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Final report

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1 Acknowledgments

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We are grateful to Mr Russell Burnett for the preparation and pyrolysis of oil palm residues using his Kon-Tiki kiln and Big-Roo unit.

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2 Executive summary

Oil palm (*Elaeis guineensis* Jacq.) is a long-term perennial crop of great economic importance to many countries in tropical Asia/Oceania, providing export revenue and much needed income to both large plantations and smallholders. Unfortunately, basal stem rot (BSR), caused by the fungus *Ganoderma boninense* Pat., poses a major threat to the oil palm industry and hence to farmers' livelihoods. A potential long-term control measure for this disease would be through improved cultural practices. In related ACIAR project "Developing a foundation for the long-term management of basal stem rot of oil palm in Papua New Guinea and Solomon Islands" (CIM/2012/086) we have confirmed that residues from previous oil palm plantings, such as windrowed logs and old palm stumps, are a source of inoculum in new plantings thus continuing the disease cycle. Therefore, a disease management measure would be to remove diseased logs and stumps from the field. However, this is a costly and time-consuming measure, especially for smallholders who seldom have the necessary machinery.

In this Small Research Activity we investigated pyrolysis of various oil palm residues (logs, fronds, and empty fruit bunches) to convert oil palm wastes into biochar, a charcoal like material. Pyrolysis promises to break the disease cycle by sanitation of diseased plant material, biochar could sequester carbon better than natural decomposition of biomass and have valuable applications.

We tested two technologies for making biochar: a low-cost flame curtain pyrolysis unit called Kon Tiki which can be manufactured in developing countries for about 1,000 AUD, and a commercially available, highly engineered, transportable pyrolysis unit called Big-Roo (approx. cost AUD40,000). We demonstrated that biochar made with both technologies promoted growth of common vegetable seedlings in both a commercial nursery in Australia and under local PNG conditions, indicating that oil palm residue could be a good clean feedstock for pyrolysis. Biochar from oil palm residues has the potential to contribute to a more circular economy by converting waste into a higher value product, which may be sold for profit and thus increase smallholders' income.

3 Background

Oil palm (OP) is economically the most important agricultural commodity in Papua New Guinea (PNG). Smallholder farmers surrounding large plantations make up *c*. 40% of OP production in PNG, while large plantations own local processing mills. Loss of revenue due to pests and disease in oil palm is of great concern both at a local and national level. The most economically significant disease in PNG is basal stem rot (BSR) which causes palm death and thus a decline in incomes, at both local and national scale. The only viable long-term control of BSR is through the use of tolerant planting material, combined with sanitation measures to reduce the carry-over of the pathogen from older, infected trees to neighbouring palms and new plantings.

In PNG OP fruit bunches are harvested manually by smallholders and also on many plantations. Although harvesting is sporadic, it is also continuous throughout the year and thus provides a steady income, with 200,000 PNG citizens directly relying on OP farming (SSR, PNG-OPRA, 2020). A commercial planting usually lasts *c.* 20 to 25 years, after which time palm productivity declines and most palms grow too tall for easy harvesting, although many smallholders try to defer re-planting until up to 30 years. Spent palms are felled after poisoning, and left windrowed, or lying between the new planting rows. Windrowing is performed for two reasons: the cost of palm removal is prohibitively expensive, especially for smallholders who rarely have the necessary machinery; and the decomposing windrowed logs returns organic matter to soil. To further reduce cost, some smallholders even leave the poisoned old palms *in situ* (i.e., dead palms standing upright), and under-plant with new oil palm seedlings below.

While windrowed logs may come from palms that had obvious BSR symptoms, asymptomatic infected palms, or uninfected healthy palms, all eventually end up colonised with *Ganoderma boninense* (Pat.), a white rot fungus, which degrades lignin as a primary carbon source. In nature the fungus plays an important role in the recycling of woody material. At replant Ganoderma brackets (spore producing basidiocarps) are found on dead palms, stumps and windrowed logs growing as a saprophyte. It has been assumed that the Ganoderma growing on dead logs produces inoculum for BSR infections of new replants. During ACIAR project CIM/2012/086 we genetically fingerprinted 300 Ganoderma isolates collected from plantation oil palms. These isolates were collected from both windrowed logs (saprophytic isolates) and from living infected palms (pathogenic isolates), over a six-year period. We demonstrated that the saprophytic and pathogenic isolates are the same population, and therefore windrowed logs are an important source of inoculum for subsequent plantings. Old logs become habitat for pathogens (e.g., Ganoderma) but also for pests (e.g., Coconut Rhinoceros Beetle, CRB).

Therefore, one obvious sanitation measure against BSR would be to remove the windrowed logs before replanting. After removal, these logs would, ideally, then be converted into a product that will not support growth of Ganoderma or other pests and pathogens. Additionally, large quantities of palm wastes are generated during harvesting of bunches. In the field, fronds are pruned off at each harvest and left in the field for soil enrichment purposes, while at the mill significant quantities of empty fruit bunches (EFB), fruit mesocarp and kernel shell are generated.

The aim of this project was to critically assess the conversion of oil palm waste into biochar in Papua New Guinea. Biochar is a charcoal-like material made via the pyrolysis of organic biomass (i.e., heating of biomass under low or no oxygen conditions). Pyrolysis has long been a part of renewable energy systems, generating syngas, bio-oils, and heat. However, it is the production of biochar as a soil additive or plant-growing media replacement that has sparked global interest more recently. Firstly, biochar has a role in carbon sequestration since a significant proportion of the carbon is stabilised by the thermal transformation process. Biochar also has the ability to elevate cation exchange capacity, thereby retention of certain plant nutrients, and can improve soil physical, microbial and moisture retention attributes. Thus, production of a quality biochar product from oil palm wastes promises to provide smallholders with a new ‘cottage style’ industry while also compensating the cost of sanitation within their blocks.

This project was a small research activity originally designed to run for 18 months, extended to 24 months due to effects of Covid-19.

4 Objectives

This series of projects, of which this SRA forms a part, contributes to the development goal of improving the livelihoods of smallholders and communities who are dependent on oil palm in PNG (and Solomon Islands) - by improving the productivity and sustainability of production of palm plantations, both large-scale and smallholder-managed. Their specific aim is to improve the long-term management of BSR disease, in the short term through the exclusion of the most susceptible genotypes and, in the longer term, through the selection of BSR-tolerant or -resistant varieties, and evidence-based disease management. As dead and infected oil palms are the primary source of infection, disease avoidance through sanitation is a crucial practice for controlling BSR disease.

This SRA's objective, within the broader research strategy, is to explore the feasibility of biochar production as a method for removing infected material from oil palm blocks. A key project output will be the evidence to inform a future business case for oil palm derived biochar production in PNG.

This project was a scoping study with the objective to determine the feasibility of biochar production from oil palm wastes in PNG with five activities:

1. Literature review on biochar for plant-related industries
2. Investigation of cost-benefit of collecting OP wastes from the field
3. Production of biochar from OP wastes, both in Australia and PNG, including analysis of chemical/physical properties of these biochars
4. Experimental trials in nursery settings in Australia and PNG to validate biochar made from OP waste for growing common vegetable(s)
5. Workshop with smallholder farmers to present findings from this SRA

5 Methodology

5.1 Biochar production:

5.1.1 Australia

Feedstock: Two oil palms identified as unsafe and thus for removal by Douglas Shire Council were donated to this project. Both palms are suspected to be pisifera fruit type and were from street plantings in Port Douglas, planted in the 1980s or 1990s. The palms were sectioned into five parts: trunk into four, and the fifth was the canopy. These sections were left to dry out for eight to 12 weeks during summer. Subsequently the trunk sections were cut into blocks of *c*. 250 mm in length with a chainsaw. These blocks were further sectioned into 60 to 90 mm diameter pieces using a wood axe. An axe was used due to the fibre content of palm trunks, especially near the canopy, jamming up the chainsaw. By contrast, the canopy (fronds) was very easy to cut up with a chainsaw.

Pyrolysis technologies: Two distinct pyrolysis units were compared. The Big-Roo pyrolysis unit is a commercially available, highly engineered, transportable, relatively low cost (AUD40,000, pers. comm. Burnett), low emission unit designed specifically for use in developing countries (Burnett et al. 2018). Within this unit air dried frond and trunk pieces were placed in alternate layers to allow gas escape during pyrolysis. The material was top lit, with the combustion/pyrolysis zone progressing down through the feed material to the base of the unit while a small amount of air was circulated through the base of the unit to aid the complete combustion of any syngas produced. Pyrolysis was complete when the temperature at the base reached 500 °C. At this point the reaction was quenched with water jets to cool the biochar.

The second technology used in this study was a low-cost Kon-Tiki flame curtain pyrolysis unit (Schmidt and Taylor, 2014), which is a kiln that can be manufactured for *c*. AUD1,000 (pers. comm. Burnett) and therefore represents a technology that is accessible for smallholder farmers in PNG. The Kon-Tiki unit and biochar were made in Australia by Russell Burnett, the Big-Roo engineer mentioned above. Pyrolysis was activated by lighting fronds, and small amounts of feed material were added regularly over the pyrolysis duration (i.e., more feed was added when previous feed material had begun to ash). When the kiln was full of biochar, the reaction was quenched with water introduced through a tap at the base of the kiln. After immersion of biochar, the water was allowed to drain overnight.

Biochars from both methods were air dried, coarsely ground in a soil grinder, pulverised using a mallet and sieved through a 5 mm soil sieve prior to use in subsequent analyses.

5.1.2 Papua New Guinea

Pyrolysis technology: To compare outcomes across PNG and Australia, a Kon-Tiki kiln was manufactured in PNG at OPRA according to dimensions available on the Ithaca Institute web site (http://www.ithaka-institut.org/en/ct/101-Kon-Tiki-flame-curtain-pyrolysis). The project funded the manufacturing of the kiln. Pyrolysis was conducted using the same methods as described above.

Feedstock: Two palm trunks were sourced from smallholders; fronds were sourced from fields and empty fruit bunches (EFB) were sourced from a palm oil mill. Fronds were cut to 300 mm lengths and trunks were cut to 60×300 mm lengths. All feedstocks were air dried and pyrolysed and included a frond and trunk mixture (i.e. comparable to the Australian feedstock) or a 100% trunk feedstock, 100% frond feedstock or 100% EFB feedstock.

The biochars were fully air dried, ground, and pulverised to <8mm.

5.2 Nursery trials:

Nursery trials were set up to test biochar for toxic or beneficial effects on plant growth using vegetables commonly grown in many countries, including Australia and PNG.

5.2.1 Australia

Both biochars, made within the Big-Roo and Kon-Tiki units, were tested. The control growing mixture without biochar contained 24.5% perlite, peat, and a complete fertiliser (as used in previous biochar trials with vegetables, Kochanek et al., 2016a). Peat was replaced with biochar at rates of 3%, 10%, 30% and 50%, and the pH adjusted as necessary with garden lime. A 100% biochar rate was not included due to its extremely alkaline pH (above pH 9) and very high salinity (see Section 7.3.1). Two vegetables were tested: lettuce (*Lactuca sativa* L. var. Cos, Yates Seeds, Sydney, Australia) and capsicum (*Capsicum annum* var. Giant Bell, Yates Seeds, Sydney, Australia). The trial was set up in a randomised complete block design in a commercial seedling nursery in Gatton Qld., Australia. Twelve true biological replications were used where one replication was a four-celled punnet (cell volume of 60mL) containing both crops. Plants were harvested at two timepoints, hence from one cell for each species × treatment × block combination at each timepoint. Two seeds were sown per cell to establish the effect of biochar on seedling emergence. In cells where both seedlings emerged, the weaker seedling was removed. One lettuce and one capsicum seedling from each replicate were sampled at three- and five-weeks post sowing, respectively, from each treatment × block combination and leaf number, leaf length, shoot and root dry weight and root proliferation (root surface area, volume, number of root tips and total root length were measured using a WinRHYZO 2019a root scanner system (Regents Instruments, Quebec, Canada). One additional lettuce and capsicum seedling was sampled at the standard transplant-planting time, being at five and seven weeks post sowing, respectively, and their dry shoot weight was measured. The different harvest times for the two vegetables were due to differences in emergence, with capsicum slower than lettuce.

5.2.2 Papua New Guinea

All biochars were tested in PNG (including both Australian-made biochars) except the EFB biochar. In PNG the control growing media was compost made from EFB without biochar and treatments had compost replaced with biochar at rates of 3%, 10%, 30% and 50%. A 100% biochar treatment was not included, in line with the experimental design in Australia. The trial was set up in a randomised complete block design with twelve true biological replications in a seedling nursery at Dami Research Station, WNB Province, PNG. The trial used lettuce (*Lactuca sativa* L. var. Cos, Yates Seeds, Sydney, Australia) sown into HyPlug trays. Each treatment x block combination used two cells, and two seeds were sown per cell to establish the effect on seed emergence. In the cells where both seeds germinated, the weaker seedling was removed. One seedling from each treatment × block combination was sampled at five weeks post sowing, and the measurements taken included leaf number, leaf length, shoot and root dry weight and root area (roots were measured using ImageJ, Version 1.53K). The second seedling from each replicate was sampled at seven weeks post sowing, and the dry shoot and root weight were measured.

5.3 Statistical analysis:

Multiple comparisons of treatments were evaluated by a general linear model analysis of variance (ANOVA) using MINITAB, Release 17 (Minitab Inc, State College, PA, USA) with block assigned as a random factor. Mean separation was performed by Tukey test at α=0.05. The *n* value corresponds to the number of true biological replicates (blocks). Across all studies, proportions were arcsine square root and count data square root transformed prior to analysis. Homogeneity of variance was met without transformation for other parameters, consequently data are untransformed. Figures were created with GraphPad Prism v.9.4.1.

5.4 Biochar agronomic analyses:

Organic product characterisation was from a composite sample of twelve or more subsamples (Kochanek et al. 2016a) for all six biochars (two from Australia and four from PNG). Agronomic biochar characterisation was in NATA (National Association of Testing Authorities, Australia) accredited facilities after drying samples at 40 °C, sieving through a 2 mm sieve and homogenisation. Electrical conductivity used a 1:5 w/v sample/water extract (Method 3A1; Rayment and Lyons, 2011); pH used 1:5 w/v sample /0.01 M $CaCl_2$ solution at 25 °C (Method 4B1/4B2; Rayment and Lyons, 2011) and acid neutralising capacity was determined as carbonates by rapid titration (Method 19A1). Total carbon and nitrogen were measured by Dumas combustion after grinding to 0.5 mm and using a TruMac CN carbon/nitrogen determinator and available orthophosphate phosphorus was assessed using Colwell bicarbonate extraction with flow injection analysis (Methods: 9B2, Rayment and Lyons, 2011; APHA 4500 P G). Exchangeable cations used Gillman and Sumpter analysis by ICP-AES (Gillman and Sumpter, 1986) and major and minor elements were determined in solution by Varian ICP-OES (Methods: 15E1, Rayment and Lyons, 2011; USEPA 6010C). The micronutrients Cu, Zn, Mn and Fe were determined by DTPA extraction by ICP-AES and in solution by Varian ICP-OES (Methods: 12A1, Rayment and Lyons, 2011; USEPA 6010C). Acid extractable elements and metals by ICP-AES used Varian ICP-OES in solution (USEPA 6010C) and acid extraction was by block digestion (USEPA Method 200.2).

6 Achievements against activities and outputs/milestones

Objective 1: To make biochar from oil palm residues.

no.	activity	outputs/ milestones	completion date	comments
1.1	Literature review on biochar	Peer reviewed publication	Published January 2022	Published in Resources, Conservation and Recycling journal (IF12.6 in 2021).
1.2	Investigate cost – benefit of biochar production by smallholders in PNG	Information on pros and cons of biochar production by PNG smallholders	June 2022	Presented in this report.
1.3	Collect oil palm material and make biochar in Australia and PNG	Australia – biochar made using the Kon-Tiki kiln and the Big-Roo unit. PNG – Kon-Tiki kiln built at PNG Oil Palm research station Dami; biochar produced from oil palm residues	May 2021	Australia: pyrolysis performed by Biochar Energy Systems (Managing Director, Mr Russell Burnett), *c.* 30% feedstock to biochar conversion rate. PNG: pyrolysis with a feedstock to biochar conversion rate of 7-27%, depending on feedstock.
1.4	Test biochar in nursery setting in Australia and in PNG	Information on quality of biochar produced from oil palm residues.	Australia – November 2021. PNG – June 2022.	Nursery trials of vegetable growth testing various biochar conducted in Australia and in PNG.
1.5	Conduct workshop to inform small holders on biochar	Benefits of field sanitation to reduce Ganoderma infection and highlight biochar plant growth promoting properties	PNG – March-April 2023	Workshop to be conducted during the field days training organised by the Oil Palm Industry Corporation (OPIC) due to safety and different geographic accessibility of smallholders.

7 Key results and discussion

7.1 Literature review on biochar

Biochar is a charcoal-like material consisting largely of recalcitrant carbon produced by pyrolysis, which is the thermochemical conversion of organic biomass under oxygen limited or absent conditions using pyrolysis. While biochar can be produced by slow pyrolysis, fast pyrolysis, torrefaction or gasification, our specific focus is biochar from pyrolysis, produced at 300–900 °C (Fan et al., 2021; Wang et al., 2020). Slow pyrolysis uses reaction conditions of 300-700 °C and a long residence time (from minutes to hours or days) and low heating rate to maximise biochar yield and quality. This low heating rate and long residence time is known as 'carbonisation' (Wang et al., 2020). By contrast, fast pyrolysis uses a very high heating rate (*c.* 1000 °C min^{-1}), residence time of <2 seconds and reaction conditions of 350-700 °C to obtain bio-oil, with biochar and gas as by-products (Wang et al., 2020). The resultant bio-oil can be used instead of diesel, whilst syn-gas (a mixture of H, CO, and some CO_2) is combustible and can be used to produce electricity. Heat is the other product of pyrolysis, which can be harnessed with some technologies (Brewer et al. 2009). We note that some publications depict syngas production from oil palm waste at temperatures >1000 °C as 'fast pyrolysis' (e.g., Brewer et al., 2009), but this process is correctly named 'gasification' (Wang et al., 2020).

Biochar differs from charcoal and activated carbon by its physicochemical properties and/or its use as a soil or growing media amendment, whereas charcoal tends to be used for heating (and cooking) and activated carbon for filtration, purification and adsorption (Zambon et al., 2016).

A literature review of biochar and how it relates to plant-based industries was prepared and published in Resources, Conservation and Recycling (Kochanek et al., 2022). Figure 1.1.1 shows the graphical abstract of the review, which was also featured on the cover of the publication issue. This publication is fully open access and can be downloaded from the journal (https://www.sciencedirect.com/science/article/pii/S0921344921007175).

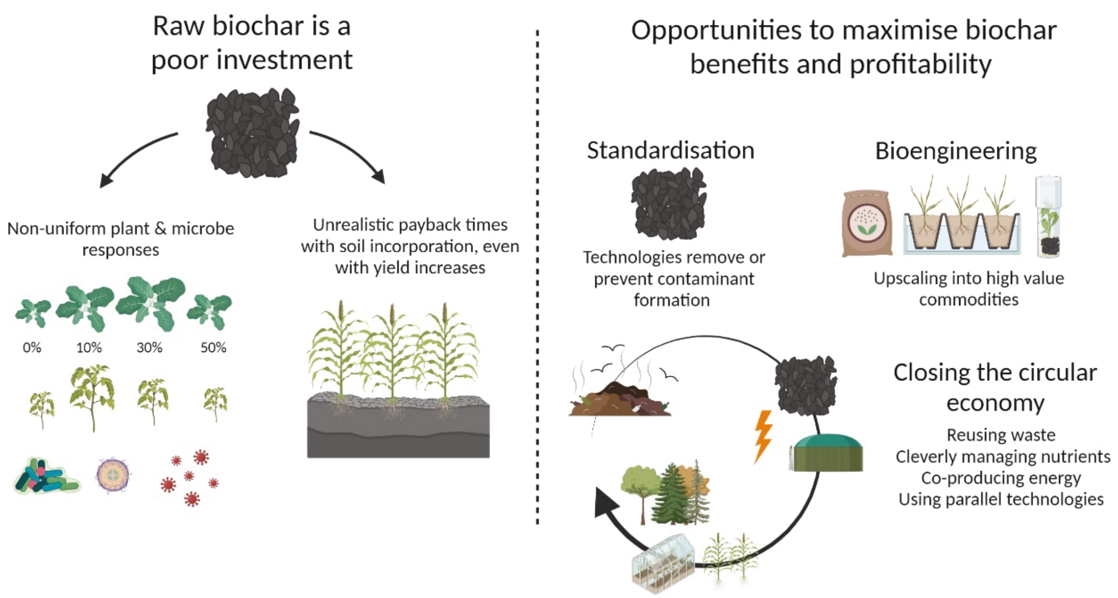

Figure 1.1.1 Graphical abstract from the review paper (Kochanek et al. 2022) generated during this project, which explained biochar applications for plant-based industries. The paper was published

in Resources, Conservation and Recycling (2021 impact factor 12.6). The review concluded that although raw biochar is too expensive for most broadacre applications and may have variable effect on crops and soil microbiota, it can be a valuable product if upscaled for specific applications, particularly if contaminants are prevented or removed and parallel technologies are used in synergy (such as composting and pyrolysis, with concomitant energy production).

The review discussed broad aspects of biochar including: the science explaining the plant-biochar relationship; biochar effects on microbiota; biochar weaknesses, opportunities and economic realities, including uses in higher income vs lower income economies; techniques for biochar standardisation; biochar commercial viability through bioengineering, synergistic technologies and the circular economy; and future perspectives.

7.1.1 Oil palm wastes as feedstocks for biochar

It has been estimated that the OP industry generates *c.* 127 million tonnes of organic waste annually in Malaysia alone (Guangan et al. 2022). In PNG this will be much lower due to the much smaller OP industry, making up <1% of world palm oil production (Our World in Data, https://ourworldindata.org/palm-oil) and lower planting density of 128 palms ha^{-1} (compared to 135-145 palms ha^{-1} in Malaysia). Oil palm residues can be sourced from both the field and the mill. Residues from the field include trunks (logs) and fronds and comprise 90% of OP waste (Nuryawan et al, 2022). Trunks become available at replant, (i.e., every 20 to 30 years) and sporadically when a palm dies due to disease or other factors. Fronds are pruned regularly, but especially during harvest (i.e., from when palms are two- to three-years old). Depending on age and block maintenance, each palm can produce between eight to 25 bunches per year. For every bunch harvested, there is at least one frond pruned and often more. Kong et al. (2014) reported that on average pruning palms generates 44 million tonnes of fronds per year in Malaysia alone, with half of the pruned fronds left to decompose and the other half removed for other uses (Karananidi et al 2020).

In PNG these residues are mostly left in the field to decompose naturally. Some smallholders chip off portions of the fallen palm trunks to use as firewood for cooking. In Malaysia 50% of pruned fronds are left to decay in the field to return nutrients to soil and the rest are used for other purposes (Karanidi et al., 2020). Palm fronds can be used for weaving, roof thatch and garden fencing. In Malaysia and Indonesia palm fronds are also used as roughage for ruminant fodder (Guangan et al, 2022, Nuryawan et al, 2022) and there is research into converting trunks to wood-based composites (recently reviewed by Nuryawan et al, 2022).

Residues from the mill include empty fruit bunches (EFB), mesocarp fibre after oil extraction and kernel shell after extraction of kernels from the fruit. Currently in PNG, EFB is used to make compost for use as a growing medium for the OP pre-nursery, where seeds are germinated and grown for three- to six-months before potting on into larger soil-filled polybags in the nursery. In Solomon Islands some EFB is also used as mulch. Mesocarp fibre and kernel shells are utilised for energy generation through low pressure boilers making mills self-sufficient for energy needs, and used as mulch, for example, in pineapple orchards to increase moisture retention and supress weeds, to provide erosion control, and to increase soil nutrient content (Kelechi et al., 2018). In Nigeria, the amount of OP waste is far greater than can be used for energy generation by the mills and excess is often dumped by the roadsides and on farms (Kelechi et al., 2018).

As a general rule, feedstocks high in lignin are better for biochar production via pyrolysis, whilst feedstocks low in lignin are better for composting. A good way to tell if a feedstock is woody is by its ash content (the minerals and inorganic matter left after combustion). Wood tends to have <1% ash by weight, straw 20-25%, green waste 10-13% and dry algae 50-75% (Ronsse et al., 2013). OP organic wastes are relatively woody, with lignin content between 21.7% in fronds to 50.7% in kernel shell, and ash content between 1% in kernel shell to 5.8% in fronds (Kong et al., 2014). Thus, OP wastes provide a potentially high quality and plentiful feedstock for pyrolysis and biochar production.

7.1.2 Pyrolysis technologies

There are many different types of pyrolysis technologies, but broadly these can be divided into batch and continuous. For batch pyrolysers, a batch of feedstock corresponding to the volume of the unit is prepared and pyrolysed at a time. The unit is then emptied, and the process repeated. For continuous pyrolysers the feedstock is inserted at one end, moved through the heat chamber where pyrolysis occurs, and biochar comes out of the other end. Continuous pyrolysers tend to be large, high through-put, industrial scale units and require constant resupply of feedstock, as well as an external source of heat to drive the reaction (Guangan et al., 2022).

Batch pyrolysers come in many sizes and complexities, ranging from a hole dug in the ground, to modern large-scale sophisticated technologies suitable for industrial applications. The end product required, which can be biochar, syngas, or bio-oil, or combinations of these, is one way to determine the best technology (Srinivasarao et al., 2013). Biochar can be produced at scale from large industrial facilities down to individual farm (Lehmann and Joseph 2009) and even at domestic level (Whitman and Lehmann, 2009) thus may be applicable to broad socio-economic situations. Units can be mobile or stationary, with mobile units offering benefits such as flexibility, reduced transport costs from local feedstock sourcing, options to use co-produced heat onsite (such as to heat greenhouses), local employment and easier, more sustainable residue management (Fytili and Zabaniotou, 2018). Nonetheless, caution is needed because many unsophisticated methods are inefficient and polluting, and mishandling can produce emissions that negatively impact air quality, human health, and biodiversity (Cornelissen et al., 2016; Azzi et al., 2019). In the context of smallholders, a low-cost pyrolysis unit that produces low gas and particle emissions and high quality biochars is needed (Smebye et al., 2017; Pandit et al., 2020; Sundberg et al., 2020).

Retorts and converters are industrial reactors capable of recovering not just biochar but also liquid condensates and syn-gases. Kilns are reactors which are used solely to produce biochar (Emrich 1985). Kilns can be made by digging a hole in the ground, or by modifying oil drums, or built from bricks. Benefits are that these technologies are cheap to manufacture, some can be mobile, and none require external heat other than initial ignition. However, some of these kilns are not efficient and result in emission of greenhouse gasses (GHG) during pyrolysis, such as pyrolysis in a poorly dug earth pit (Srinivasarao et al., 2013).

For OP smallholders a low cost, easy to use, portable batch pyrolyser would be the most versatile option. Whilst such a technology would not handle all the OP biowaste generated at replant, it would be sufficient for dealing with a sporadic supply of trunks and a steady supply of palm fronds. The Kon-Tiki flame curtain pyrolysis kiln is a simple and effective open cone shaped kiln that was largely developed by Schmidt and Taylor (2014). It was designed to be easy to operate, portable but still capable of processing kilograms of biowaste, generating *c.* 1000 L of biochar per batch. To increase pyrolysis efficiency the kiln is ideally designed as a frustum (a cone cut by 2 horizontal planes) with a 60 to 65-degree wall angle, 1650 mm top diameter and 400 mm bottom diameter. It can be made from steel (portable) or dug from the earth (not portable but cheaper). It utilises the flame curtain principle, where the feedstock is lit from the top, and the flames burn up gases escaping from the feedstock, thus reducing emissions. Although the kiln lacks a temperature control, the working temperature has been reported as 650-700 ^{o}C (Schmidt and Taylor, 2014). Depending on feedstock, a single person can operate two to four kilns simultaneously, producing 1-1.5 tonnes of biochar per 2-8 hr run, an amount similar to a medium sized industrial plant (Schmidt and Taylor, 2014). Another advantage of this kiln is that it largely avoids the need for external fuel for combustion. Conversion rates for biochar production in the Kon-Tiki range from 13 to 32%, depending on the feedstock used (Cornelissen et al., 2016).

7.1.3 Pyrolysis of oil palm wastes

Pyrolysis as a means of dealing with OP wastes has been investigated for a considerable time, mostly in Malaysia (reviewed by Kong et al., 2014 and more recently by Guangan et al, 2022). However, most of the literature describes either small scale laboratory-based experiments, with very small batch pyrolysers (i.e., only mg to gram feedstock capacity), or large units at OP mills and more concerned with bio-oil and energy production than making biochar. The reported conversion rates ranged from 12.4% to 47% of original weight. These conversion rates are dependent on many factors, including pyrolysis technology and the biowaste used, with all major OP wastes tested. Recently, flame curtain pyrolysis using the Kon-Tiki kiln (both metal and earth dug) was used to convert OP fronds to biochar in Malaysia (Karananidi et al., 2020). The reported conversion rates were 19% and 14% by weight from the earth and metal kilns, respectively, when pyrolysed from 50 kg of air-dried fronds. This study looked at biochar use in acidic soil amelioration and it's potential for climate change mitigation. Until recently, there have been no studies exploring biochar production and/or biochar use by OP smallholders. Encouragingly, in 2022 Wild Asia has partnered with Biochar Life, Ithaca Institute, and the Pond Foundation to create the WAGS BIOchar for Smallholders initiative (http://oilpalm.wildasia.org/4545/new-biochar-smallholders/). The WAGS project is about supporting farmers to utilise their OP waste by producing biochar to regenerate their soils and to supplement their incomes via selling carbon removal credits on global markets.

7.1.4 Biochar uses

Generally, biochar is too expensive and valuable for farmers to spread tonnes on their fields (Vochozka et al., 2016; Azzi et al., 2019; Kochanek et al., 2022). Nonetheless, in the tropics, where soils are often acidic, addition of biochar to soils improves yields by regulating pH via its characteristic basic nature, and thus liming capacity, which in turn can alleviate aluminium (Al), P and other elemental stresses, even at times outperforming lime (Hale et al., 2020). Additionally, biochar can improve coarse-textured, highly leached soils with low organic carbon content (<10 g OC kg^{-1} soil or organic matter content < 2%) largely due to soil water- and nutrient-holding improvements (Marousek et al. 2019; Guo, 2020). Biochar can also reduce N_2O and NH_4 emissions from waterlogged soils, such as SE Asian rice cultivation (Amelung et al., 2020), although emission reductions in paddy soils have been disputed (Liu et al., 2019). Also, biochars can directly provide some plant-available mineral nutrients, such as phosphorus or potassium (Kochanek et al., 2016b; Buss et al., 2020), or indirectly, for example via increased soil biota activity accelerating nutrient mineralization (e.g., Tian et al. 2021 observed enhanced P mineralisation in P deficient soils with biochar additions).

Bioengineering raw biochars into higher-value and better-performing products promises to enhance profitability and commercial opportunity far more than applications of raw biochar to soil (Kochanek et al., 2022). For example, biochar can be used as an accelerator for composting (as reviewed by Bong et al., 2021), as a soil conditioner and organo-mineral fertiliser carrier (*viz.* biochar compound fertilisers; Marousek et al., 2019; Chew et al., 2020), as a substitute for soilless growing medias, such as peat in potting mix (Jindo et al., 2020), and as an activated carbon replacement, for example for tissue culture applications (Di Lonardo et al., 2013). Biochar has also been used as insulation in buildings, as an adsorbent for soil and water contaminants, such as dyes and pesticides, as well as for water filtration (Schmidt 2012) and can be used in compostable toilets to reduce odours (Pers. comm. Frank Strie, Terra Preta Developments). Biochar specifically manufactured from OP residues has been used as a biofertilizer in oyster mushroom cultivation, nearly doubling mushroom yields (Liew et al., 2018).

Biochar can also be used in carbon sequestration since the thermal transformation stabilises a significant proportion of the carbon into an aromatically-enriched and biologically inert form (Lehmann, 2007). Additionally, the pyrolysis process can retain *c*. 50% of the carbon content of the feedstock in contrast to the *c*. 10 to 20 % retained during natural decomposition of biomass over a 5-to-10-year period, and < 3% that remains in ash after complete burning (Lehmann et al., 2006). Compared to EFB use as mulch/compost, pyrolysis results in emissions reduction of 102 kg Mg^{-1} of EFB (Robb and Dargusch, 2018). Thus, carbon emission reductions could be substantial if all OP waste was pyrolysed. Additionally, up to a doubling of climate benefits can be observed with careful nutrient management within biochar systems (Azzi et al., 2019)

Another substantial benefit of pyrolysis is in waste management and sanitation. Both incineration and pyrolysis destroy organic contaminants with similar efficiency, including live microbes, organic compounds such as hormones and antibiotics, and microplastics. However, only pyrolysis retains a large portion of the feedstock carbon and some nutrients within the biochar (Joseph et al., 2021).

7.2 Cost-benefit of biochar production by smallholders in PNG

In PNG *c.* 37% of land under OP cultivation is owned by smallholders on >20K blocks (>54K ha) contributing to 27.3% of total palm oil production. These statistics are not precise as the number of smallholders are in flux for various social and family reasons. There are three categories of oil palm production by smallholders: 1) VOP is village-based palm oil production on customary land, involving participation by the local landowners in the palm industry; 2) LSS is production of palm oil on state-leased land; and 3) CRP which is production on customary land by aliens who have purchased the land from customary landowners. Over the last 30 years the smallholder population has increased from nuclear families into big extended families and multifamily operations after many blocks were leased to settlers from different regions.

The standard block size varies between 2 ha for VOP, 2-4 ha for CRP and 6 ha for LSS. Some LSS blocks, particularly those at the boundaries or edges of the LSS have bigger blocks of 10 -12 ha, with a planting density of 120 palms per hectare (i.e., lower than on most plantations in PNG).

Yield of fresh fruit bunch (FFB) per hectare varies between location, palm age, block maintenance and impact of pests and diseases. Palms begin to produce bunches from *c*. 2 years of age, with peak bunch production at *c*. 7 to 9 years of age followed by a slow decline in bunch yield until replant. Thus, accurate comparisons are hard because data on area planted include both mature and immature palms, which means that yields calculated from the total production and total area planted underestimate yield from mature palms. Nevertheless, available data indicate that smallholder yields are considerably lower than those for plantations. An average yield for mature plantation palms is *c.* 30 t ha^{-1}; while for LSS it is *c.* 18-20 t ha^{-1}; for VOP it is *c.* 10 t ha^{-1} and for CRP it is *c.* 15 t ha^{-1}.

Infection with Ganoderma leads to loss in palm oil production both indirectly by reducing FFB number and weight, and directly by killing oil palms. It is difficult to estimate economic loss due to infection with Ganoderma since yield loss/reduction depends on several factors including inoculum load (which is dependent on the previous crop), disease severity, disease progression over time, palm age, and other abiotic and biotic factors. Yield loss due to Ganoderma infection can be estimated by taking into consideration both palms that have died due to disease, and palms which are still standing but producing fewer and lighter bunches. According to research by the Smallholder and Socioeconomics section at Oil Palm Research Association of PNG (PNG-OPRA), average production for a

1 ha smallholder block is 13 t year^{-1} in West New Britain Province (WNBP), and 11 t year^{-1} across PNG. Income from OP blocks is dependent on monthly FFB price, which is determined by the world market price, and at the end of 2022 was PGK428.61 t^{-1} FFB (*c.* AUD181.25, using average conversion rate of AUD0.4229 to PGK1).

Introduction of sanitation measures to control Ganoderma infection in smallholder blocks is critical to control Ganoderma transmission in the field by minimising inoculum load and to stop disease spread. Field studies in Malaysia showed that sanitation could reduce rate of Ganoderma infection from 43.38% to 0.93% among 10 year old palms (Idris et al., 2004), although that paper looked at cost/benefit of trunk injection of fungicide to control BSR. To calculate the cost-benefit of adopting sanitation of palms infected with Ganoderma, profitability economics from yield and yield loss should be determined based on the current FFB price per ton. At current price, the net annual income (after cost of maintenance etc) per 1 ha smallholder block (with 120 palms) is estimated at PGK4660, thus each palm generates PGK39 per year, or PGK897 over a lifespan of 23 productive years (assuming re-plant after 25 years).

In Malaysia, Ganoderma infection can lead to FFB yield reduction between of 0.04 t ha^{-1} and 4.34 t ha^{-1} from 10 and 22 year old palms, respectively (Roslan and Idris, 2012). In PNG, a case study of 200 selected blocks (400 ha) in the WNB (West New Britain)-Hoskins Project area will be used for the economic yield loss estimation caused by Ganoderma infection. Small holder OP blocks in WNB-Hoskins Project span over 25,839 ha with 8,029 blocks. FFB yield reduction model was established for BSR disease severity for second generation OP planting (i.e., re-planting OP after previous OP crop) using the backward elimination-based regression method (Assis et al., 2016). The model suggests that Ganoderma infection with different disease severity (mild, medium, and severe) would cause yield losses of 3.91%, 20.13% and 19.27% respectively (Assis et al., 2016), and dead palms cause 100% yield loss.

Overall, Ganoderma infection rate in the 200 smallholder blocks (400 ha) within WNB-Hoskins Project was 6.8% based on surveys conducted in 2020-2022, resulting in a loss of net income of 6% (rate of infection was calculated on the assumption that all palm mortality was caused by Ganoderma). In 2022 6% equated to PGK113,560 or PGK283 ha^{-1}. If infection rate could be reduced to 1% via sanitation, the cost of yield loss could be reduced by PGK283 ha^{-1} year^{-1} to PGK47 ha^{-1} year^{-1}.

In other countries, such as India, smallholders supplement their income by making and selling charcoal/biochar (Srinivasarao et al., 2013). Economic feasibility of biochar production is dependent on 1) production cost, including that of feedstock, transportation of feedstock, cost of consumables (e.g., ignition); 2) human capital cost including salary; and 3) equipment cost, including capital cost of unit manufacture, renovation, installation, and maintenance (Liew et al., 2018). In the case of smallholders in WNBP, production costs would be minimal as a metal Kon-Tiki kiln can be transported to the feedstock (i.e., the field) and the cost of consumables is small (e.g., matches or similar form of ignition source, as well as fuel for the chainsaw etc). Thus, human capital, such as the time to process palm residues into uniform sized pieces, would be the most significant ongoing cost to pyrolysis unless an industrial chipper/shredder, that can shred large plant parts, could be sourced. Equipment and capital costs would therefore include kiln manufacture/purchase, and purchase of equipment, such as chainsaw, a wood axe, or chipper/shredder, if not already owned. The Kon-Tiki kiln is a simple device requiring little maintenance and should last many years without needing major maintenance. The cost of producing 1 L of biochar from OP residues in this study ranged from PGK7.1 for trunk biochar (AUD3), to PGK1.5 for frond biochar (AUD0.63), with the average of PGK4.2 (AUD1.78). This cost includes the capital cost of manufacturing the Kon-Tiki kiln by NBPOL construction personnel (*c.* PGK4300 or AUD1818), plus a total of 8 hr of four OPRA personnel for preparation of feedstocks and other costs (*c.* PGK2000 for various supplies, AUD846) although these latter costs are research-scale based. By comparison biochar made commercially in Australia retails for AUD5.50 L^{-1} (Terra Preta

Developments) to AUD 10 L^{-1} (Green Man Char). Manufacturing-scale costs tend to be orders of magnitude lower than research-scale based, thus production costs by smallholders in PNG should be lower than for this project, especially if cheaper kilns could be sourced or if more biochar per worker can be produced (e.g., multiple kilns operating simultaneously).

Robb and Dargusch (2018) performed financial analysis of Indonesian made EFB biochar application to broadacre agriculture in Australia. EFB biochar was applied at rates between 1 and 40 Mg ha^{-1} to sugarcane, cotton (both irrigated and dryland) and wheat. The study found that higher value crops, such as sugarcane and irrigated cotton, resulted in a positive return on investment (up to 143% for sugarcane at 40 Mg ha^{-1} application rate) when biochar was applied to improve yield and under a standard fertilizer regime. For lower value crops (wheat and dryland cotton) a negative return on investment was observed (down to -87% for wheat at 1 Mg ha^{-1} application rate) when biochar was applied to improve yield. EFB biochar application as a substitute for fertiliser was not profitable for any crop or application rate, however the EFB biochar was not augmented with nutrients. As discussed in Kochanek et al. (2022), broadacre application of biochar has very long payback times and so it is better to develop either local (PNG) markets for OP biochar, such as bio-fertilisers for market gardens in PNG regions with poor soils (e.g., Madang or Milne Bay Provinces) or convert OP biochar to higher value products such as plant growing media or oyster mushroom bio-fertilisers for export to higher income countries. Kochanek et al., 2015 noted that biochar manufactured in Australia from sugar-cane trash could cost-effectively replace peat used in Australian nurseries even at a cost of AUD1000 t^{-1}.

7.3 Biochar production from oil palm feedstocks in Australia and PNG

Biochar in Australia was manufactured from two mature palms that were sourced from Port Douglas, Qld. These palms were from street plantings and slated for removal by the city council. The palms were of an unknown genotype, possibly pissifera fruit type, and of an unknown age. The palms (both trunks and fronds) were air dried for eight to 12 weeks, cut with chainsaw and/or axe into *c*. 80 × 250 mm sized pieces and pyrolyzed. Pyrolysis used two distinct technologies. The first technology, a Big-Roo, is either a mobile or fixed batch pyrolysis kiln which includes a feed crate that holds *c*. 2.4m^3 of feedstock. Feedstock was lit from the top, and the combustion was finished when the bottom reached 500 °C meaning actual pyrolysis was *c*. 600 °C (pers. comm. Burnett). The process took 2.5 hr and was quenched by spraying water jets to cool the biochar (Fig 1.3.1 and 1.3.2 depict the Big-Roo unit). The unit was selected because it is highly engineered yet mobile and relatively low cost (*c.* AUD40,000, pers. comm. Burnett).

Figure 1.3.1. The 'Big-Roo' batch pyrolyser mobile unit used in this study.

Figure 1.3.2. The Big-Roo unit being lowered onto the feedstock crate containing the oil palm trunk and fronds, ready for pyrolysis. The rear door is attached to seal the unit prior to ignition.

The second technology used in this study was a Kon-Tiki flame curtain pyrolysis unit, which is a simple but effective frustrum shaped kiln that was developed by Schmidt and Taylor (2014). Building instructions are on the Ithaka Institute website (http://www.ithaka-institut.org/en/ct/101-Kon-Tiki-flame-curtain-pyrolysis). The base is 400 mm in diameter, the top is 1650 mm, and the sides are at 60^{o} angle to give optimum air circulation to the syngas stream for complete pyrolysis. These kilns usually pyrolyse material at a working temperature of 650 - 700 ^{o}C (Schmidt and Taylor, 2014) but the unit lacks instrumentation. In this kiln, a small amount of feedstock was stacked at the base, lit with a match, and then more material was added as pyrolysis continued over six hours. Once the kiln was full, the biochar was quenched by flooding with water. In total, 300 L of each biochar was produced in Australia and biochar production properties are summarised in Table 1.3.1.

Table 1.3.1. Biochar production properties when made from oil palm wastes in Australia using a Big-Roo and Kon-Tiki kiln.

Technology	Feedstock composition	Starting amount	Biochar made	Conversion rate	Cost
Big-Roo A	80% log, 20% fronds	1.2m^3	0.4m^3	33%	medium
Kon-Tiki A	90% log, 10% fronds	1.2m^3	0.35m^3	30%	low

In total, 300 L of each biochar was produced.

The conversion rates were comparable across both technologies and were similar to conversion rates reported for various OP feedstocks pyrolysed by other technologies. For example, Liew et al (2018) reported conversion rates of 33% to 38% by weight after microwave pyrolysis of all types of OP feedstocks. By contrast, Karananidi et al. (2020) reported conversion rates for OP fronds of only 14% using a Kon-Tiki kiln. The reported conversion rates for various OP residues ranges from 12.4% to 47% by weight and depends on technology, with no clear trend as to which combination gives best results (Guangan et al. 2022).

In PNG various technology possibilities were explored for producing biochar around West New Britain but a Kon-Tiki kiln (Fig 1.3.3 and as described above) was manufactured by NBPOL personnel to enable direct comparison to the Australian Kon-Tiki made biochar.

Figure 1.3.3. The Kon-Tiki kiln manufactured in PNG for this project by NBPOL personnel with an oil palm trunk feedstock undergoing pyrolysis.

Four feedstocks were prepared for biochar production, as described in Table 1.3.2. OP trunk material was sourced from two fallen palms from two different smallholder blocks. Fronds were collected from fields adjoining the OPRA research facility. EFB was sourced from a local mill.

Table 1.3.2. Biochar production from various oil palm wastes in PNG.

Technology	Feedstock composition	Starting amount (L)	Biochar made (L)	Conversion rate
Kon-Tiki PNG	100% trunk	615	84	13.66
Kon-Tiki PNG	100% fronds	553	152	27.49
Kon-Tiki PNG	90% trunk, 10% fronds	597.5	102	17.07
Kon-Tiki PNG	100% EFB	650	48	7.38

The conversion rate for trunk+fronds from the Kon-Tiki kiln in PNG (17.1%) was lower than the conversion rate in Australia (30%). Conversion rate for 100% frond feedstock in PNG was encouragingly high at 27.5% which was considerably higher than reported by Karananidi et al. (2020; 14%) using the same technology, and comparable to that reported by Abnisa et al. (2013b, 30%). Conversion rate of 100% trunk feedstock in PNG was less impressive (13.7%) and well below the 33.6% conversion rate reported by Abnisa et al. (2013b) for the same feedstock. The conversion rate for EFB was particularly low (7.4% in this study versus 29% reported by Abnisa et al., 2013a). This may be because the EFB feedstock was pyrolysed without cutting up into smaller pieces. Alternatively, the EFB feedstock may have been partially composted at time of pyrolysis and thus had a low energy value, as was previously observed for green waste fines versus the woody component by Kochanek et al. (2016a). In PNG EFB is used to produce compost that is then used to grow oil palm seedlings in the pre-nursery, or as mulch. Thus, further study of EFB as feedstock for biochar was omitted from plant growth trials in this study.

It is expected that conversion rates may improve with increased experience of operators. Thus it may be of value to engage the Australian operator and Big Roo inventor, Mr Russell Burnett, as a consultant to travel to Dami Research Station and workshop/demonstrate pyrolysis techniques for OPRA/OPIC personnel and smallholders in a future project.

7.3.1 Biochar characterisation:

Organic product characterisation was for all six biochars (two from Australia and four from PNG) and their chemical properties most likely to affect plant growth are shown in Table 1.3.3. As expected, all biochars had an alkaline pH of 8.3-10.5. Furthermore, all biochars were extremely saline (ECe 16.7-48.5 dS m^{-1}), except PNG EFB which was moderately saline (4.2 dS m^{-1}; Hazelton and Murphy, 2007). Since the crops used in this study will not grow in such saline conditions, 100% biochar was not tested as a substrate in this study (lettuce will not grow at >1.0 dS m^{-1} and tomato at >2.5 dS m^{-1}; Hazelton and Murphy, 2007). Biochars had 45-69% total carbon content and 0.3-2.2% total nitrogen content. While such nitrogen levels in soil would be classified as high to very high (Hazelton and Murphy, 2007), caution is needed since element values, particularly N, can be incorporated within the biochar carbon matrix and not available to plants (Kochanek et al. 2016a). However, potassium and phosphorus may be exceptions since plant available K tends to increase during pyrolysis (Yao et al., 2010) while P can be high in ash-abundant biochars (Wang et al., 2012). Phosphorous levels were very high, with PNG Frond biochar containing up to 7 times higher P levels (2900 mg kg^{-1}) than the other biochars (550-880 mg kg^{-1}). Exchangeable potassium, which is immediately available to plants, was also more than double in PNG Frond biochar (76 $cmol_c kg^{-1}$) relative to other biochars (12-36 $cmol_c kg^{-1}$).

PNG Frond biochar also had the highest acid neutralising value or NV (25) relative to the other biochars (7.7-10), which represents the capacity of the biochar to neutralise soil acidity (Hazelton and Murphy, 2007). Nonetheless, the studied biochars could not completely replace lime or dolomite as liming agents for acidic soil, since their NV of 7.7-25 is well below that of pure lime (NV 100), good agricultural lime (95-98, $CaCO_3$), poor lime (60-75), good dolomite (92-102, $MgCaCO_3$) and poor dolomite (60-75; Hazelton and Murphy, 2007), unless their application rates were very high. All biochars had a high to very high cation exchange capacity (CEC) of 32 to 82 $cmol_c kg^{-1}$, which means that the biochars are likely to contribute to soil structural stability and nutrient availability for plant growth (Hazelton and Murphy, 2007) and this CEC is likely to increase further over time (Crane-Droesch et al., 2013). Heavy metals in biochars were within or below normal levels found in soils, hence are not shown here. Sodium levels were low in PNG EFB biochar (0.2 $cmol_c kg^{-1}$), high to very high in other PNG biochars (1.8-2.6 $cmol_c kg^{-1}$) and very high in both Australian biochars (8.5-11.0 $cmol_c kg^{-1}$). It is possible that at least some of the sodium content was due to sea breeze as the Australian palms were growing within a kilometre of the seacoast and were harvested before onset of the wet season whilst the PNG trunks and fronds were collected from blocks within 5 km of the coast and during the wet season. Washing, quenching and/or pre-conditioning of biochars is known to remove excess salts (Kochanek et al. 2022). Although Australian biochars were quenched, this was clearly inadequate as both were highly saline, and more washing (before or after pyrolysis) is likely needed for feedstocks from coastal zones.

Table 1.3.3. Chemical properties of biochars produced in this project using the Big-Roo and Kon-Tiki units that are most likely to affect plant growth.

		Trunk + Frond feedstock			PNG Kon-Tiki		
Analysis	Unit	Australia Big-Roo	Australia Kon-Tiki	PNG Kon-Tiki	PNG Trunk	PNG Frond	PNG EFB
Electrical Conductivity	dS/m	4.9	9.6	3.7	3.4	9.9	0.9
ECe[1]	EC × 4.9	24.0	47.0	18.1	16.7	48.5	4.2
pH ($CaCl_2$)	pH units	9.8	10.2	9.7	9.5	10.5	8.3
Total Carbon	%	57.0	59.0	63.0	69.0	45.0	56.0
Total Nitrogen	%	0.7	0.3	0.3	0.3	0.3	2.2
Acid Neutralising Capacity	% $CaCO_3$ Equivalent	7.7	8.7	9.2	7.8	25.0	10.0
Phosphorus (Colwell)	mg kg^{-1}	570.0	550.0	560.0	390.0	2900.0	880.0
Aluminium	$cmol_ckg^{-1}$	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Calcium	$cmol_ckg^{-1}$	2.8	1.7	3.8	3.4	3.0	6.4
Potassium	$cmol_ckg^{-1}$	27.0	36.0	29.0	26.0	76.0	12.0
Magnesium	$cmol_ckg^{-1}$	1.0	0.4	1.0	0.9	0.6	2.2
Ca:Mg ratio	$cmol_ckg^{-1}$	2.8	4.6	3.9	3.8	5.1	2.9
Sodium	$cmol_ckg^{-1}$	8.5	11.0	1.9	1.8	2.6	0.2
Cation Exchange Capacity (effective)	$cmol_ckg^{-1}$	39.0	49.0	35.0	32.0	82.0	21.0

[1] Approximate ECe assumes a multiplier of 4.9, as for peat (Hazelton and Murphy, 2007).

7.4 Nursery trials to test biochar produced from oil palm wastes Australia

Nursery trials tested study biochars for potential phytotoxic and beneficial effects on plant growth using rates of 0 (control), 3, 10, 30 and 50% biochar, as shown in Fig 1.4.1.

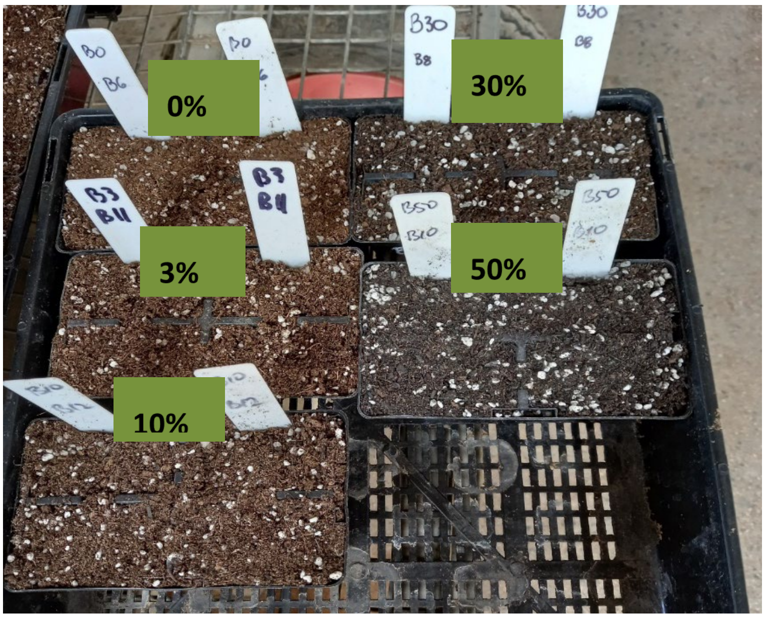

Figure 1.4.1. Plant growing media in an Australian commercial nursery, with peat replaced by biochar showing an increasingly darker colour with increasing amounts of biochar (0, 3, 10, 30 and 50%). Shown here are punnets with biochar made in Australia within the Big-Roo pyrolyser (punnets with Kon-Tiki biochar looked similar).

Figure 1.4.2. Biochar trials in Australia were within a commercial nursery using standard industry practice for maintenance. Here lettuce and capsicum seedlings are shown at three weeks post sowing.

In general, crop growth responses to both biochars were similar and highly dosage dependent, being very positive, positive, or neutral at low dosages (3% biochar) and neutral to toxic at high dosages (≥30% biochar; Figures 1.4.3 and 1.4.4) relative to the control without biochar.

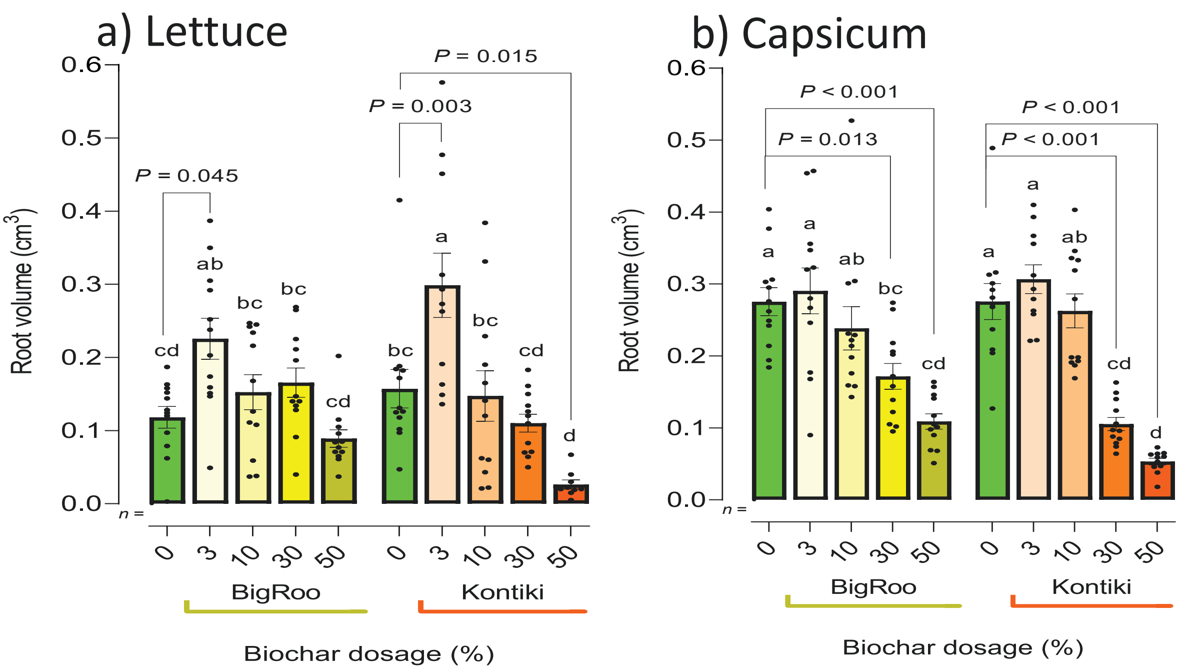

Figure 1.4.3 Root volume of (a) lettuce and (b) capsicum seedlings in response to 0, 3, 10, 30 and 50% Big-Roo and Kon-Tiki biochar applications when grown within Australian nursery conditions. Statistical analysis/graphing were carried out using GraphPad Prism, Version 9.4.1 (GraphPad Software, San Diego, CA, USA) and MINITAB, Version 17 (Minitab Inc., State College, PA, USA). General Linear Model analysis of variance was used to compare the effects of technology (BigRoo and Kontiki) and biochar dose (0, 3, 10, 30, 50%) and their interaction, with block as a random factor. The letters and *P* values represent means that are different to one another with a post-hoc Tukey test (α = 0.05). The exact sample size (*n*) for each block (true biological replication) is given as a discrete number in each panel. Significant differences for lettuce, dose: $F_{4,95} = 17.73$, $P < 0.001$, tech × dose: $F_{4,95} = 2.92$, $P = 0.025$; capsicum, dose: $F_{4,97} = 42.52$, $P < 0.001$. Transformation did not improve homogeneity of variance so data are presented untransformed.

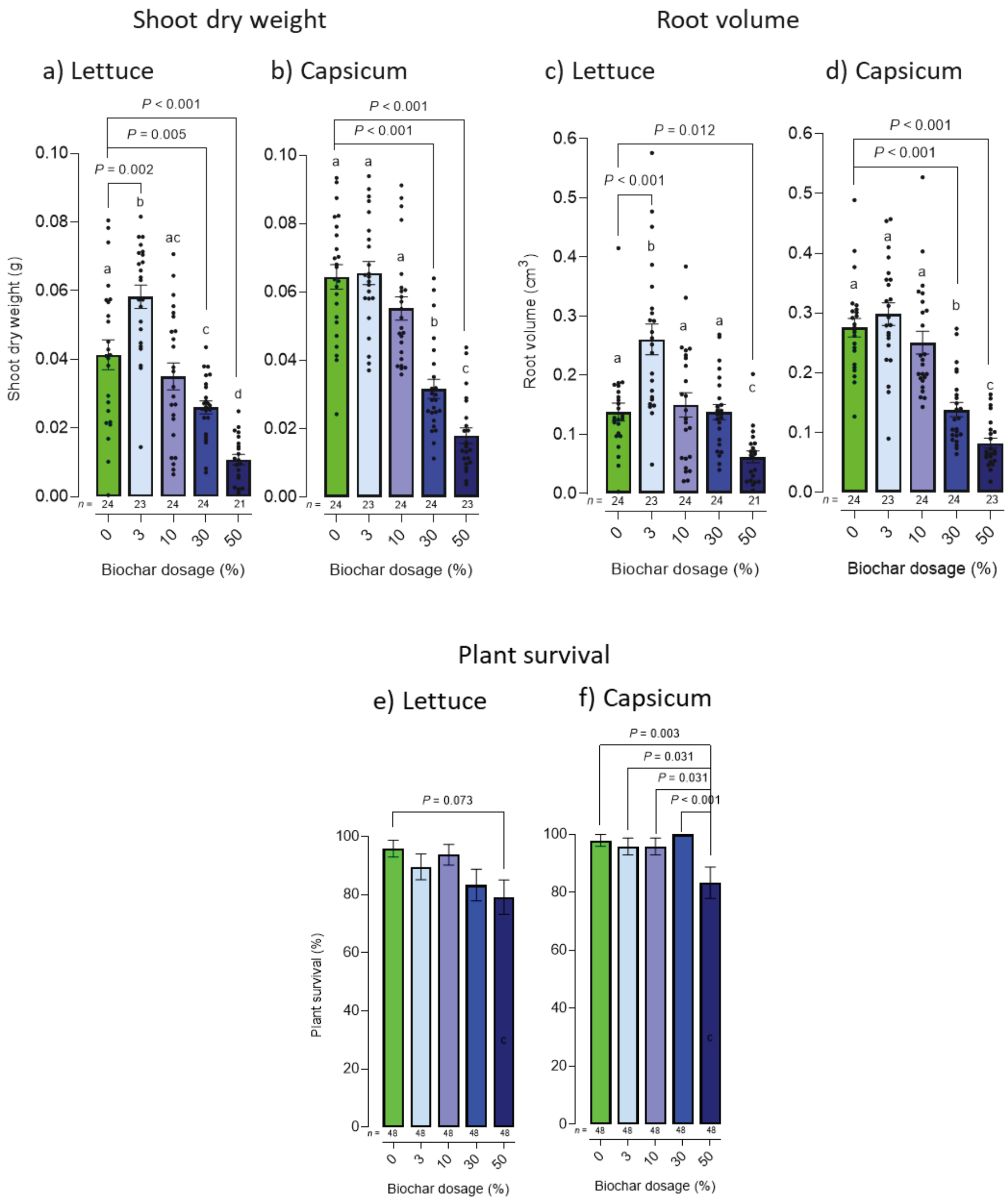

Figure 1.4.4. Seedling shoot and root development and plant survival of (a, c, e) lettuce and (b, d, f) capsicum seedlings in response to 0, 3, 10, 30 and 50% biochar applications when Big-Roo and Kon-Tiki biochar results were combined. Statistical analysis/graphing were carried out using GraphPad Prism, Version 9.4.1 (GraphPad Software, San Diego, CA, USA) and MINITAB, Version 17 (Minitab Inc., State College, PA, USA). General Linear Model analysis of variance was used to compare the effects of the Australian technologies (BigRoo or Kontiki) and biochar dose (0, 3, 10, 30, 50%) and their interaction, with block as a random factor. The letters and *P* values represent means that are different to one another with a post-hoc Tukey test ($\alpha = 0.05$). The exact sample size (*n*) for each block (true biological replication) is given as a discrete number in each panel. Significant differences for shoot dry weight for **a.** lettuce, dose: $F_{4,95} = 31.50$, $P < 0.001$, **b.** capsicum, dose: $F_{4,97} = 61.0$, $P < 0.001$; root dry weight for **c.** lettuce, dose: $F_{4,90} = 14.22$, $P < 0.001$, **d.** capsicum, dose: $F_{4,96} = 34.7$, $P < 0.001$; plant survival for **e.** lettuce, dose: $F_{4,99} = 2.63$, $P = 0.035$, **f.** capsicum, dose: ns, dose × technology: $F_{4,97} = 2.35$, $P = 0.055$. Proportions were √arcsine transformed prior to analysis, otherwise transformation did not improve homogeneity of variance so data are presented untransformed.

However, there was some variation between crops in their positive response to biochar dosage, as has been demonstrated previously (Kochanek et al., 2016a, 2016b, 2022). For example, root volume of lettuce seedlings was more than doubled by 3% Big-Roo and Kon-Tiki biochar applications to growing media relative to the control (Figure 1.4.3a, 1.4.4c) while capsicum root volume was similar to the control (Figure 1.4.3b). Similar trends were observed for shoot growth (Figure 1.4.4a,b). The fact that such low biochar application rates resulted in better or similar results as peat is positive because low rates provide better return for the effort of biochar production.

By contrast, growth and survival tended to be suppressed similarly for both crops by higher biochar doses, with 50% biochar doses almost always reducing plant survival and damaging roots and shoots relative to the control (Figure 1.4.4) and 30% usually damaging plants relative to the control (Figure 1.4.4 for all parameters except lettuce root volume). This may be due to the very high salinity levels found in both Australian biochars.

Seedling emergence percentage was not significant and is not shown.

7.5 Nursery trials to test biochar produced from oil palm wastes Papua New Guinea

A parallel nursery experiment was set up in PNG to test three PNG-made biochars (Frond+Trunk biochar, Trunk biochar and Frond biochar made in the Kon-Tiki kiln), and the two Australian made biochars (Frond+Trunk biochars made by the Kon-Tiki and Big-Roo units in Australia) for phytotoxic or beneficial effects on lettuce. Biochar made from EFB was not used as this feedstock had a very low conversion rate. The growing media used compost made from EFB which is normally used to grow oil palm seedlings in the pre-nursery (i.e., for sowing pre-germinated seeds obtained from the breeders at OPRS). The pH of the compost/biochar mixes was not measured (to mimic smallholder conditions), but the compost had a neutral pH.

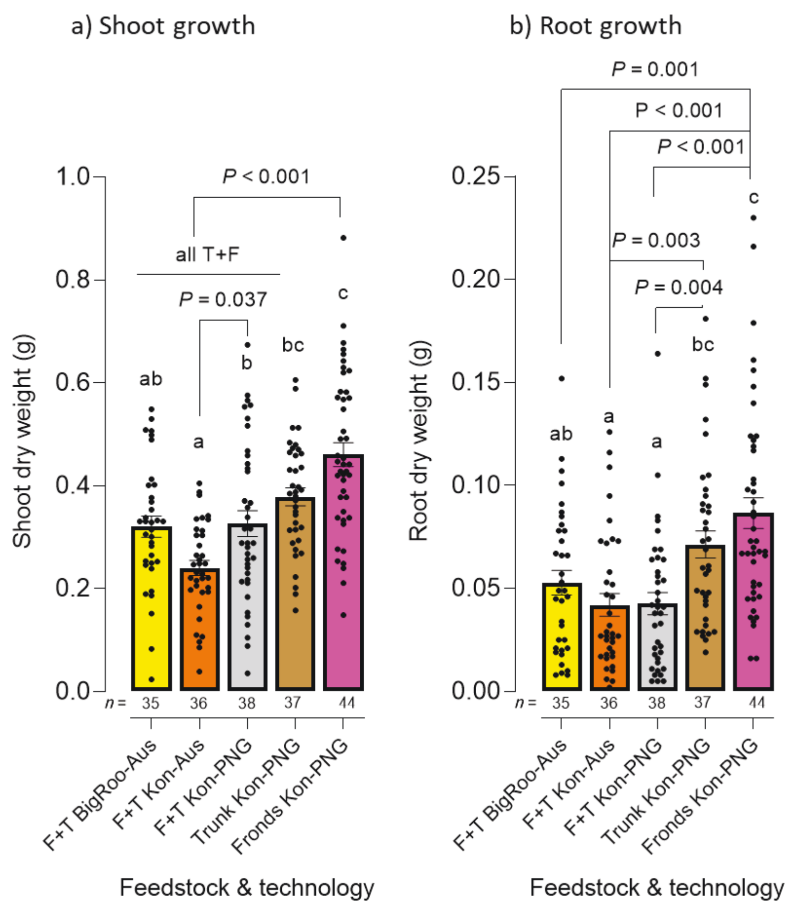

Figure 1.4.5. Shoot and root development of lettuce seedlings in response to study biochars when grown for five weeks in a PNG nursery. The biochars shown are three PNG-made biochars (Frond+Trunk biochar, Trunk biochar and Frond biochar made in PNG by the Kon-Tiki kiln) and the two Australian-made biochars (Frond+Trunk biochars made by the Kon-tiki and Big Roo units in Australia). Results shown are combined across all dosages for each biochar. Feedstock abbreviations: F, frond; T, trunk, F+T, 90% trunk+10% frond; biochar technologies: Kon, Kon-Tiki-kiln; Big Roo, Big-Roo unit; Aus, Australia. Statistical analysis/graphing were carried out using GraphPad Prism, Version 9.4.1 (GraphPad Software, San Diego, CA, USA) and MINITAB, Version 17 (Minitab Inc., State College, PA, USA). General Linear Model analysis of variance was used to compare the effects of biochar type, with block as a random factor. The letters and *P* values represent means that are different to one another with a post-hoc Tukey test ($\alpha = 0.05$). The exact sample size (*n*) for each block (true biological replication) is given as a discrete number in each panel. Significant differences for shoot dry weight: $F_{4,163} = 7.94$, $P < 0.001$; root dry weight: $F_{4,158} = 14.36$, $P < 0.001$. Transformation did not improve homogeneity of variance so data are presented untransformed.

The biochar made in PNG from 100% palm fronds was superior to all biochars made from Fronds+Trunk (Figure 1.4.5), regardless of where they were made (i.e., PNG or Australia) or which technology was used (i.e., Kon-Tiki or Big Roo). In fact, lettuce seedlings grown in the Frond biochar displayed both heavier shoots and roots, than those from media containing the Frond+Trunk biochars.

It is also worth noting that the biochar made from Fronds in PNG resulted in improved survival at high biochar dosages relative to the control (Figure 1.4.6, 30-50%) and the Trunk biochar followed a similar trend. By contrast, the Fronds+Trunk biochars harmed plants at dosages at or above 30-50% (Figure 1.4.4).

We surmise that this could be due to the higher nutrient value of the Frond biochar since its P and K levels were up to seven times greater than in other biochars. Its acid neutralising capacity and CEC were also the highest. Conversely, it is possible that the Frond+Trunk feedstock, being a mixture of course and fine materials, may have trapped volatile organic compounds that then recondensed on the biochar surface and affected plant growth positively at low doses but negatively at higher doses (observed by Kochanek et al. 2016b, mechanisms explained extensively in Kochanek et al., 2022). Salinity is unlikely to be the reason since the PNG Frond biochar had the highest salinity of all biochars tested (ECe 48.5 dS m^{-1}). Regardless of the reason, this result is promising since palm fronds are a common and continuously produced waste, being generated at every harvest.

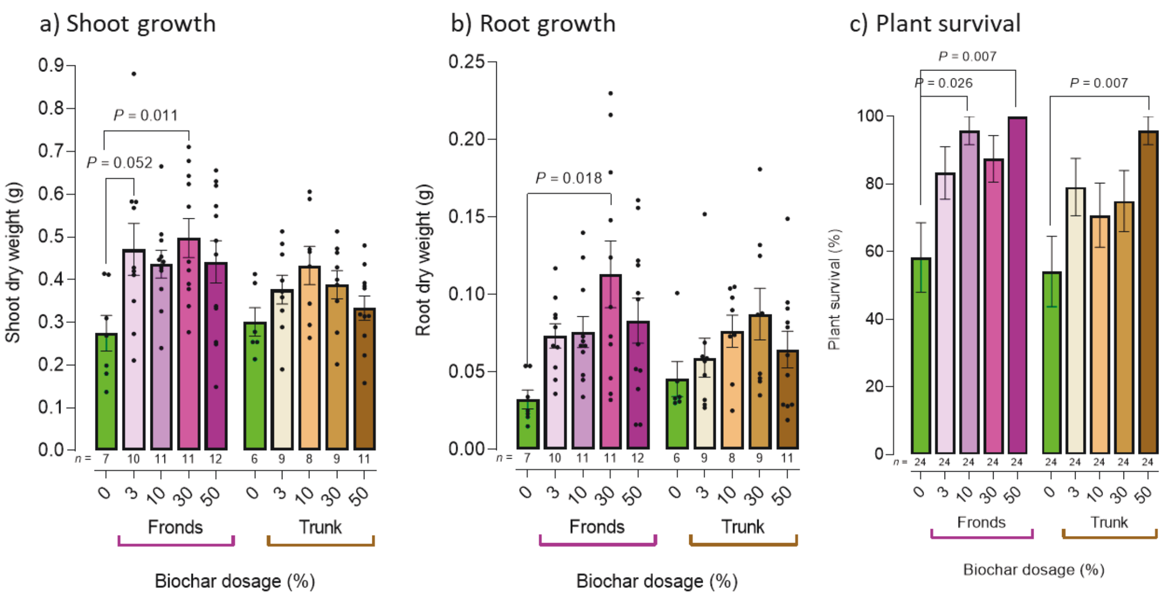

Figure 1.4.6. Lettuce seedling (a) shoot and (b) root development and (c) plant survival in response to biochars applied at 0, 3, 10, 30 and 50% to compost and grown in a PNG nursery. Biochars were made from fronds only or trunks only in PNG using the Kon-Tiki kiln, under PNG conditions. Seedlings were harvested at five weeks post sowing. Statistical analysis/graphing were carried out using GraphPad Prism, Version 9.4.1 (GraphPad Software, San Diego, CA, USA) and MINITAB, Version 17 (Minitab Inc., State College, PA, USA). General Linear Model analysis of variance was used to compare the effects of feedstock (Frond or Trunk) and biochar dose (0, 3, 10, 30, 50%) and their interaction, with block as a random factor. The letters and P values represent means that are different to one another with a post-hoc Tukey test ($\alpha = 0.05$). The exact sample size (n) for each block (true biological replication) is given as a discrete number in each panel. Significant differences for shoot dry weight, feedstock = $F_{1,73} = 4.15$, $P = 0.045$, dose: $F_{4,73} = 3.78$, $P = 0.008$; root dry weight, dose: $F_{4,97} = 61.0$, $P < 0.001$; root dry weight, dose: $F_{4,73} = 3.08$, $P = 0.021$; plant survival, dose: $F_{4,219} = 4.41$, $P = 0.002$. Proportions were √arcsine transformed prior to analysis otherwise transformation did not improve homogeneity of variance so data are presented untransformed.

Overall, when comparing results across technologies, biochars made from Fronds+Trunk with the Big-Roo and Kon-Tiki had surprisingly similar effects on plant growth, regardless of whether they were made in Australia or PNG. Thus, the cheaper and easier to move Kon-Tiki unit may be as good as the bigger more expensive Big-Roo. However, one advantage of the bigger unit was the faster speed of pyrolysis (2 hr vs 6 hr) and bigger batch processing capacity (2.4 m^3 vs 1 m^3). Nonetheless, for both technologies it would take considerable time to pyrolyse all old logs at replant. Hence these mobile units may be more useful at harvest times, when fronds are concomitantly pruned, and to remove diseased logs during the 20-30 year life of the plantation. For replant, multiple units or a larger, centralised processing unit could be utilised instead.

7.6 Workshop with smallholders in PNG to demonstrate biochar production.

COVID-19 lockdowns have caused delays in all aspects of this project, especially in PNG. These delays had knock-on effects on the collection of nursery data in PNG with collection of results coinciding with political campaigning and general elections in PNG. Unfortunately, the social situation in PNG before, during and post elections has been very volatile and unsafe to conduct a workshop (or any larger gathering). When the social situation returns to normal, OPRA personnel will organise the workshop with OPIC and smallholders on biochar production and applications.

8 Impacts

8.1 Scientific impacts – now and in 5 years

Once dried sufficiently, oil palm fronds and trunks pyrolyse readily, at conversion rates from 7% up to 35%. Fronds as feedstock have the advantage of being easy and quick to process for pyrolysis, however it is the removal and sanitation at high temperatures (pyrolysis) of infected palm trunk that will provide a break in disease cycle and reduce yield losses and thus income losses for the smallholders. Further research and process optimisation is likely to result in higher or more uniform conversion rates.

Biochars made in the low cost (Kon-Tiki) kiln have at least as good properties as biochar made in medium cost (Big-Roo) kiln, and on some parameters better.

For biochars made from Fronds+Trunks, low application doses of 3 to 10% had generally positive effects on growth of common vegetables, being better or comparable to peat. For biochars made from Fronds or Trunks alone, high doses of 10-30% resulted in the best vegetable growth outcomes.

8.2 Capacity impacts – now and in 5 years

A Kon-Tiki kiln has been made in PNG which allows for on-site pyrolysis of various oil palm wastes. The kiln is small enough for easy transport, such as on a utility vehicle (i.e., without the need for a tow bar on a car), from one block to another. It is conceivable that smallholders can take turns in borrowing the kiln to remove infected palm material from their blocks on a needs basis. The relatively low cost of this type of pyrolyser means that additional kilns may be obtained by smallholders, either on a family-wide scale or to be shared by the village/local community. In PNG, oil palm production in a smallholder block is a family business with blocks often supporting multiple/extended families (up to 13 nuclear families) and thus labour is always available when an opportunity to earn extra income arises. In addition, youth unemployment rate varies from region to region (SSR – PNGOPRA), but is usually high, thus labour would not be in shortage for biochar production. Furthermore, oil palm farming, especially at the smallholder level is not an intensive agriculture, since farmers harvest bunches twice monthly (with pruning done at the same time) and fertilise annually, and block upkeep does not require extensive hours. Thus, neither labour nor time would be considered limiting factors in biochar production for smallholders. Furthermore, every smallholder has a chisel (used in harvesting) which can be used to process feedstock for pyrolysis, thus avoiding the need for a chainsaw (which would be quicker, but more expensive).

8.3 Community impacts – now and in 5 years

The capacity to produce good quality biochars from smallholder oil palm blocks may have positive outcomes if a market and/or practical applications for the product can be found and exploited.

8.3.1 Economic impacts

Production of biochar via pyrolysis by the smallholders in PNG may potentially lead to improved livelihoods via 1) enhanced block sanitation by removal of infected palm logs from their blocks and thus reduction of income loss due to BSR (and other pests and diseases) spreading to healthy palms; 2) a cottage style industry where the biochar is sold for cash, thus generating additional income; 3) by increasing vegetable production from market gardens supplemented with biochar based fertiliser; 4) by selling carbon removal credits if/when such a scheme becomes available in PNG; 5) by upgrading biochar into higher value product, such as growth media for plants or mushrooms.

8.3.2 Social impacts

As this was a short pilot SRA, minimal social impacts were recorded from this project. Once OPRA personnel conduct the workshop on sanitation and pyrolysis, it is expected that smallholders will ask for further details. For example, smallholders would be interested in the nutrient value of the biochar in comparison to expensive fertilisers. Some smallholders would also be interested in the possibility of using home-made biochar as replacement for EFB compost which is hard for them to acquire but which they are keen to use in new OP replants to enhance growth, preserve humidity and increase survival rate in the field.

Most importantly, biochar production would be very attractive to the 15% of smallholders who are currently reluctant to replant their senile palms for fear of income loss during the two years before replanted young palms begin to produce bunches. Furthermore, the positive effect of biochar on vegetable growth may encourage many smallholders to replant part of their block and invest in the other part to grow garden and cash crops to support their livelihood (as recommended by the One Hectare Replant Plan proposed by PNG-OPRA to promote replanting of senile palms in smallholder blocks).

Poverty and high unemployment rates among the youth of PNG is a very serious social and economic obstacle and having an opportunity to utilise oil palm wastes and residues to control Ganoderma infection and produce a valuable product to create new job opportunities would be a great step to develop the oil palm smallholders' local communities.

8.3.3 Environmental impacts

Production of biochar from oil palm wastes, a common resource in oil palm blocks and plantations, allows for sequestration of carbon, with the caveat that pyrolysis is performed with sophisticated technologies that do not negatively impact air quality, human health etc. To ensure correct pyrolysis by smallholders, training by an experienced operator (e.g., Russell Burnett who produced both Australian biochars) should be provided in the future. Without proper pyrolysis technique, less carbon is trapped in the biochar matrix and more escapes into the atmosphere as CO_2 and other carbon moieties. Pyrolysis allows for sanitation of infected logs, which will reduce disease incidence and reduce need for fungicide/pesticide applications.

8.4 Communication and dissemination activities

Regular meetings (via online platforms) were conducted between UQ and OPRA to discuss project matters.

Within OPRA, the project is reported in monthly progress reports to the Research Director, Mr Cheah See Siang who provides a monthly brief to the OPRA board. Also, we include the project reports (progressive) as part of quarterly reports to the PNG OPRA board and which are also included in OPRA annual reports.

Manuscript published: J Kochanek, RM Soo, C Martinez, A Dakuidreketi and AM Mudge (2022) Biochar for sustainable intensification of agro-ecosystems – mechanisms behind potential gains and steps towards commercial viability. Resources, Conservation and Recycling 179:106109.

Oral presentation: J. Kochanek, E. Jaber, E. Tokilala and A. Mudge. (2022) Pyrolysis of oil palm wastes as a possible sanitation measure against the fungal disease basal stem rot. 11th Australasian Soilborne Disease Symposium, Cairns, Qld, Australia.

Poster presentation: E.H.A. Jaber, J. Kochanek and A.M. Mudge (2022) Pyrolysis of oil palm wastes offers opportunities for disease management, improved plant growth and closing the circular economy. TropAg International incorporating Harlan IV, Brisbane, Qld, Australia.

9 Conclusions and recommendations

9.1 Conclusions

This small research activity project has been successful in meeting its objectives. This project is unique because this is the first time pyrolysis of oil palm (OP) residues from smallholder blocks has been investigated in PNG. Most published investigations of OP waste pyrolysis have concentrated on plantations and mills, not smallholders.

Through funding provided by this project, a Kon-Tiki kiln has been manufactured in West New Britain Province, which is an asset that will last for many years. In addition, OPRA personnel have gained experience in its operation and will be able to assist Oil Palm Industry Corporation (OPIC) and smallholders in its safe use.

Oil palm fronds and trunks pyrolyse readily once dry and at conversion rates of 30 to 33% in Australia and 7.4% to 27.5% in PNG, depending on technology and feedstock composition. This is either better or on par with published literature. Conversion rates PNG are likely to become higher with training and increased operator experience. Importantly pyrolysis of OP wastes in both medium and low-cost kilns produced biochars with high to very high cation exchange capacity (CEC), meaning that all biochars are likely to contribute to soil structural stability and nutrient availability for plant growth.

Nursery trials with common vegetables conducted in both Australia and PNG demonstrated that, overall, all biochars were beneficial or neutral at low to medium doses (3% for Frond+Trunk biochars, 10-30% for Frond or Trunk biochars) but harmful to plant growth at higher doses (≥30-50% for Frond+Trunk biochars, 50% for Frond or Trunk biochars). Poor vegetable response to higher doses of biochars may be due to the high salt content (particularly in Australian biochars), and/or volatile organic compounds that recondensed on the biochar surface and affected plant growth positively at low doses but negatively at higher doses (particularly possible for Frond+Trunk biochars (Kochanek et al., 2022). Surprisingly, biochar made with 100% fronds outperformed all other biochars in PNG nursery trials, possibly due to higher CEC, higher nutrient value (especially P and K levels) and/or absence of volatile organic compounds on the biochar surface.

Given that biochar performed better than or similarly to peat in Australian commercial nursery trials when dosages were optimised, smallholders could thus sell biochar for profit, such as to plant nurseries, mushroom growers or farmers (thereby creating a cottage style industry and supplementing incomes) or could be used in home and/or market gardens to improve crop yields (which would also increase incomes). Given high biochar carbon levels, biochars could also help make oil palm production carbon neutral, and if carbon creditsmarkets eventuate in PNG, could also become an additional income stream.

Such commercial opportunities from biochar production will thus further incentivise smallholders to remove infected palm material from the field and reduce BSR infection levels in subsequent replants.

9.2 Recommendations

To maximise the findings from this small research activity, a new biochar project should be designed within the context of the oil palm smallholders in PNG and expanded to Solomon Islands, and perhaps other Pacific nations. New investigations should focus on testing biochars made from field residues (fronds and trunks) by the smallholders under various conditions and for various uses. As most of the biochars were either highly or very highly saline, a way of reducing salinity should be investigated and tested, such as by additional washing/quenching before or after pyrolysis.

Further research should specifically also quantify biochar's potential in direct disease suppression, in particular suppression of Ganoderma infection and BSR. Biochar can sometimes reduce or delay disease in plants (reviewed recently by de Medeiros et al., 2021). This effect has been observed for necrotrophic and biotrophic fungal pathogens, and both foliar and soil borne pathogens. To our knowledge effects of biochar on Ganoderma growth and infectivity have not been previously studied. This should be expanded to kitchen/market garden produce for improved disease management that could lead to higher diversity of food and more food thus increasing food security and incomes for smallholders.

Nearly all OP smallholders have kitchen gardens and many also a market garden from which produce is sold to supplement incomes. Effect of biochar on yield after application to different garden soils should be ascertained. WNBP, where OPRA headquarters are located, has fertile volcanic soils. However, other OP growing regions, e.g., Oro and Milne Bay Provinces, have poorer soils which may benefit from amelioration with OP biochars.

Long term testing of biochar effects on soil should be included, specifically how to maintain nitrogen levels in tropical soils without washing out during the monsoon rains. In the context of soils, future research could also determine if a) biochar-fertiliser complexes (*viz*. biochar compound fertilisers) are more resistant to leaching in high rainfall areas, b) biochar in soils provides temperature buffering of the root zone to expand harvest times/growing seasons (i.e., for sub-optimally high and low temperatures).

An economist should be engaged to help target markets for biochar and incorporate whole of industry metrics (not just the on-farm). New business opportunities could include carbon credits; peat-like but sustainable, stable, and carbon-sequestering high value media products for use in intensive industries such as nursery and floriculture production; use of biochar as an adsorbent for improving composting toilets in rural areas; and as biofertilizer in mushroom cultivation.

Furthermore, the new project could be expanded to Fiji to sustainably remove senile coconut palms which are no longer productive but take up valuable arable land, are hazardous during cyclonic events and harbour the Oryctes beetle, which can also be a pest on other palm species. Coconut palms are similar to oil palms in size and longevity and thus difficult to remove from the field or garden without incurring cost of machinery hire. ACIAR had funded a project to convert coconut trunks into veneer using a circular lathe as a way of dealing with this issue, however, during processing *c*. 60% of the palm trunk is wasted and that could be utilised for biochar production to generate additional income for the local economy.

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