



FINAL REPORT

Pilot-scale production of enhanced-value anaerobic digestion waste (digestate) derived bioproducts on the Darling Downs



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The Fight Food Waste CRC recognises the value of knowledge exchange and the importance of objective peer review. It is committed to encouraging and supporting its research teams in this regard. The author(s) confirm(s) that this document has been reviewed and approved by the Project Leader and Industry Partner.

This project has also been evaluated by the Fight Food Waste CRC publication review panel. These reviewers evaluated its:

- methodology articulated clearly
- positioning of findings within the current literature
- acknowledged compliance with food safety standards
- conclusions against results
- relevant human and/or animal ethic approvals obtained



Table of Contents

Executive Summary	6
1. Introduction	7
Previous Research & Literature	7
Gaps in Current Knowledge, Aims and Objectives	9
Scope and limitations	10
2. Methodology	11
3. Results and Discussion	16
Glasshouse Experiment	16
Incubation experiment	18
Field testing of granulated biofertiliser	20
4. Fertiliser replacement values of FW based OMF.....	21
5. Conclusions & Recommendations	22
6. Impact and Ongoing Monitoring	24
7. Acknowledgements	24
8. References	25
Appendix A – Project Summary	Error! Bookmark not defined.
Appendix B – Supporting Material(s).....	Error! Bookmark not defined.

List of Figures

Figure 1. EIRICH’s R02VAC EVACTHERM® consist of explosion-proof mini plant with mixing reactor (1), top-mounted vapor filter (2), condenser with integrated liquid collecting container (3) and vacuum pump module with pressure controller (4). Figure courtesy of insert acknowledgement (if applicable).....	14
Figure 2. Granulated organo-mineral fertiliser.....	15
Figure 3. Preparation of glasshouse trial	16
Figure 4. Pots in incubation chamber	16
Figure 5 Steps of harvesting ryegrass in glasshouse trial	17
Figure 6. Dry yield-to-nitrogen response for individual treatments with varying rates of applied nitrogen. Weights are averages of 3 cuts from 3 pots	18
Figure 7. Cumulative weight yield-to-treatment response across all amendments	18
Figure 8. Phosphorus availability for different treatments after 60 days of incubation	19
Figure 9 Changes in exchangeable Zn, Cu and Cr concentration during 60 days of incubation.....	20
Figure 10. Application of granulated OMF fertiliser	21



List of Tables

Table 1. Physicochemical characteristics of used soils	12
Table 2. Physicochemical characteristics of used biosolids and biochar.....	12
Table 3. Chemical composition of food-waste-derived digestate.....	13
Table 4. Treatments and N based rates applied to ryegrass grown in pots (note the zero treatment is not included), and field-equivalent amount of fertiliser product (t/ha).....	15
Table 5. Summary of ryegrass dry weight for 4 cuts	17
Table 6. Available phosphorus (mg/kg of soil) with time of experiment	18

Definitions:

Anaerobic digestion	A series of biological processes in which microorganisms break down biodegradable material in the absence of oxygen. One of the end products is biogas, which is combusted to generate electricity and heat, or can be processed into renewable natural gas and transportation fuels
Biosolids	Treated sewage sludge. Biosolids are the major by-product of the wastewater treatment process. When treated and managed appropriately, they can be beneficially used for a number of purposes
Co-digestion	A process whereby energy-rich organic waste materials (e.g., Fats, Oils, and Grease and/or food scraps) are added to dairy or wastewater digesters with excess capacity to produce methane.
Digestate	The major byproduct of the digestion, semi-stabilized material rich in organic matter and minerals
Food waste	Materials for human consumption that are subsequently discharged, lost, degraded, or contaminated and is composed of organic waste and leftovers from residences, restaurants, cafeterias, canteens, and markets
Sludge	The solids which are removed from wastewater by primary and secondary treatment.



Executive Summary

Food waste (FW) and sludge production in Australia will continue to increase in response to population growth (Buhlmann et al., 2019). Disposal of organics and sludge through landfill is increasingly regarded as non-environmentally friendly and carries a significant cost. Agricultural recycling of FW digestate and biosolids is considered an environmentally beneficial option, but there are many logistic and practical difficulties that need to be overcome, including unbalanced chemical composition and physical properties not suitable for standard farm spreading equipment.

At present, food waste is poorly utilised and commonly disposed of in landfills or incinerated, in Australia food waste contributes to 3 percent of greenhouse gas emissions (FIAL, 2021). One method of FW management is recycling FW to soil as an amendment. Current rates of food waste digestate and biosolids uptake by farmers is low due to the unbalanced nutrients composition and overall (poor) physico-chemical quality of the material which does not meet the requirements of modern farming practices and farm equipment (Antille, 2011).

This research was conducted with the aim to develop a new commercial product that maximises the nutrient recovery from FW digestate and sludge by improving the composition and physical characteristics of the final product. This research utilises a purpose-built prototype equipment whereby FW digestate blended with urea is turned into solid granular fertiliser. A multi-scale experimental work that included laboratory, glasshouse and field-based studies was conducted to:

- Develop the specifications for novel, enhanced-value FW digestate-derived organo-mineral fertiliser (OMF) that meet the requirements for field application using standard farm equipment (physical and mechanical properties) and nutritional needs of crops (chemical composition).
- Experimentally evaluate the proposed product formulation (s) and product format, determine the agronomic value of OMF.

Two FW comprising materials were used: biosolids containing co-digested FW from a wastewater treatment plant and liquid FW digestate from a commercial anaerobic digestion facility. Two varieties of OMF were made: a) pelletised OMF by combining biosolids containing co-digested FW with commercially available urea fertiliser; b) granulated OMF by combining biochar, FW digestate, Ca bentonite with commercially available urea fertiliser. Both pellets and granules were formulated based on the proportions of total nitrogen concentration provided from used ingredients. Pelletised OMF was made manually at UniSQ research facilities using a laboratory scale pelletiser. Granulated OMF was manufactured at UniSQ research facilities using laboratory scale EIRICH Intensive Mixer system which allows the complete production of fertiliser granulates in one process step by means of agglomeration from dry powders and suitable for manufacturing organic based fertiliser.

A multi-scale experimental work included: a) laboratory study – incubation and leaching experiments; b) glasshouse study – pot trial; c) field-based study – testing application of granulated OMF on soil using standard spreading equipment. The results of research have demonstrated the fertilising potential of FW digestate, biosolids containing co-digested FW and OMF for use in Australian arable and grass cropping systems. The product specifications for novel fertiliser materials have been established, and if appropriate product quality control procedures could be implemented, acceptability by farmers should not be a barrier to increasing the amount of biosolids and FW digestate (and derived fertiliser materials) currently being recycled to agriculture. Produced granulated product meets quality criteria and the requirements of current farming practices and farming spreading equipment. The field trial demonstrates the successful distribution of the granulated material in field condition.



In the glasshouse experiment, all fertilised pots exhibited significantly higher yield than the unfertilised controls. Biosolids containing co-digested FW, pelletised biosolids containing co-digested FW and urea treatments increased dry matter yield comparing to control pots by 63% for biosolids and pelletised biosolids and 41% for urea treated ryegrass. The rates of N application linearly increased yield in all treated pots. Based on current results, it is concluded that biosolids and pelletised biosolids are more efficient than mineral fertiliser for all rates applied in terms of producing higher yield. The application of biosolids increased heavy metals availability comparing to control and pelletised biosolids amended soil, but the concentration of heavy metals in all amendments were under the maximum levels accepted by the current Queensland legislation and both pelletised biosolids and biosolids used in this study are suitable for land application.

Future agronomic studies should consider investigating options for improving nutrient use efficiency through adjustments to the timing of fertiliser application and fertiliser placement and the longer-term effects of routine fertiliser applications on potentially toxic elements (both heavy metals and organic contaminants). Effort should be spent on upscaling and improving the granulation technology and ensuring the physical and mechanical properties of FW digestate, biosolids and OMF are such that they meet the requirements of modern farm spreading equipment. The assessment of such fertiliser properties, as documented in this work, may be used as guidance to improve, and standardise, the quality of biosolids-derived fertilisers. The knowledge gained through this project, coupled with novel lab-scale granulation equipment installed at the Centre for Agricultural Engineering at the University of Southern Queensland, can be used to inform and test organic-based fertiliser technology. There is also a need to perform further and more detailed economic analyses when the actual cost of production of FW digestate based OMF to the required quality are known. Fertiliser N replacement value data and the yield-to-nitrogen response relationships produced by this study can be used to inform such economic analyses.

1. Introduction

Disposal of biodegradable wastes, including food waste (FW) through landfill is regarded as non-sustainable both from the environmental and resource-recovery perspectives (EEA, 2001). Agricultural recycling of FW digestate and biosolids is considered the best practicable environmental option (Marchuk et al., 2023), but there are many logistic and practical difficulties that need to be overcome, including unbalanced chemical composition and physical properties not suitable for standard farm spreading equipment (Antille, 2011). Optimisation of the physico-chemical properties of digestates and biosolids should ensure acceptability by farmers and secure the agricultural route for disposal. The practice of recycling is supported by the legislation, provided that the FW biosolids used on agricultural land do not present a risk to the environment, and provided that potential contaminants, such as heavy metals, and pathogens are not transferred to the food chain.

Previous Research & Literature

FW and sludge production in Australia will continue to increase in response to population growth. FW from households, cafeterias, restaurants, supermarkets, and processing plants contributes to a large fraction of municipal solids waste (Saqib et al., 2019; Mickan et al., 2022). Globally, the valorisation of FW into digestate through the process of anaerobic digestion is becoming increasingly popular. As a result, a large amount of FW digestate will need to be properly utilised (O'Connor et al., 2022). According to Food Innovation Australia Ltd (FIAL), 2021, in Australia, it is estimated that about 2.46 million tonnes of FW is generated annually from household food waste alone: this costs the Australian economy AU\$19.3 billion annually (FIAL, 2021). Currently, food waste is poorly utilised and commonly disposed of in landfills, contributing to 3 percent of Australia's greenhouse gas emissions including CO₂, CH₄, and N₂O (FIAL, 2021; Munesue et al., 2015). Food waste management aims to encourage the recycling of the FW to soil as an



amendment (Tampio et al. 2016; Ren et al., 2020). Anaerobic digestion of various organic wastes or food for renewable energy and the production of nutrient-rich liquid and/or solid digestates are established measures that can alleviate loads on landfill while simultaneously recovering nutrients from waste resources (Zarezadeh et al. 2019; Ren et al., 2020).

Biosolids containing co-digested food waste, are the main solid end-product of urban wastewater treatment, comprised of sewage sludge treated to achieve a certain quality that reduces or eliminates health and environmental risks and improves beneficial use characteristics (Marchuk et al., 2023). In Australia, around 350,000 dry megagrams (Mg) of biosolids were generated in 2021 and, its use in agriculture has increased from 55 % in 2010 to 73 % in 2021 (Vero, 2022). Biosolids applied to agricultural land can increase crop yield through improvements in soil physico-chemical properties, and agronomic responses are reported to be greater in weathered soils, which are common across Australia (Reid, 2002). Beneficial reuse of nutrients from biosolids is important to offset the demand for chemical fertilisers as this can provide a dual benefit, namely: reducing fertiliser price pressures on agriculture, and decreasing greenhouse gas emissions associated with chemical fertiliser production (Marchuk et al., 2023). Studies on the emissions avoided by use of nutrients in biosolids have shown that for every Mg of dry biosolids used, around 6 Mg of CO₂ can be avoided (Darvodelsky, 2012). Application of biosolids for agriculture has significant potential because of the volumes produced that could be used for its nutrients and carbon content (fertilising and soil conditioning), at comparatively lower costs (Marchuk et al., 2023).

Digestate is a by-product of anaerobic digestion and can be recovered and used as an organic fertiliser which offering an attractive to commonly used mineral fertilisers. The use of digestate as fertiliser has significant environmental benefits compared with synthetic fertilisers. FW digestate promotes nutrient recovery and bio-circulation within the food supply chain and can, unlike synthetic fertilisers, improve soil physical and chemical properties such as water holding capacity and ability of soil to retain more nutrients in plant-available forms. Moreover, FW digestate contains all the necessary macro- and micronutrients and other organic elements including some plant hormones which can also result in positive influences on plant growth and development (Ren et al., 2020). Recently, increased studies have been performed to understand the role of food-waste-derived fertilisers as soil amenders (O'Connor et al., 2021). Food-waste digestates contain plant growth-promoting compounds and molecules, and, as well, they contain plant growth-promoting microbes and have great potential to increase plant yield, above that obtained using mineral fertiliser alone (Cheong et al., 2020; Qi et al., 2018). Furthermore, the high organic matter and humic acids within the digestate have been found to improve soil structure, decrease water evaporation loss in soils, and enhance nutrient cycling (O'Connor et al., 2021). The high carbon levels in digestates can enhance long-term capacity of soils to hold water and has the potential to amend soils in dry climates or sandy soils. In a field experiment, Jurgutis et al. (2021) observed an increase in soil organic carbon in eroded, loamy Retisol by 11.9% – 15.7% through the application of digestate. Solid digestate was observed to have an increased soil carbon compared to liquid digestate. The study by Fernandez-Bayo et al. (2017) observed an increase plant-available water by 11–17% in food-waste digestate amended soils compared to the control (soil). Digestates can also provide significantly higher plant growth when applied to low-fertile soils. Jurgutis et al. (2021) recorded a significant increase in grass (*Panicum virgatum* L.) biomass. The application of 170 kg N ha⁻¹ of solid digestate to the soil recorded a harvest of 14.90 t ha⁻¹ compared to the control of 4.92 t ha⁻¹, more than 3 times increase in plant yield. Findings of Coelho et al., 2019, reported that FW digestates positively affect forage crop yields, especially grasses, with increases in plant growth either similar or exceeding those from equivalent amounts of traditional mineral fertilizers (Ren et al. 2020). However, the study by Greenberg et al. (2019) recorded that digestate containing maize silage had a decreased plant growth of rye in sandy soil when compared to mineral fertiliser (9.3 Mg ha⁻¹ in digestate, 10.6 Mg ha⁻¹ in mineral fertiliser). Additionally, digestates can be mixed with other organic substrates such as composts to increase nutrient contents and promote plant growth. For instance, Mickan



et al. (2022) showed increased nutrients and plant growth when applying of FW-derived digestate, with and without biochar to potting mix. Addition of biochar with FW digestate decreased the availability of soil mineral N by decreasing the mineralisation of nitrogen which reduced the risk of N loss. Additionally, the use of biochar with FW digestate could delay the release of N and thus be used as a biologically friendly nitrification inhibitor for a slow-release fertiliser. Nonetheless, these data should encourage alternative uses of FW digestate as a nutrient source in land application.

Typically, biosolids have been applied to land in their original form (liquid or dried). Sustainable farming practice aims to balance nutrient inputs with outputs. An 'ideal' fertiliser supplies nutrients only on the basis of plant demand, in relation to its phenological stage, and to prevent environmental impacts associated with over-application or poorly timed application. There are significant differences in nutrient availability between digestate and mineral fertilisers. Nutrients in mineral fertilisers are generally in a soluble form, and when applied are immediately plant available. In contrast, a large proportion of nutrients in FW digestate are in organic forms which must first to be mineralised to be plant- available. This presents both a challenge and an opportunity by blending or reacting mineral fertilisers with organic fertilisers to produce so-called organo-mineral fertiliser (OMF). Such fertiliser mixes or products could balance the rapid release properties of nutrients from mineral fertilisers with sustained slow mineralisation and release of nutrients from an organic component, and, additionally, could improve soil structure, drainage, water availability, and increase soil carbon to promote crop growth (Sakrabani, 2020). The use of such products represents a technological advancement but requires consideration of several important product and application-related factors to enable successful use in broad-acre agriculture. Before the application of FW digestate, post treatment is necessary to reduce the volume and phytotoxicity (in line with relevant state, federal and local regulations), accelerate the stabilisation, and conserve nutrients. This has the potential to significantly reduce transport costs associated with delivery of product to areas that need the nutrients. While numerous studies have explored the effect of combined applications of biochar and manure on C and N cycling in soils, relatively little is known about the effect of combined applications of FW digestate and biochar (Martin et al., 2015).

Gaps in Current Knowledge, Aims and Objectives

The use of digestate as a fertiliser faces logistical challenges due to the low nutrient content as compared to synthetic fertilisers, especially if digestate is to be used in conventional agriculture (high-nutrient input systems) (Mickan et al. 2022). Current rates of organic fertiliser uptake by farmers are low due to the overall (poor) physico-chemical quality of the sludge, which does not meet the requirements of modern farming practices and farm equipment. In addition, digestate is susceptible to significant N losses through biologically and chemically induced volatilisation, due to storage conditions (e.g., uncovered tank), land application method (spraying, trailing hose) and environmental conditions (heat, wind) during land application (Nkoa, 2014). To alleviate the logistical and operational costs in agriculture, FW digestate could be used as a nutrient source in production of OMF. This strategy reduces transport constraints and uses digestate in land application, thereby promoting the circular economy through sustainably produced OMF (Dahlin et al., 2019).

This research was conducted to help overcome some of the challenges presented by the physico-chemical properties of FW digestate to assist in securing the agricultural route for the disposal of this materials. Optimisation of the physico-chemical properties of FW digestates is, therefore, a pre-requisite to ensure land application is environmentally safe and agronomically efficient, and it is a requirement for increased acceptability by farmers. Our aim is developing a new commercial product(s) that maximise the nutrient recovery from FW digestate and sludge by improving the composition and physical characteristics of the final product. This research utilises a purpose-built prototype equipment whereby FW digestate blended



with urea will be turned into solid granular fertiliser. A multi-scale experimental work that included laboratory, glasshouse and field-based studies was conducted to:

- Develop the specifications for novel, enhanced-value FW digestate-derived products (OMF) that meet the requirements for field application using standard farm equipment (physical and mechanical properties) and nutritional needs of crops (chemical composition).
- Experimentally evaluate the proposed product formulation (s) and product format, determine the agronomic value of OMF.

The project has the potential impact of reducing a portion of the 7.6 million tonnes of food waste generated p.a. nationally by transforming the digestate into value-added OMF (FIAL, 2021). Such a development will enable improved resource use efficiency and will likely deliver tangible benefits both to growers (reduced reliance on mineral fertilisers) and the wastewater industry and municipalities (reduced cost of disposal and increased benefits of food waste co-digestion) and increase opportunities to meet long-term nutrient recycling targets.

Scope and limitations

This report has been prepared by Centre for Agriculture Engineering (CAE), University of Southern Queensland, for Fight Food Waste Ltd (CRC Entity) and may only be used and relied on by these parties for the purpose agreed between the Project Partners as set out in Project Agreement.

The services undertaken by CAE in connection with preparing this report were limited to those specifically detailed in the report and are subject to the scope limitations set out in the report.

The opinions, conclusions and any recommendations in this report are based on conditions encountered and information reviewed at the date of preparation of the report. CAE has no responsibility or obligation to update this report to account for events or changes occurring subsequent to the date that the report was prepared.

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2. Methodology

The project assesses the agronomic/nutrients value of biosolids contained food waste and food waste digestate based organo-mineral fertiliser: in laboratory, glasshouse and field conditions.

The project plan is summarised as followed:

- Laboratory testing and analysis of all materials used in experimental work.
- Design, formulation and production of organo-mineral fertiliser, based on food waste digestate.
- Glasshouse study: assessing agronomic/fertiliser potential of biosolids containing food waste.
- Inter-laboratory trial: incubation experiment using granulated organo-mineral fertiliser.
- Field testing of granulated organo-mineral fertiliser.
- Assessment of fertiliser replacement values of FW based OMF.

Biosolids containing co-digested food waste was readily available at the experiment location as well as existing pelletising equipment. In order to deliver the project in a timely manner, glasshouse experiments were undertaken on pelletised biosolids containing co-digested food waste. Granulation is, however, the preferred method of OMF formulation over pelletising as it is more efficient and less time and labour intensive. Furthermore, this project focused on the beneficial reuse of FW, and it was preferred to have food-waste specific digestate tested. After specific food waste digestate and granulator was sourced, field trials assessing the physical characteristics and incubation trials assessing release of nutrients were undertaken.

Soil, biosolids, biochar and FW digestate characteristics

Two soils from Queensland were used in this study, namely 1. clayey Ferrosol (Rhodoxeralf, US Taxonomy) from the Agricultural Field Station Complex at the University of Southern Queensland and 2. acidic sandy Yellow Chromosol (Alfisol, US Taxonomy) from the Gatton area, Queensland. Selection of these soils was based on their differences in mineralogy, texture, and pH. Soil samples were collected from the 0.0–0.20 m depth by a hand auger, air-dried, and sieved to 2 mm. Physicochemical properties of the soils are presented in Table 1. In terms of heavy metal and trace elements concentrations both soils have low levels of heavy metals concentration below the limit values of the maximum allowable soil contaminant concentration (EPA Queensland, 2020).

Standard methods were used for the determination of pH and EC (1:5 soil/water) (Rayment and Lyons, 2011) and particle size distribution (Gee and Bauder, 1986). Total carbon and nitrogen concentration were measured by ignition with a Leco elemental analyser (Leco Corporation, St. Joseph, MI, USA). Total phosphorus and heavy metal content of soil, biochar and biosolids was analysed by inductively coupled plasma mass spectrometry (ICP-MS) (ELAN 6000, Perkin Elmer, Switzerland) after acidic digestion ("Aqua regia" HNO₃/HCl, 3/1) in a microwave oven (Multiwave, 3000 Anton Paar, USA). For plant-available phosphorus soil was extracted with 0.5M sodium bicarbonate solution adjusted to pH 8.5 and analysed using a LaChat Quickchem flow injection analyser.



Table 1. Physicochemical characteristics of used soils

Soil properties	Units	Ferrosol ¹	Yellow Chromosol ¹	Maximum allowable contaminant concentration ²
pH (1:5 soil/water)	-	6.0	5.5	
EC (1:5 soil/water)	dS/m	0.03	0.01	
Total Carbon	%	3.5	1.7	
Total Nitrogen	%	0.3	0.2	
Total Phosphorus	%	0.13	0.06	
Clay	%	57	14	
Total Zn	mg/kg	62.0	42.7	200
Total Cu	mg/kg	39.3	8.5	100
Total Cr	mg/kg	77.7	13.5	100
Total Pb	mg/kg	9.3	11.0	150
Total Ni	mg/kg	52.5	67.2	77
Total As	mg/kg	3.4	4.2	20
Total Cd	mg/kg	0.02	0.03	1

¹ Australian Soil Classification (Isbell, 1996)

² EPA Queensland, 2020

Biosolids containing co-digested food waste were sourced fresh from a Wastewater Treatment Plant which primarily anaerobically digests wastewater treatment plant sludge and co-digests food waste. Prior to analyses, fresh biosolids were dried at 100°C in oven for at least 12 hours, ground and sieved through 2 mm sieves to achieve homogeneity. Biochar was sourced from biosolids feedstock from wastewater Treatment Plant. The biochar was industrially produced in a thermal gasification system. Biochar materials was air-dried and sieved to pass 2 mm. Physico-chemical properties, nutrients and heavy metal content are presented in Table 2.

Table 2. Physicochemical characteristics of used biosolids and biochar

Properties	Units	Biosolids	Biochar	Maximum allowable Contaminant concentration ¹
pH (1:5 soil/water)	-	6.9	8.2	
EC (1:5 soil/water)	dS/m	8.86	1.07	
Total Carbon	%	38.6	34.9	
Total Nitrogen	%	6.2	4.6	
Total Phosphorus	%	2.6	3.1	
Total Zn	mg/kg	597	1032	2500
Total Cu	mg/kg	528	373	2000
Total Cr	mg/kg	79	4.3	500
Total Pb	mg/kg	34.7	17.5	420
Total Ni	mg/kg	130.1	36.2	270
Total As	mg/kg	4.9	5.1	20
Total Cd	mg/kg	1.4	0.7	20

Liquid FW digestate was obtained direct from the digesters from commercial anaerobic digestion facility, primarily treating food waste as the principal input. A detailed analysis of the nutrient composition of the digestate is shown in Table 3.



Table 3. Chemical composition of food-waste digestate

Properties	Units	FW Digestate
pH (1:5 soil/water)	-	7.5
EC (1:5 soil/water)	dS/m	39.0
TS ¹	%	3.28
VS ²	%	2.05
Nutrients		
Total Nitrogen	mg/L	3500
Total Phosphorus	mg/L	240
Total Potassium	mg/L	1100
Total Sulphur	mg/L	34
Heavy metals		
Total Zn	mg/L	8.1
Total Cu	mg/L	0.53
Total Co	mg/L	0.05
Total Ni	mg/L	0.11
Total Mn	mg/L	2.3

¹ Total Solids; ² Volatile Solids

Production of organo-mineral fertilisers

Formulation and production of pelletised OMF

Combinations of organic (biosolids containing co-digested food waste) and inorganic nitrogen (N) fertiliser (Urea) were formulated as pelletised products (OMF-BS) with pellets size suitable for transport and spreading. OMF-BS formulation was proposed which has a N content of 15%. This was achieved by adding urea (46% N) to the biosolids containing co-digested food waste (6.2% N) until an N:P ratio of about 15:2 was achieved. Formulation materials were mixed, water added to reach saturation, material pelletised and dried at room temperature (to decrease ammonia volatilisation) for 72 hours. N/P/K composition of the final product is shown in Table 4.

Formulation and production of granulated OMF

The liquid FW digestate contains nitrogen (mainly as ammonium) which is susceptible to N loss as a fertiliser and also faces logistical constraints for agricultural use. Other constraints for digestate as a nutrient source include legislative; waste and environmental regulations, and economic; high transportation and infrastructure costs, and complications associated with odour (Mickan et al., 2022). Biochar is a solid carbon residue by-product from pyrolysis, can adsorb and retain nutrients and alter microbial N-cycling processes (Kizito et al., 2015). FW digestate combined with biochar can prevent nutrients loss and has the potential to be used as a substitute for chemical fertilizer.

Granulated OMF (OMF-FW) was made by combining FW digestate, biochar, commercially available urea fertiliser and Ca bentonite. Prior to granulation liquid FW digestate was mixed with ground biochar, dried at room temperature (to minimise ammonia volatilisation) for 72 hours and thermally treated at 105°C for 16 hours to reduce/eliminate pathogens (Al-Gheethi et al., 2018). OMF-FW was formulated based on the proportions of total N provided from urea, biochar-FW digestate mix until an N:P ratio of about 15:2 was achieved (Table 4). Before granulating, all materials were ground to <100 µm, as required by granulating equipment. Bentonite was added as a binding agent.

Table 4 Nutrients composition of pelletised and granulated OMF



Product	Units	Nitrogen	Phosphorus	Potassium
Pelletised OMF-BS	%	15	2.0	1.7
Granulated OMF-FW	%	15.5	2.1	0.9

Granulated OMF-FW was manufactured at UniSQ research facilities using laboratory scale EIRICH Intensive Mixer system (Figure 1) which consists of explosion-proof mini plant with mixing reactor (1), top-mounted vapor filter (2), condenser with integrated liquid collecting container (3) and vacuum pump module with pressure controller (4). EIRICH granulator allows the complete production of fertiliser granulates in one process step by means of agglomeration from dry powders and suitable for manufacturing organic based fertiliser. Depending on material and grain size, granules between 0.1 mm and 8 mm can be produced.

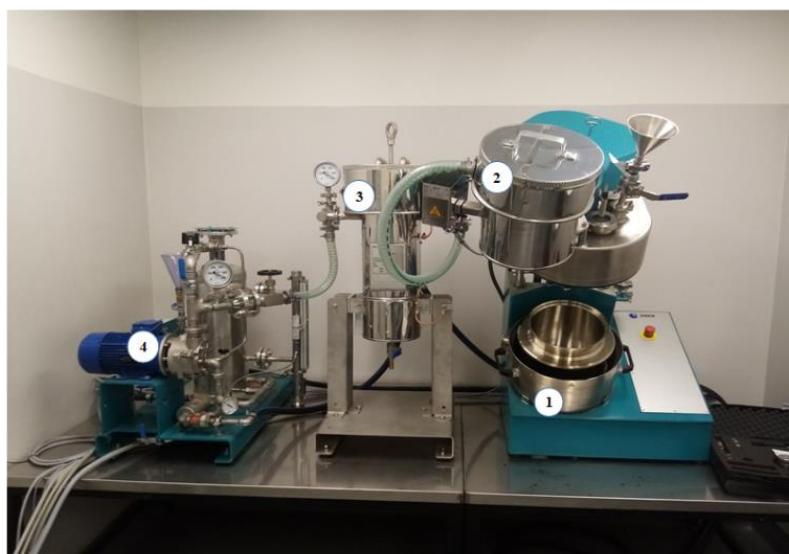


Figure 1. EIRICH's R02VAC EVACTHERM® granulator.

Firstly, the ground raw materials were weighed and dosed. Secondly, they were transferred to the intensive mixer and initially mixed dry for 60 sec. Following this, water was dosed, and distributed under high speed at short time intervals. The speed of mixing pan was then reduced with the aid of the frequency inverter to granulate the completely wetted particles. The unique advantage of granulating within the mixer means no monitoring is necessary during the process. Figure 2 illustrates the final product.



Figure 2. Granulated organo-mineral fertiliser.

Glasshouse Experiment using pelletised OMF-BS

This experiment was conducted at the Agricultural Science and Engineering Precinct, University of Southern Queensland (USQ), Toowoomba. Climatically the region is subtropical with warm humid summers and mild dry winters. During the experimental duration the ambient temperature in the glasshouse ranged $22\pm 3^{\circ}\text{C}$ (day/night) with relative humidity of 55–65%. A total of 50 pots (200 mm diameter, 4.5 L volume) were prepared, each containing 4 kg of soil (Figure 3). Pots were performed in triplicate using the following treatments: 1. Control, 2. Biosolids containing co-digested FW (BS) only, 3. OMF-BS (Biosolids containing co-digested FW + Urea), 4. Urea only. The rates of application corresponded to an equivalent of nitrogen additions of 150, 225, 300, and 450 kg/ha (Table 5). The soil in the pots was packed to achieve a dry bulk density of about 1.2 g cm^{-3} , which was the density found in-field conditions. During the preparation of pots, the soil was mixed with the corresponding fertiliser material to conform a layer of 50 mm beneath ryegrass seeds (*Lolium perenne* L.) to avoid their direct contact with fertiliser. The seeds of ryegrass were sown and covered with 1-1.5 cm of soil. Moisture contents were maintained around 70% of measured field capacity via application of water. The experiment used a completely randomised design with fertilizer treatments setup in triplicate ($n = 3$) and controls replicated five times ($n = 5$).

Table 5. Treatments and N based rates applied to ryegrass grown in pots (note the zero treatment is not included), and field-equivalent amount of fertiliser product (t/ha).

N applied, kg/ha	Biosolids, t/ha	OMF, t/ha	Urea, t/ha
150	2.42	1.00	0.33
225	3.63	1.50	0.49
300	4.84	2.00	0.65
375	6.05	2.50	0.82
450	7.26	3.00	0.98



OMF-BS product



Application of OMF-BS



Plants emergence (after 7 days)

Figure 3. Preparation of glasshouse trial

Incubation study

Soil incubation techniques have been extensively used to determine nutrients and heavy metals release from organic materials applied to agricultural soils. A 60-day incubation study was conducted to determine the potential of biosolids and granulated organo-mineral fertiliser to release heavy metals into soil over time. Soils were amended with the BS and the granulated OMF-FW at two rates: 5% and 10%, denoted as BS 5 BS 10, OMF 5 and OMF 10 treatments plus control samples with no treatment. All the treatments were replicated three times. The mixtures (soil + amendment) were poured into pots and incubated at 40°C in the incubation chamber (Figure 4). The soil moisture content was adjusted weekly to 75% of field soil capacity using deionized water. Sampling events were performed after 3, 10, 30 and 60 days of incubation. The soil from each pot was analysed at each sampling event.



Figure 4. Pots in incubation chamber

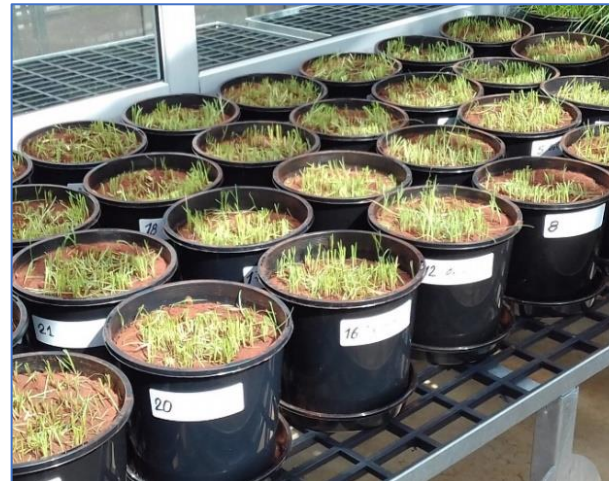
3. Results and Discussion

Glasshouse Experiment

A total of four cuts were performed at regular time intervals of 30 days. The grass was cut at 20-mm above the soil surface and the harvested plant material oven-dried at 70°C for 96 hours for determination of dry matter yield.



Ryegrass before first cutting events (30 days)



Ryegrass harvesting after 30 days growing cycle

Figure 5 Steps of harvesting ryegrass in glasshouse trial

The results of dry mass weight for all treatments are presented in Table 6. The results from Table 6 also displayed graphically in Figures 6 and 7 below. These figures illustrate performance of different treatments with different N application rates comparing to control ryegrass pots without any treatment.

Table 6. Summary of ryegrass dry weight for 4 cuts

Treatment	n	N rates (kg ha ⁻¹)	1st cut ± SD (g)		2nd cut ± SD (g)		3rd cut ± SD (g)		4th cut ± SD (g)	
Control	5	0	2.23	± 0.43	4.29	± 0.27	1.88	± 0.33	1.57	± 0.13
BS	3	150	3.92	± 0.30	4.33	± 0.33	3.27	± 0.30	3.00	± 0.15
	3	225	3.28	± 0.20	4.27	± 0.29	3.60	± 0.21	3.07	± 0.15
	3	300	3.90	± 0.22	4.77	± 0.37	4.44	± 0.33	3.65	± 0.36
	3	375	4.51	± 0.61	5.11	± 0.32	4.12	± 0.73	3.41	± 0.14
	3	450	4.78	± 0.42	5.85	± 0.41	4.90	± 0.30	3.37	± 0.23
OMF-BS	3	150	4.38	± 0.17	4.85	± 0.18	4.20	± 0.10	3.34	± 0.33
	3	225	3.65	± 0.79	4.97	± 0.20	4.66	± 0.27	3.38	± 0.14
	3	300	3.94	± 0.16	4.88	± 0.43	4.99	± 0.21	3.48	± 0.18
	3	375	3.08	± 0.53	4.77	± 0.49	4.67	± 0.44	3.29	± 0.05
	3	450	3.17	± 0.43	4.05	± 0.40	4.79	± 0.26	3.49	± 0.40
Urea	3	150	2.39	± 0.47	4.26	± 0.80	4.74	± 0.22	3.20	± 0.17
	3	225	1.95	± 0.44	3.84	± 0.19	4.34	± 0.26	3.47	± 0.13
	3	300	1.96	± 0.25	3.78	± 0.22	4.45	± 0.22	3.42	± 0.39
	3	375	2.12	± 0.16	4.69	± 0.22	4.44	± 0.34	3.22	± 0.18
	3	450	1.81	± 0.08	4.39	± 0.23	4.50	± 0.19	3.51	± 0.10

In general, all fertilised pots exhibited significantly higher yield than the unfertilised controls. BS, OMF-BS and urea treatments increased dry matter yield comparing to control pots by 63% for BS and OMF-BS and 41% for urea treated ryegrass. The rates of N application linearly increased yield in all treated pots. Based on current results, it is concluded that BS and OMF-BS are more efficient than mineral fertiliser for all rates applied in terms of producing higher yield.

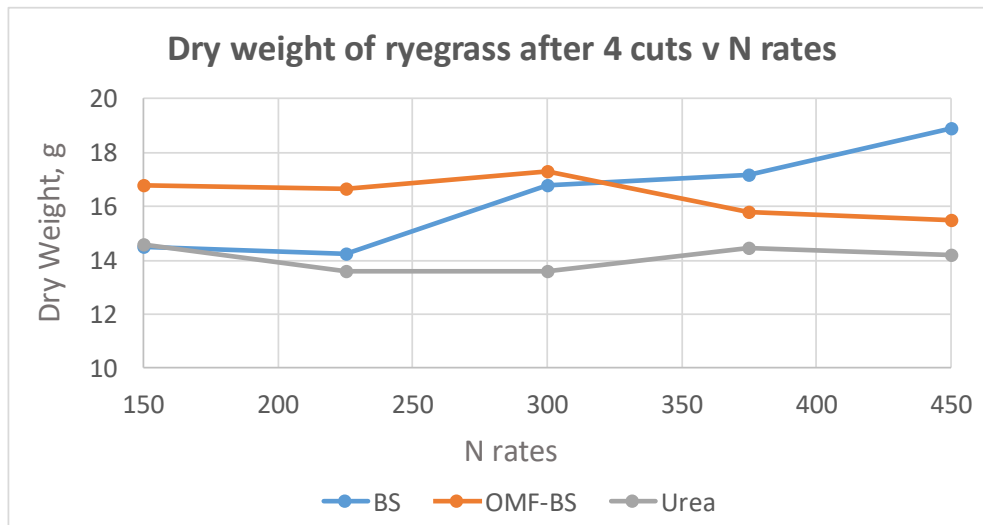


Figure 6. Dry yield-to-nitrogen response for individual treatments with varying rates of applied nitrogen. Weights are averages of 3 cuts from 3 pots

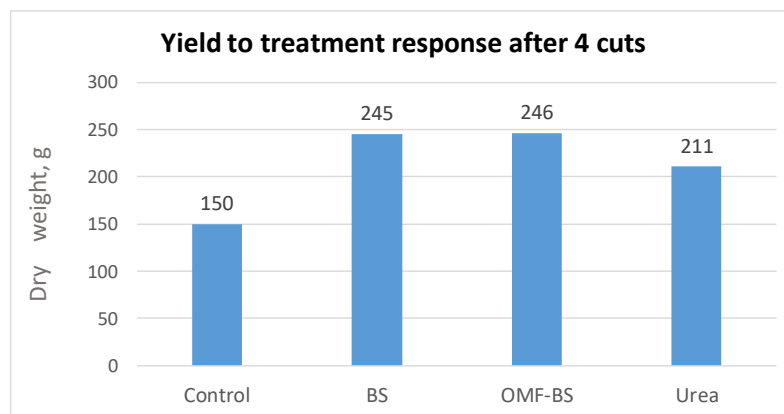


Figure 7. Cumulative weight yield-to-treatment response across all amendments

Incubation experiment

In this experiment, the effect of incubation time on soil available P was determined for a number of organic amendments. Our study found that the application of OMF-FW and BS in sandy loam soil has considerably increased phosphorus availability for plants. The available (Colwell) soil phosphorus concentration increased with increasing incubation time in all treatments (Table 7 and Figure 8) comparing to control. The effectiveness of the treatments in this incubation study on the available phosphorus increase was in the order of Control > OMF-BS > BS.

Table 7. Available phosphorus (mg/kg of soil) with time of experiment

Treatment	0d	3d	10d	30d	60d
Control	6	3	3	5	7
OMF-FW 5%	207	218	245	274	296
OMF-FW 10%	330	351	372	411	425
BS 5%	248	368	384	425	530
BS 10%	507	568	620	817	934

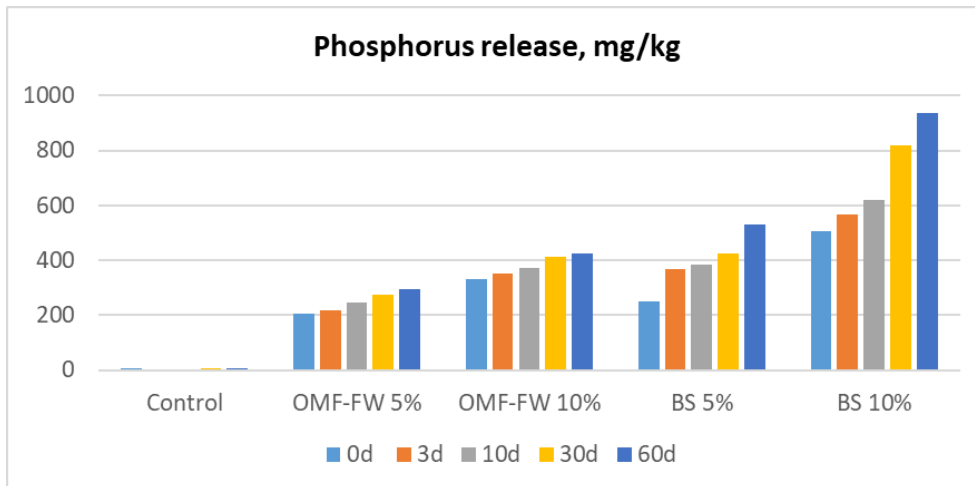
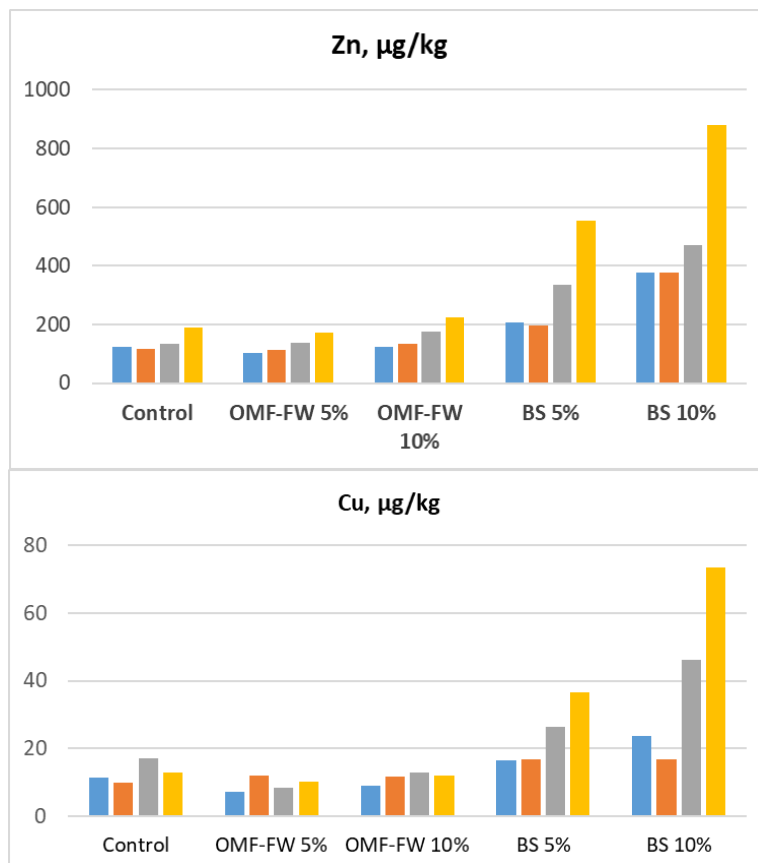


Figure 8. Phosphorus availability for different treatments after 60 days of incubation

The changes in the exchangeable fraction of heavy metals – Zn, Cu and Cr due to OMF-FW and BS application were examined along the subsequent days of incubation (Figure 9). In Queensland, permissible metal levels in biosolids for land application are Zn = 300 – 250 (Grade A – C) mg/kg; Cu = 150 – 2000 mg/kg and Cr = 100 – 500 mg/kg (EPA Queensland, 2020). The OMF_FW and BS used in this study are suitable for land application after taking consideration of total metal loadings per annum.



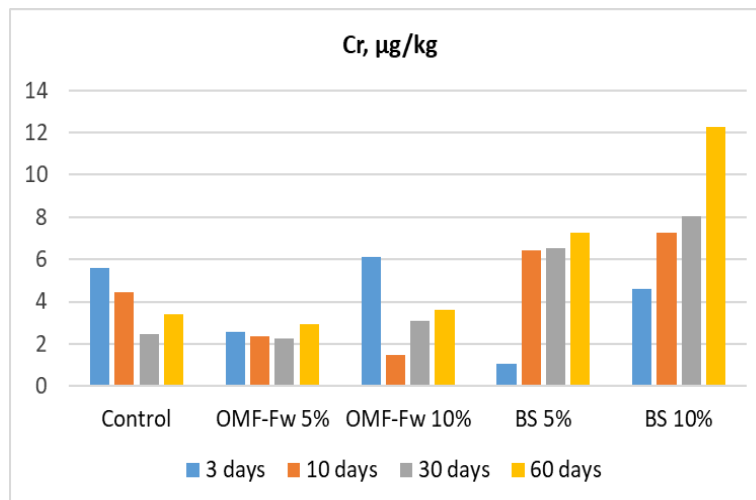


Figure 9 Changes in exchangeable Zn, Cu and Cr concentration during 60 days of incubation

The concentration of heavy metals in control soil and all amendments were under the maximum levels accepted by the current Queensland legislation (EPA Queensland, 2020). The increase in total heavy metal content following a single biosolids addition (highest heavy metals content) was negligible: 0.9 mg/kg for Zn, 0.07 mg/kg for Cu and 0.01 mg/kg for Cr. Even though all current regulations are based on the total content of elements, there is general consensus that the toxicity of elements is related to their availability (Sanchez-Monedero, 2004). Figure 9 depicts change in exchangeable fraction of heavy metals applied with amendments over 60 days period. The greatest increase in available Zn, Cu and Cr occurred in soil amended with 5 and 10% of BS.

Field testing of granulated biofertiliser

The granulated fertiliser was applied to the Centre for Agricultural Engineering Ag Plot facilities located in Toowoomba. Initial field spreading was performed using a “Vicon SuperFlow PS403 VITI” spreading system with distribution of fertiliser via an agitator and on-board computer. This automated system enabled spreading width and speed to be controlled during application. A total quantity of 4 kg of granulated fertiliser was produced in the initial trial and spread during first field trial. Figure 10 below show the spreader, application in field and the uniformity of distribution of granules in field. The first trial demonstrates the successful distribution of the granulated material.

“Vicon SuperFlow PS403 VITI”

Distribution of applied granules on a field

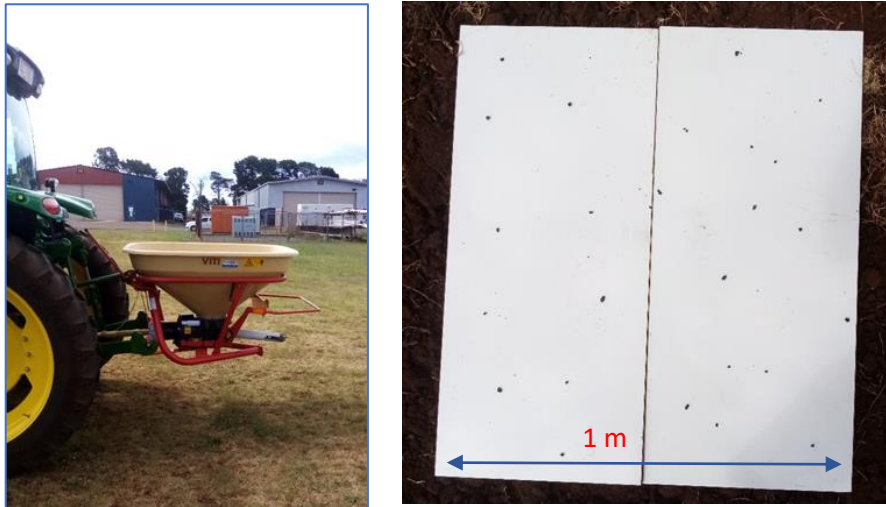


Figure 10. Application of granulated OMF fertiliser

4. Guidelines for use of pelleted/granulated digestate on crops

In order to apply pelleted or granulated food waste digestate or biosolids on crops, several considerations must be addressed. This report focusses on the following:

1. Regulations for biosolids and/or digestate use
2. Fertiliser replacement value

Regulations for biosolids and/or digestate use

Incorporating biosolids or digestate requires strict compliance with relevant government regulations and legislation. These regulations vary by country and Australian state. Therefore, anyone utilizing pelleted or granulated food waste digestate or biosolids should carefully review the local regulations and legislation that are pertinent to their area ensuring that the source of these pellets/granules complies with all regulations.

For example, In Queensland, it is important that the entity collecting and digesting food waste has an appropriate environmental authority in place and the beneficial reuse of biosolids or food waste digestate as a soil conditioner/fertiliser is conducted in accordance with the End-of-Waste Code for Biosolids (ENEW07359617) or end use requirements as specified in the environmental authorities for the relevant licensed facility (e.g. fit-for-purpose product quality and characteristics, permissible contaminant levels, permissible end uses).

Fertiliser replacement value of FW based pelletised and granulated OMF

When considering using pelleted or granulated food waste digestate or biosolids it is important to consider the fertiliser replacement value specifically N, P and K. These values may change depending on the consistency of the food waste being digested and production formulation of the pellets/granules. We recommend assessing these values prior to using these products.

For example, Table 8 provides estimates for the fertiliser replacement value of N, P and K, in FW based biosolids and digestate used in this experiment according to their total nutrient content and per unit nutrient price for an industrial fertiliser. In July 2023 prices for urea fertiliser (46%N) is AU\$615/ton, for monoammonium phosphate (21.9%P) is AU\$827/ton and for potash (60%K) is AU\$619/ton (Quinn, 2023).

Please note, the fertiliser replacement values shown in Table 8 do not include the potential benefits to soil health from FW based products (such as increased carbon content, improved soil structure and water



holding characteristics). Soil health benefits are difficult to express in simple economic terms and are unique to every location and depends on soil types.

Fertiliser replacement values also do not include costs for OMF field application or for OMF formulation and production, as a laboratory scale granulator was used and costs of operations would not be reflective of a full-scale operation. These fertiliser replacement values mean that for each tonne of FW based biosolids and FW digestate used for granulation, farmers could save AU\$159 and AU\$113 correspondingly.

Table 8. Fertiliser replacement value of FW based digestate and biosolids in OMF

Nutrient	Concentration of dry weight, %	Mass per tonne, kg	Value per kg, AU\$	Fertiliser Replacement Value per dry tonne of final product, AU\$
Pelletised FW based OMF				
N	4.83	48.3	1.34	64.7
P	2.03	20.3	3.78	76.7
K	1.75	17.5	1.03	18.0
Total				159.4
Granulated FW based OMF				
N	1.74	17.4	1.34	23.3
P	2.13	21.3	3.78	80.5
K	0.84	8.4	1.03	8.7
Total				112.5

5. Conclusions & Recommendations

This report investigated design, production and agronomic performance of granulated organo-mineral fertiliser that contained FW digestate and biosolids blended with mineral fertiliser. FW digestate and FW containing biosolids could be used as a nutrient source in production of OMF. The produced granulated product meets quality criteria and the requirements of current farming practices and farming spreading equipment. The field trial demonstrated the successful distribution of the granulated material in field condition. The concentration of heavy metals in all amendments were under the maximum levels accepted by the current Queensland legislation and both OMF and biosolids used in this study are suitable for land application after taking consideration of total metal loadings per annum (EPA Queensland, 2020). Moreover, levels of heavy metal in soil did not exceed permissible levels after application of amendments. The product specifications for novel fertiliser materials have been established, and if appropriate product quality control procedures could be implemented, acceptability by farmers should no longer be a barrier to increasing the amount of biosolids and FW digestate (and derived fertiliser materials) currently being recycled to agriculture.

Further, this research demonstrated a new product that maximises the nutrient recovery from FW digestate and sludge by improving the composition and physical characteristics of the final product.

The results of research have also demonstrated the fertilising potential of FW digestate, biosolids containing co-digested FW and OMF for use in Australian arable and grass cropping systems. We conclude that the OMF is a promising alternative product for sustainable agriculture.

Future Works



The knowledge gained through this project, coupled with novel lab-scale granulation equipment, can be used to inform and test organic-based fertiliser technology. Effort should be spent on upscaling and improving the granulation technology and ensuring the physical and mechanical properties of OMF are such that they meet the requirements of modern farm spreading equipment. The assessment of such fertiliser properties, as documented in this work, may be used as guidance to improve, and standardise, the quality of biosolids-derived fertilisers.

Future agronomic studies should consider investigating options for improving nutrient use efficiency through adjustments to the timing of fertiliser application and fertiliser placement and the longer-term effects of routine fertiliser applications on potentially toxic elements (both heavy metals and organic contaminants). There is also a need to perform further and more detailed economic analyses when the actual cost of production of FW digestate based OMF to the required quality are known. Fertiliser N replacement value data and the yield-to-nitrogen response relationships produced by this study can be used to inform such economic analyses.



6. Impact and Ongoing Monitoring

Use of biosolids and other organic waste as a fertiliser contributes to the global circular economy, benefits society through reducing greenhouse gas emissions by displacing fossil-fuel derived fertilisers, reduces food waste and generates profit for industry.

Conversion of food waste digestate and biosolids, largely regarded as waste, into value-added OMF offers increased opportunities to meet long-term nutrient recycling targets. The development of value-added product from digestate opens up the market not only for anaerobic digestion but also improve resource use efficiency, delivering tangible benefits both to growers (reduced reliance on mineral fertilisers) and the wastewater industry and municipalities (reduced cost of disposal).

It is anticipated that this project will create new circular economy jobs through increased adoption of anaerobic digestion and newfound production of granulated OMF.

Synthetic chemical fertiliser is the main market competitor, with granulated digestate aimed at partial displacement of domestic chemical fertiliser use. Granulated products could displace domestic fertiliser use specifically N, P and K demand. High moisture content of feedstocks is a major cost driver, with transport over long distances being cost prohibitive. Granulation improves market potential by simultaneously drying and formulating a granulated product, e.g. for transport of granulated municipal biosolids from population centres to major grain growing regions.

This project has a dual action on reducing greenhouse gas emissions. The direct impact is through the partial displacement of domestic chemical fertiliser use as indicated above. The additional indirect benefit is through the use of biogas to displace fossil fuels. i.e. biogas captured from the anaerobic digestion of food waste and combusted turns methane (global warming potential 25) into CO₂ (global warming potential 1) and displaces fossil fuel-derived energy. By comparison, landfill without gas capture simply releases methane emissions into the atmosphere.

Based on the results of this project, UniSQ will continue to develop new OMF products and investigate viable beneficial re-use pathways for the food waste digestate to contribute to the fight against food waste and will continue to update the project funders with relevant activities to ensure the impact of this project into the future.

7. Acknowledgements

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