0.009
Mass from Nuku'alofa (kg/day)	27.9	13.4	17.4	208.9
Mass from Nuku'alofa (kg/year)	10183.5	4891.0	6351.0	76280.9
Scaled by efficiency factor (*0.8) (kg/year)	**8135.9**	**3898.2**	**5084.5**	**61024.7**

Table 2 presents the nutrient mass budget for Nuku'alofa human waste streams. If collected and appropriately processed (see findings of *Sub-research question #2*), roughly 8 tonnes of N, 4 tonnes of P, 5 tonnes of K and 60 tonnes of C could be available for use as biosolid fertiliser.

It should be acknowledged that values from *Table 2* reflect the total mass (kg/year) of N, P, K and C theoretically available, but does not reflect the mass of macronutrient in plant-available form. For example, plant-available nitrogen (PAN) comes in both organic (nitrate) and inorganic (ammonium) forms. According to Gilmour and Skinner (1999), roughly 80% of PAN is in organic form as nitrate (NO^{3-}) which decomposes to create inorganic nitrogen in the form of ammonium (NH^{4+}). If incorrectly applied, this plant-available ammonium can quickly volitise to ammonia which is toxic to crops. *Sub-research question #3* findings will discuss how this can be avoided through sustainable cropping techniques and rotations patterns.

Plant-available phosphorus comes in two inorganic forms: dihydrogen phosphate ($H_2PO_4^-$) and phosphoric acid (HPO_4^{2-}). Commonly referred to as orthophosphates, these are the forms used by most crops (Robertson et al, 2014). Finally, potassium (K) is taken up by plants at K^+. Heavy clay soils have higher cation exchange capacity (CEC) which allows higher retention of K than light, sandy soils . Soil on Tongatapu, along with most Pacific islands, has low to very low K levels (Gangaiya & Morrison, 1998).

#2: Waste conversion processes

The aim of this research question is to evaluate existing waste conversion processes in order to identify which is most appropriate in the context of Tongatapu. Although Tonga's waste stream is clean compared to most other countries, unprocessed biosolids may still carry bacteria and other pollutants toxic to humans and plants. Waste conversion processes are necessary to abate risks from pathogens.

Presently, transport and spreading remain two of the largest barriers to wide-spread biosolid use (CRC CARE, 2013). This section considers a product that is light-weight, easily transportable, nutrient-rich, socially acceptable, and easily-spreadable on fields. The literature review revealed three main techniques: solar drying, hydrothermal carbonisation, and pyrolysis. After each of these procedures the waste can be converted into various forms ranging in weight, appearance, ease of transport and visual likeness to the original product.

Solar drying, as its name suggests, is a process through which human waste is dewatered for ease of transport and pathogen reduction prior to land application (O'Shaughnessy et al, 2007). Recent studies have found that the majority of nitrogen lost in solar-drying comes from ammonia volatilisation, while organic nitrogen (plant-available) remains relatively stable and ammonium levels decrease with moisture loss (O'Shaughnessy et al, 2007). Solar drying requires little specialised equipment. Instead, drying beds are used, distributing biosolids over a larger area to speed up drying. Some downsides are apparent including the necessity of fine weather (sunshine and limited rain), loss of macronutrient content over long drying times, and the similarity of the original and final product.

Hydrothermal carbonisation (HTC) is a novel process which negates some of the solar-drying downsides through time-efficient conversion. HTC uses heat and pressure to transform wet, heterogeneous human waste into hydrochar, an energy-rich product (18-36 MJ/kg) which still contains intrinsic value in the form of carbon (Lu et al, 2012). This technique retains 45-75% of carbon content, minimising greenhouse gas release. This CO2 retention is more environmentally-friendly than waste degradation from landfilling, composting and incineration (Lu et al, 2012). In saying that, responsible incorporation of HTC products into soil is necessary to retain carbon level. This process may help achieve a dual-benefit of waste conversion to fertiliser while staying environmentally conscious. HTC is also achieved at lower temperatures with simpler equipment than many other thermal conversion techniques such as combustion, incineration, and pyrolysis (Lu et al, 2012). Unfortunately, the equipment used is still specialised that may be inaccessible due to cost in developing nations like Tonga.

The final method is pyrolysis. Pyrolysis is defined as the thermochemical decomposition of organic material at high temperature and in absence of oxygen (Czajczynska et al, 2017). This heating treatment produces an end-product with similar energy potential (11-35 MJ/kg) to HTC, making them easily comparable. One of the greatest advantages of this product is that many types of waste (industrial, domestic, agricultural, etc) can be used. Such flexibility does come with the major downside of high intensity lab work requirements to set optimal process conditions with particular inputs. According to Czajczynska et al (2017), however, limited research on mixed domestic food waste (similar nutrient breakdown to waste streams focused on here) has been conducted.

The above waste conversion processes are all excellent methods of transforming human waste into a useful, nutrient-rich, chemical fertiliser alternative. They may not, however, all work for Tonga's geography, culture and goal. *Table 3* below lays out the advantages and disadvantages for each.

Table 3: Advantages and disadvantages of waste stream conversion methods

	Advantages	**Disadvantages**
Solar-drying	- Low effort/labour - Limited specialised equipment required	- Time intensive/High NPK leaching - Similar to original product
HTC	- Retains carbon in high energy product - Environmentally advantageous	- Specialised equipment required - Expensive and requires skilled labour
Pyrolysis	- Can handle variation in inputs - High energy end-product	- Little existing research on human waste - Specialised equipment required - Requires lab work to optimise conditions

The optimal conversion method for Tongatapu may lie in a mixed-method approach. This design could take the advantages of all conversion processes to create a product rich in NPK and carbon. The choice to collect waste from the city of Nuku'alofa means that waste streams will likely be higher in pathogen, pharmaceutical and industrial pollutants, suggesting HTC and pyrolysis are more advantageous processes. These two methods require heating biosolids to 150-360°C, producing a safer end-product for agriculture. If further investigations collect biosolids from rural regions (cleaner waste streams) on Tongatapu or other PICs, solar-drying should be revisited as an appropriate conversion technique.

#3: Cropping recommendations

This research question is designed to pull all findings thus far into applicable recommendations for cropping sequences to achieve nutrient-rich soils for agriculture. Thoughtful cropping sequences create resilient systems which can withstand intensification of agriculture and variation in climates without nutrient leaching. Moreover, sustainable cropping results in longer-lasting benefits from biosolid fertiliser application (Gilmour & Skinner, 1999). This section considers preparation of land, volume and technique of biosolid application, and cropping sequence recommendations.

According to IFAD, about 88% of Tongan people live in rural areas depending on farming and fisheries for their income and livelihoods (IFAD, 2021). Subsistence and cash crops are widely cultivated in Tonga, with most family farms growing starchy vegetables such as taro, sweet potato, cassava, coffee or cocoa for food security, food and income (De La Pena & Plucknett, 1971). Therefore, this research question not only identifies sustainable cropping recommendations, but sequences that suit Tongatpu's history, culture and available resources. This will include taro (representing perennial starchy root vegetables), legumes (representing perennial proteins), and coconuts (representing perennial cash crops). Cover crops, although excellent for improving soil fertility, controlling diseases, insects, soil erosion, and weeds and conserving soil moisture, will not be considered in this study as to make land as agriculturally productive as possible (Fangeria et al, 2012).

As of 2001, two-thirds agricultural land on Tongatapu was root crops (Halavatau & Halavatau, 2001). There is significant history of taro (*Colocasia esculenta)* growing on Tongatapu, a plant primarily grown for its starchy root vegetable but is also consumed as a leaf vegetable (AgriFutures, 2017). Traditionally, taro is grown without the assistance of chemical fertilisers. With increasing intensification, however, taro farming is depleting NPK and carbon in soils. Taro production has been widely researched across the world. Suminarti et al. (2016) and the ICAR-Central Tuber Crops Research Institute

(ICAR-CTCRI) found that optimum cormel yield (16-17 t/ha) stemmed from application of 124.6, 19.2 and 134.9 kg/ha of N, P and K respectively. Many studies since have found similar macronutrient requirements for taro in the ratio of ~ 4:1:5 (N:P:K) (Raju & Byju, 2018). Human waste from Nuku'alofa therefore holds the potential macronutrient resources for 40-200 ha of taro-devoted agricultural land. The wide land area range is a result of a "one-size fits all" biosolid fertiliser product on crops that have varying nutrient requirements. This downside to human waste repurposing will be further discussed in the *Limits and Assumptions* section.

Legume crops (chickpeas, lentils, soybeans, etc) have a unique opportunity for use in sustainable agriculture. These crops are notable for their symbiotic nitrogen-fixing bacteria, which can act as an important substitute for nitrogen fertiliser (Bhattacharjee et al, 2008). Legumes actively convert nitrogen (N2) into ammonia (NH3) which is usable by plants (N2 + 8H+ + 8e- = 2NH3 + H2). This can significantly decrease nitrogen loss through runoff, erosion, and gaseous emissions, in turn benefiting the environment and soil health (Postgate, 1998). According to Griffith (1974), application NPK fertilisers depend largely on legume production intensity. Fortunately, legumes do not need additional N application, but will require ~ 40 kg/ha of P and K (Singh et al, 2010). These requirements suggest legumes have a positive role to play in 95-125 ha of sustainable cropping systems.

Coconut (*Cocos nucifera* L.), a perennial crop, is widely grown in humid tropical regions. In Tonga, coconut is grown both for cash export and home consumption (Halavatau & Halavatau, 2001). Their sturdy tree structure results in 60 year life spans, if not disrupted by natural disasters or land repurposing (Maheswarappa et al, 2011). Although specific reported nutrient requirements vary, there is general agreement on a 5:1:8 N:P:K ratio, with appropriate application rates of 500g N, 320g P, and 1200g K per palm. With average coconut tree density in Tonga ranging from 100-150 palms/ha, that is 62.5 kg N, 40 kg P, and 150 kg K required per hectare per annum (Maheswarappa et al, 2011). The largest benefit of growing coconuts is the opportunity for dual-cropping. Coconut trees offer shade through canopy and space in the understory for annual crops to grow.

Table 4: NPK requirements of Taro, legumes and coconut

	Taro	Legumes	Coconut
N requirement (kg/ha)	124.6	0*	62.5
P requirement (kg/ha)	19.2	40.0	40.0
K requirement (kg/ha)	134.9	40.0	150.0
Farmable area (ha/yr)	40-200	95-125	35-130

** nitrogen may be required in highly degraded soils or for the first few seasons to build soil nutrient stocks*

Table 4 above produces a rough idea of how much land area could be sustainably farmed given the human waste stream from Nuku'alofa. The wide range in area is a result of different crops having varying required volumes of NPK nutrients. Nonetheless, the areas are of significant size to show how human waste streams can benefit the agricultural industry on Tongatapu.

Land preparation and a potential cropping sequence are outlined here. Cropping rotation is the practice of growing different crops in succession on the same parcel of land to preserve the productive capacity of the land (Bullock, 2008). Recent research has claimed that 50% of food grown worldwide is produced in biologically-simplified agrosystems which do not utilise cropping rotation (FAOSTAT, 2013). Monoculture demand on land ecosystems has resulted in a host of environmental costs, including diminished SOC stocks. King & Blesh (2018) have found perennial crops to be the answer to monoculture damages. These systems avoid major nutrient loss through crop removal. Growing functionally diverse crops (varying in physiological traits and management factors) which prioritise use of specific macronutrients help to balance the system. According to King & Blesh's (2018) study, cover crops and perennials can increase SOC levels by 6.2% and 12.5% respectively, while cereal grains and legumes were found to decrease the SOC stock.

If grains must be incorporated into the system for cash export, one potential crop rotation sequence may begin with a cereal, followed by legumes, then taro. The legumes growing immediately after the cereal helps to stabilise nitrogen levels (GRDC, 2018). Since all three are perennial crops, rotations could last as long as 4 years allowing crops to mature. However, there should be no more than two consecutive rotations of cereal/legume production. If possible, these crops should be planted as the understorey crop to coconut fields. This produces nearly twice the food mass on the same area of land.

With effective nutrient budgeting and biosolid fertiliser application, this land could be sustainably cropped into the future.

Land preparation and proper fertiliser application is vital to avoid immediate nutrient leaching. If simply applied to the soil surface, up to 22% of nitrogen can be lost within the first 26 hours (O'Shaughnessy et al, 2008). To reduce losses to the environment, biosolids should be incorporated 6-10cm down into soils through tilling. With this intervention only 2.9% of nitrogen is lost. This treatment should be done immediately following application onto the surface to increase retained macronutrient quantity (O'Shaughnessy et al, 2008). Further nutrient leaching can be reduced through split fertiliser application. Sitthaphanit et al (2009) suggests applying half the fertiliser volume pre-planting followed by the second half 7-14 days after seedling emergence increases uptake of NPK. These interventions are especially relevant to Tongatapu's sandy soils as they are prone to leaching in a high-rainfall tropical climate (Sitthaphanit et al, 2009).

Limits and Assumptions

It should be acknowledged that this research privileges inherent Western researcher bias that using human waste streams as a chemical fertiliser alternative should be undertaken for social, environmental and economic benefits. Moreover, it should be recognised that this research is conducted at an Australian tertiary institution by non-Tongan researchers. As mentioned before, this is largely due to COVID-19 travel restrictions and available resources. Any future extensions of this research must include representative stakeholders from Tongatapu, including farmers, land owners, and the wider Tongatapu community.

As research progressed, it became clear that Tonga-specific datasets for nutrient budgets, diets, waste conversion, etc were few and far between. In lieu of research findings specific to Tonga, Pacific-specific datasets were used. If this alternative was still not possible, nations with similar diet profiles (high fat, sugar, carbohydrate, and preservative foods) were assumed. Where appropriate, global averages were used. For example, research conducted by Rose et al (2014) claimed phosphorus and potassium values in grams/capita/day (g/cap/day) as an average for 28 countries, ranging from 1-4 in Human Development Index Classifications (HDIC). Although the review included Tonga (HDIC = 2), data was displayed as an average for developed nations (HDIC = 1/2) and developing nations (HDIC = 3/4). Thus the developed nations' numbers were used in the below calculations (see *Findings*).

Further key assumptions include the high efficiency factor (80%). The literature review methodology of this study resulted in a relatively arbitrary value of 80%. Generally, its purpose is to reflect a non-perfect system whereby waste, and therefore nutrients, are lost in collection, conversion and application. Furthermore, not all NPK in the end-product is plant available, as discussed before. In-country fieldwork is critical to gauge an accurate efficiency factor. This will require a full run-through by which stakeholders at every level (collection homes, labour force, processing workers, and farmers) are consulted. Projects such as these do not flourish and continue through international aid, but by local social uptake. Stakeholder interest and support must critically be gained if this model is to be implemented.

Further assumptions come from generalising the human waste stream of Nuku'alofa residents. There will be nutrient variation within and between household waste streams depending on community, lifestyle, cultural norms, level of commercialism, etc. Although it's not a booming metropolis by Australian standards, Nuku'alofa is the center of business, work, shopping and trade. This inherently creates a more polluted and diverse waste product. This is the most significant downside to using the Nuku'alofa's waste. Rural areas of Tongatapu would have a cleaner waste stream free of many of these contaminants. The trade-off, however, increases complexity and necessary coordination for collection. These logistics are equally as important as the nutrient potential itself. Without adequate logistics planning, biosolid fertiliser has limited potential for the future of sustainable agriculture on the island.

Discussion

The implications of these findings are far-reaching. Most notably, insufficient resources and funding for this research in PICs has resulted in a clear knowledge gap. The nutrient potential of human waste for biosolid fertiliser has been extensively researched in India (Simha et al, 2017), Thailand (Schouw et al, 2002: Pinatha et al, 2020), Africa (Ghana: Cofie et al, 2005, Uganda: Andersson, 2015), Vietnam (Phuc et al, 2006), and others nations around the world. PICs, however, have been slow to implement human waste fertilisers into agriculture. Significant research suggests this is a matter of cultural tradition. While applying latrine wastes to agricultural land is an ancient practice in Thailand, it is considered taboo, dirty, and a health risk in PICs such as Tonga (Tait 2021, personal communication). While these views have led to decades of limited research, this research, in conjunction with studies such as Tait et al (2015) on waste treatments, provide an opportunity to identify and overcome social barriers to waste inclusion in Pacific regions. Any further research must critically involve local stakeholders as to not privilege Western bias' in favour of these interventions.

Further discussion is required for the size estimations of croppable land. The largest agricultural area suitable for farming given the nutrient load from Nuku'alofa waste streams is 200 ha. Given that 170 km^2 of Tongatapu is currently used for agriculture, a substitution of 2 km^2 for biosolid-driven agriculture is a surprisingly small estimation. This equates to a 1.2% reduction in chemically fertilised land. In light of these findings, benefits in other domains should be explored. For example, human waste in Tonga is often dumped into lagoons or washed into waterways during rainfall events. The sediment-rich, brown-coloured lagoon on Nuku'alofa's southern edge, Fanga'uta Lagoon, shows how detrimental fecal matter can be to aquatic-ecosystem health (see *Image 1*). The removal of human waste from lagoons would decrease water-borne diseases and eutrophication (process of water quality deterioration with excess NPK nutrient load) (Bhagowati & Ahamad, 2019). These environmental benefits are equally, if not more, significant than the established agricultural benefits (Spangberg et al, 2014).

Image 1: Aerial photo showing eutrophication and pollution in Fanga'uta Lagoon resulting from waste stream dumping (European Space Agency, 2016)

Compared to chemical fertilisers, nutrient content of human waste is relatively low (4% N, 2% P, 2.5% K). This raises questions about the amount of product needed to fill the nutrient requirements of agricultural land. According to the findings from this study, if 100 ha are farmed with biosolid fertiliser that's an application rate of roughly 2,400 kg/ha/year. In more manageable terms, that's about 300g per square meter. In comparison, the most nutrient intensive crop from the recommendations list (taro), only requires 280 kg/ha/year of chemical NPK fertilisers. A mass decrease of over 88%. This means the use of biosolid fertilisers requires higher transport, processing and labour resources. Further investigations must address whether collective environmental and agricultural benefits of human waste use outweigh the inherent resource requirements.

Although outside the scope of this study, organising supply logistics is a necessary part of creating a functional model. Additional topics beyond the scope of this research include gaging social uptake of biosolid fertilisers, determining a market for the product, and the economic feasibility. While worthwhile, resources and time excluded their addition to the study at hand. Research institutions such as CSIRO, ACIAR and universities are positioned to answer these unknowns in future studies.

Finally, the growing importance of human waste fertilisers in the future should be discussed. With population and affluence growing in Tonga, sanitation risks from poor human waste treatment and disposal pose ever-larger risks to the community and environment. This suggests expanding opportunities for safe and efficient waste repurposing for agriculture. Increasing population in Nuku'alofa will result in a growing volume of waste available for conversion to biosolid fertiliser, as well as a growing market for its use. Development in collection and conversion methods may also result in increased nutrient-reclaiming efficiency. Inevitably, increasing population will put pressure on existing agricultural land. Biosolids may help increase farming capacity, increasing productivity instead of land-use. Following further investigation on incorporating the rural waste streams (regional population of Tongatapu = 51,779), Tongatapu could have an economically viable future in biosolid fertiliser production. If future research deems its use in Tonga socially unacceptable, production for export (i.e. tourism industry, cruise ships, etc) should be considered.

Conclusion

It is quite evident that human waste streams have the potential to close agricultural nutrient gaps on Tongatapu, however, the extent of this potential is currently unknown. This research should be viewed as a starting point for future investigations in Tonga and neighbouring nations, helping to fill in the rest of this under-researched picture of resource recycling. Determining efficient and appropriate strategies of converting human waste streams to biosolid fertilisers will help rejuvenate soils, resulting in social, environmental and economic benefits. Opportunities for this sector will grow with an increasing population and need for productive land, helping to secure a stable future for Tonga and other PICs.

Resources

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