THE KĀPITI COAST DISTRICT COUNCIL BIOSOLIDS STRATEGY – INVESTIGATING VIABLE RESOURCE RECOVERY OPTIONS

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ABSTRACT

Globally there has been a paradigm shift from disposal to resource recovery of biosolids. The Kāpiti Coast District Council is in a favourable position to be a leader with municipal biosolids beneficial use in New Zealand. This is due to high quality Grade 'A' equivalent biosolids being produced from its sludge treatment systems which allow various beneficial use options to be a possibility.

Cardno BTO updated Kāpiti Coast District Council's existing district-wide biosolids strategy to identify any alternative biosolids disposal options superior to the current method (disposal of dried sludge at the Otaihanga Landfill). The biosolids strategy methodology followed to determine and justify the preferred biosolids disposal/reuse option involved comparison by 1) a financial analysis, 2) a multi-criteria analysis and 3) consideration of best engineering practice.

The biosolids reuse/disposal options considered for evaluation included disposal at the Otaihanga Landfill (the current option), an alternative landfill where any potential environmental effects are minimised, monofilling, application to expressway land, and to forestry land. Emerging treatment options were discussed in detail and it was recommended to investigate these options further once findings from pilot plant trials and any scaled up processes are known.

KEYWORDS

Biosolids, Biosolids Strategy, Resource Recovery, Beneficial Use

1 INTRODUCTION

The Kāpiti Coast District Council (KCDC) wanted to update their existing district-wide biosolids strategy (previously completed in 2009) to identify any alternative biosolids disposal options superior to the current method (disposal of dried sludge at the Otaihanga Landfill). Globally there has been a paradigm shift from disposal to resource recovery of biosolids. The Kāpiti Coast District Council is in a favourable position to be a leader with municipal biosolids beneficial use in New Zealand. This is due to high quality Grade 'A' equivalent biosolids being produced from its sludge treatment systems which allow various beneficial use options to be a possibility.

Sludge treatment at the Paraparaumu Wastewater Treatment Plant (WWTP) consists of thickening, dewatering, and drying processes which achieve Grade 'A' stabilisation (treated by an appropriate pathogen removal and vector attraction reduction method/s). Otāki WWTP sludge is also transported 23km and treated at the Paraparaumu WWTP. This existing sludge treatment system is the preferred long-term treatment option due to significant past and planned future capital investment. It produces a biosolids product allows a wide range of beneficial use options to be a possibility.

The main drivers for the biosolids strategy update were to assess if there were better biosolids disposal options available to the Council, more accurately determine the available capacity at the Otaihanga Landfill, and to account for several updates to the Council's strategic plans since the previous study, particularly the following:

1. Kāpiti Coast District Council - Carbon and Energy Management Plan

   The Council recently adopted a carbon and energy management plan, joined the carboNZero programme, and became CEMARS$_1$ certified, to transparently demonstrate its commitment to addressing the Council's contribution to climate change. The current biosolids disposal route has a relatively high carbon emission compared to alternative disposal routes. A key requirement to meet emissions reduction targets in the future is for the current biosolids Greenhouse Gas (GHG) emissions from disposal to be mostly eliminated.

2. Councils of the Wellington Region - Waste Management and Minimisation Plan 2011-2017

   The purpose of the Waste Management and Minimisation Plan is to describe a collective vision of how the Councils will meet their long-term goals for waste management and minimisation for the Wellington region. The following actions are to be conducted by Kāpiti Coast District Council by 2017:

   a. Investigation of further options for beneficial recovery/reuse of wastewater sludge/biosolids

   b. Develop an Otaihanga Landfill closure and aftercare plan

2 EXISTING BIOSOLIDS TREATMENT AND DISPOSAL

The current sludge treatment process at the Paraparaumu Wastewater Treatment Plant remains the preferred treatment option now and into the future. The Grade 'A' stabilisation quality achieved from this treatment process allows various beneficial use options to be a possibility. KCDC currently disposes of its biosolids from the Paraparaumu WWTP to the Otaihanga Landfill. The current backup option is transportation and disposal at the Silverstream Landfill (outside of the district, and at high transportation and disposal costs).

2.1 CURRENT TREATMENT

The Paraparaumu Wastewater Treatment Plant (WWTP) consists of a five stage Bardenpho nutrient removal treatment process that produces a waste sludge stream withdrawn from the Return Activated Sludge (RAS) produced in the clarifiers. The Waste Activated Sludge (WAS) is thickened in a Dissolved Air Flotation (DAF) thickening process from 0.8%DS to around 2.5%DS, dewatered in a decanter centrifuge to 18%DS, then dried in an indirect heat sludge dryer to approximately 75%DS (see Photographs 1 and 2). Dried sludge is stored in a skip bin that is taken off site for disposal.

Photographs 1 & 2: Paraparaumu WWTP Sludge Treatment Building (left), and Sludge Dryer (right)

In addition to the indigenous sludge produced at the Paraparaumu WWTP, Otāki WWTP sludge is also treated at the Paraparaumu WWTP. This allows KCDC to produce a single, high quality biosolids product to dispose of instead of having two biosolids streams of different grade and quality. The sludge treatment at the Otāki WWTP consists of a clarification process followed by thickening to around 6-8%DS (see Photographs 3 and 4), prior to transportation and dosing into the Paraparaumu WWTP inlet works during times of low influent loading.

Photographs 3 & 4: Otāki WWTP Sludge Treatment System (left), and Thickening Centrifuge (right)

The current sludge treatment processes are the preferred treatment option now and into the future, with renewal of the sludge dryer scheduled to take place during the 2013/2014 financial year. The treatment process achieves Grade 'A' stabilisation (treated by a pathogen removal process, as well as a vector attraction reduction method) that allows various beneficial use options to be available now and into the future.

2.2 CURRENT DISPOSAL OPTION

Currently, dried sludge is trucked daily from the Paraparaumu WWTP to the Otaihanga Landfill for mono-filling. A particular area at the back (south-west) of the landfill is used for dried sludge and screenings from the Paraparaumu WWTP. Sludge is mixed with either sawdust or non-compostable green waste and then covered with cleanfill. Sawdust is preferable however less forestry in the area has led to a shortage of sawdust for this application.

KCDC own and operate the Otaihanga Landfill located in Paraparaumu. Since 2007, the site only accepts a relatively small amount of material, approximately 8000 tonnes per year. A large proportion of the material comprises dried biosolids and cleanfill with a small proportion of WWTP screenings.

The Otaihanga Landfill has an existing resource consent that expires in 2029. Although there is 16 years remaining on the resource consent, the available capacity was previously unknown. KCDC have applied for a consent variation for a maximum future landfill height, which would provide capacity for disposal of anticipated biosolids and screening from the Paraparaumu WWTP, as well as cleanfill until 2029.

KCDC has also committed to developing a closure and aftercare plan, and to investigate further options for beneficial recovery/reuse of municipal sludge/biosolids by 2017.

3 BIOSOLIDS CHARACTERISATION

In summary, KCDC produce municipal biosolids at approximately 3-5m^3/day, which can be characterised as being very stable, high in organic and nutrient value, and extremely low in pathogen contaminants.

Photograph 5: A Sample of the Paraparaumu Dried Biosolids

3.1 PROJECTED QUANTITIES

The Paraparaumu and Otāki WWTP's currently serve a combined population equivalent of 48,000, which is estimated to increase to 58,000 in 2032 (MERA, 2012). The current and future biosolids quantities are estimated to be around 800 and 1100 Tonnes of Dry Solids per year for 2013 and 2032 years respectively, at between 75-85% Dry Solids content.

3.2 NUTRIENTS

Table 1 shows the average nutrient content from testing of some samples of the biosolids. The results are compared with nutrient concentrations from typical soils (soil information from Hill Laboratories – Soil Testing for General Agriculture).

Table 1: Paraparaumu WWTP Biosolids Nutrient Testing - Percentage Dry Weight and (mg/kg)

Nutrient	Biosolids Concentrations	Typical Soil Concentration Ranges
Carbon	40.7% (407,000)	4-20.0% (40,000-200,000)
Nitrogen	6.7% (67,000)	0.2-1.0% (2,000-10,000)
Phosphorous	3.6% (36,000)	0.07-0.2% (700-2,000)

The comparison shows the biosolids are high in nutrient value – particularly nitrogen and phosphorus, relative to typical agricultural soils and will therefore encourage plant growth. The relatively high phosphorous content of the biosolids is due to the wastewater treatment plant being designed specifically for phosphorous removal. The phosphorus is taken up in the activated sludge and ultimately contained in the biosolids.

3.3 PATHOGEN CONTENT (STABILISATION GRADE)

Table 2 shows the average pathogen content from testing of some samples of the biosolids. The biosolids pathogen concentrations are compared to the pathogen limits from the document "Guidelines for the Safe Application of Biosolids to Land in New Zealand (2003)".

The results demonstrate that the biosolids present a minimal risk to human health.

Table 2: Paraparaumu WWTP Biosolids Pathogen Testing

Pathogen	Biosolids Concentrations	Grade 'A' Limit	Detection Limit of Test
E. Coli	Not Detected	<100 MPN/g	3 MPN/g
Campylobacter	Not Detected	<1/25g	1
Salmonella	Not Detected	<1/25g	1

Compliance with the pathogen concentrations is one aspect of the stabilisation requirements of the "Guidelines for the Safe Application of Biosolids to Land in New Zealand". The Paraparaumu biosolids are equivalent to Grade 'A' stabilised biosolids. This is because of the high temperature ($155^{O}C$) at which the sludge is dried, the fact that the source of the sludge is secondary (activated sludge) solids only, and the level of moisture content reduction that occurs within the dryer.

3.4 METALS CONTENT (CONTAMINANT GRADE)

Table 3 shows the average metals content from testing of some samples of the biosolids. The biosolids metal concentrations are compared to the metals limits from the document "Guidelines for the Safe Application of Biosolids to Land in New Zealand".

The results are generally very good, showing low concentrations of metals. The results show that the concentration of copper does not meet the 'Grade a' (contaminant) guidelines (post 2012). However this is common for municipal biosolids in New Zealand because of the use of copper water pipes. Mercury is also slightly elevated with respect to the post 2012 limits. If the biosolids were to be mixed with other materials, such as sand and peat before placement, then the blend would easily meet the soil application limits.

Table 3: Paraparaumu WWTP Biosolids Metals Concentrations and Contaminant Limits (mg/kgDS)

Metal	Sampled Average Aug 2011	Sampled Average Pre-2011	Grade 'a' Limit		Grade 'b' Limit	Soil Limit
			Pre-2012	Post-2012		
Arsenic	4	3	20	20	30	20
Cadmium	0.94	1	3	1	10	1
Chromium	10	17	600	600	1500	600
Copper	136	239	300	100	1250	100
Lead	13.8	25	300	300	300	300
Mercury	1.11	1.5	2	1	7.5	1
Nickel	9	10	60	60	135	60
Zinc	293	272	600	300	1500	300

4 OPTIONS CONSIDERATION AND SELECTION

4.1 PREVIOUS BIOSOLIDS STRATEGY

Alternatives to disposal at the Otaihanga Landfill were evaluated as part of the 2009 KCDC Biosolids Strategy project; results of the study indicated that disposal to the Otaihanga Landfill was the best disposal option at the time.

Only treatment and disposal options considered still viable were re-evaluated as part of the updated biosolids study, as well as new options that have emerged since the 2009 biosolids strategy.

The 2009 biosolids strategy considered the following treatment options: Anaerobic Digestion, Geo-textile Bag Dewatering, Thermal Heat Drying, and Pyrolysis.

The 2009 biosolids strategy considered the following disposal options: Land Application (Forestry, Mine Rehabilitation, Agriculture/Horticultural, and General Distribution), Landfilling, Monofilling, Vitrification, Incineration, Composting, and Vermicomposting.

4.2 EMERGING BIOSOLIDS RESOURCE RECOVERY OPTIONS

The paradigm on biosolids is changing; biosolids are being viewed less as a waste product and more as a resource, either for its nutrient or energy value. A number of technologies have been developed or are being developed to harness the resources contained in biosolids. This section outlines some emerging technologies that are being trialled or are in operation regionally and internationally.

Emerging technologies present a potential opportunity to decrease the volume of biosolids disposed to landfill, a concept supported by KCDC policy. The KCDC has a commitment to consider emerging technologies, as further development may present an opportunity for the KCDC in the future.

4.2.1 INTERNATIONAL PERSPECTIVE

There are a number of international emerging biosolids resource recovery technologies that are currently in full scale production. Generally these technologies are only sustainable for large quantities of biosolids which provides the economy of scale to justify the capital investment.

A good example of this is biosolids gasification, a thermo-chemical process that converts dried biosolids at high temperatures with little or no oxygen present, into a synthesis gas (syngas). The syngas can then be used to produce electricity as well as other valuable products such as chemicals, fertilisers, substitute natural gas, hydrogen, and steam. There are currently a small number of full-scale installations around the world, all of which range from six tonnes of dry solids per day and approximately US$7M capital costs upwards (PNCWA (2012)). The following are examples of such installations:

- Kopf – Balingen, Germany (2002-present)
- Kopf – Mannheim, Germany (in commissioning phase)
- MaxWest – Sanford, FL (September 2009-present)
- Tokyo Bureau of Sewerage – Kiyose, Japan (July 2010-present)

In Australia, two thirds of all biosolids produced are applied to the land as a fertiliser, soil conditioner or soil replacement product. Application to agricultural land is by far the largest end use in Australia, followed by use in composted products. Of note, less than 5% of biosolids are landfilled in Australia, a stark contrast to the New Zealand situation, where landfilling remains the most common route for sludge disposal.

4.2.2 NATIONAL PERSPECTIVE

Nationally, there is a number of emerging biosolids resource recovery technologies currently being developed to try and best utilise biosolids as a viable resource, on a scale relevant for the New Zealand Market. In particular, there are several variants of the biosolids gasification process being developed, with the aim of significantly reducing the volume of biosolids, as well as producing valuable by-products such as chemicals, fertilisers, and electricity. Some of the most promising biosolids treatment technologies being developed for the New Zealand market are presented in Table 4 below.

Table 4: Biosolids Resource Recovery Options in Development for the New Zealand Market

Emerging Options in NZ	Description	Developer / Client	Status
Thermal oxidation (Terax process)	Thermal oxidation process uses heat, pressure and air to convert sewage into valuable by-products, such as chemicals, fertiliser and energy. Scion's approach differs from others in this field in that it controls the deconstruction process to yield useful chemicals for downstream bioconversion, rather than complete breakdown to CO_2 and water.	Scion / Rotorua District Council	Large scale pilot plant trial
Wet air oxidation (Wetox Process)	A catalyst is added to the sludge subjected to high temperatures and pressures to break the organic matter down into base components, in particular carboxylic acid (valuable by-product), and steam (for electricity production).	Victoria University / Palmerston North City Council	Large scale pilot plant trial
Microwave pyrolysis	A microwave drying process combined with a pyrolysis process.	SpectioNZ / KCDC, WCC	Pilot plant trial
In-vessel composting	Low cost in-vessel composting solution.	BIOBAGGA / KCDC	Proven solution overseas

As many plants have experienced, there is a risk of failure when developing a new technology. It was therefore decided that these options be investigated further by KCDC in the future once findings from pilot plant trials and any scaled up processes are known.

5 COMPARISON OF FEASIBLE OPTIONS

5.1 FEASIBLE BIOSOLIDS DISPOSAL/REUSE OPTIONS

Table 5 presents the disposal options that were identified as technically feasible and therefore considered for evaluation in this biosolids strategy update. The previous biosolids strategy in 2009 evaluated a variety of disposal options, but only options considered still viable have been re-evaluated as part of this study, as well as new disposal options that have come about since the last biosolids strategy.

The preferred biosolids disposal/reuse option was determined by taking into account the results of a financial analysis, a multi-criteria analysis, and best engineering practice.

The noise attenuation requirements of the expressway mean that a significant amount of fill material is needed for road berms and bunds and subsequent landscaping. Topsoil materials blended with biosolids are widely used internationally and in some areas of New Zealand as a landscaping material. There is the potential to apply the Paraparaumu WWTP biosolids as landscaping material on the expressway berms. It is proposed that the Alliance consider this option, as it eliminates the need for chemical fertilizer on landscaped areas and offers a beneficial use for biosolids.

Table 5: Feasible Disposal/Reuse Options

Disposal/Reuse Options	Comments
1 Otaihanga Landfill (current option)	This option maintains the status quo biosolids disposal option. **Advantages:** Well proven, low complexity option Maximum flexibility for future disposal or reuse options Biosolids remain within Kāpiti region **Disadvantages:** Unlined landfill with no biogas collection systems leading to possible environmental effects Dependant on the current request for resource consent variation to be approved Plans and strategies would prefer beneficial use options
2 Lined Monofill Cells	This option would significantly reduce the negative environmental effects of the current biosolids landfill operation. **Advantages:** Biosolids remain within Kāpiti region No adverse environmental effects (has both leachate and gas collection and disposal systems) **Disadvantages:** Higher cost than the current landfill operation Requires a resource consent variation Plans and strategies prefer beneficial use options
3 Silverstream Landfill (current back-up option)	The current standby option. This is outside of the district, but is considered to be an environmentally acceptable option. **Advantages:** Can be considered a beneficial use option - Silverstream landfill collects biogas for energy production Minimal environmental effects due to landfill being lined and with gas collection **Disadvantages:** Biosolids are not disposed of within the Kāpiti district Longer transportation distance increases risk of an accident/spillage
4 Expressway Land Application	Blending with fill material and topsoil during the construction of road berms, bunds, and landscaping for the McKays to Peka Peka (M2PP) Expressway currently in development. After the completion of the expressway, periodic biosolids reapplication is also proposed under this option. There is potential for application to other expressways planned within the district also. **Advantages:** Beneficial use option – acceptable to all plans and strategies Low cost beneficial use option Biosolids soil blend increase the nutrient value of the soil **Disadvantages:** Requires a resource consent Requires restricted access during spreading Land area required is dependent on being able to apply to future expressway/railway options Public perception and iwi acceptance concerns
5 Forestry Application (KCDC purchased land)	Council owned land and wood to be used as boiler fuel. **Advantages:** Potential for few bulk application sites Biosolids can act as a good fertiliser Beneficial use of biosolids **Disadvantages:** Public perception and iwi acceptance concerns High transportation costs
6 Forestry Application (others land)	Forestry land owned by others. **Advantages:** Potential for few bulk application sites Biosolids can act as a good fertiliser Beneficial use of biosolids **Disadvantages:** Public perception and iwi acceptance concerns High transportation costs

5.2 FINANCIAL ANALYSIS

Table 6 presents the whole life cost estimates for the disposal options considered, in terms of annual average costs which allow for the fact that each disposal option has a potentially different operating life. 'Expressway Land Application' (Option 4) is the most cost effective option with an assessed discounted cost per tonne of biosolids of $88/T, which is significantly lower than all of the other options. In comparison, the current practice of disposing biosolids at the Otaihanga landfill was assessed to have a discounted cost per tonne of biosolids of $118/T.

Table 6: Whole Life Costs (in 2012 dollars)

Disposal Options	Years	CAPEX Total	OPEX Annual Average	Wood Fuel Savings	NPV Annual Average	Cost per Tonne Biosolids $/Tonne Discounted Annual Average
1 Otaihanga Landfill (current option)	9	$0	$135,000	$0	-$135,000	$118
2 Lined Monofill Cells	20	$2,580,000	$126,000	$0	-$255,000	$205
3 Silverstream Landfill (current back-up option)	20	$0	$211,000	$0	-$211,000	$170
4 Expressway Land Application	20	$50,000	$107,000	$0	-$109,000	$88
5 Forestry Application (KCDC purchased land)	20	$1,530,000	$217,000	$1,610,000	-$213,000	$172
6 Forestry Application (others land)	20	$200,000	$185,000	$0	-$195,000	$157

5.3 MULTI CRITERIA ANALYSIS

A Multi-Criteria Analysis (MCA) workshop was conducted to help determine the most suitable disposal/'beneficial use' option/s for the KCDC biosolids. A MCA is a way to grade a number of different options based on qualitative and quantitative rankings for a number of different criteria. Criteria such as economic, functional, 'environmental and regulatory framework', and 'social and cultural' are weighted representing their importance, and each option is scored for each criterion.

The MCA workshop was facilitated by Cardno BTO using decision software Criterium DecisionPlus™. All project stakeholders had key input into the criteria weighting as well as the option scores. Figure 1 presents an overview of the multi-criteria analysis hierarchy used for this project.

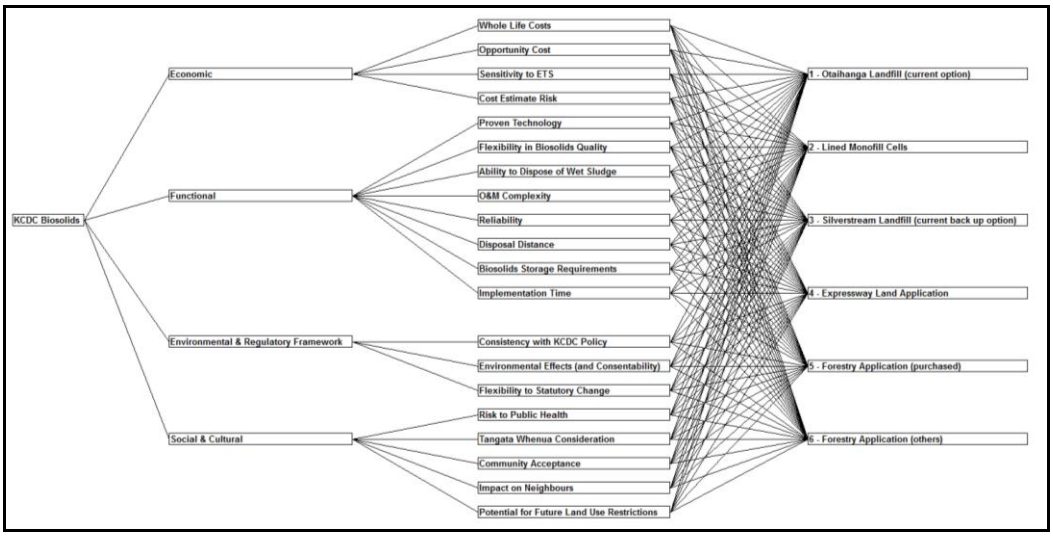

Figure 1: Multi-criteria Analysis Hierarchy

Both Figure 2 and Table 7 present the biosolids disposal options multi criteria analysis results and rankings. The highest ranked option from the multi criteria analysis workshop was Option 4 ‘Application to Expressway Land’, mostly due to it being the most cost effective option. The second ranked option was the current disposal option (Option 1 ‘Disposal at the Otaihanga Landfill’) which rated second highest on ‘economic’ and ‘functional’ criteria. Option 2 ‘Lined monofill cells’ ranked fourth overall, but ranked the best for ‘functional’, ‘environmental and regulatory framework’, and ‘social and cultural’ criteria, while it was assessed as the highest cost option, and therefore was ranked last for the ‘economic’ criterion.

Table 7: Multi Criteria Analysis Results and Rankings

Option	Overall Score	Ranking				
		Overall	Economic	Functional	Environmental & Regulatory Framework	Social & Cultural
1 Otaihanga Landfill (current option)	62%	2	2	2	6	5
2 Lined Monofill Cells	57%	4	6	1	1	1
3 Silverstream Landfill (current back-up option)	59%	3	4	3	3	2
4 Expressway Land Application	73%	1	1	4	2	3
5 Forestry Application (purchased land)	44%	6	5	5	4	6
6 Forestry Application (others land)	45%	5	3	6	5	4

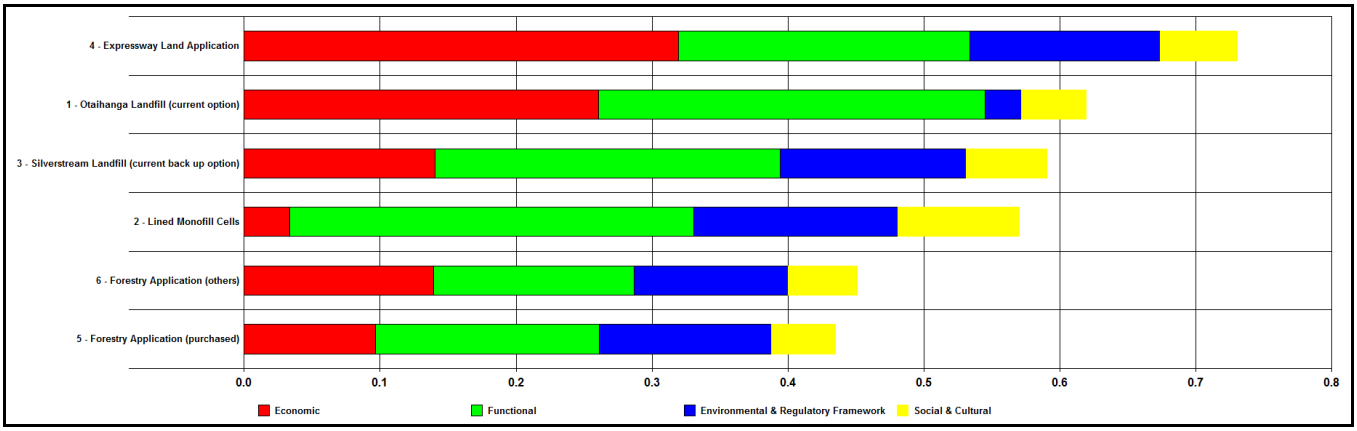

Figure 2: Multi Criteria Analysis Results and Rankings

6 CONCLUSIONS

Globally there has been a paradigm shift from disposal to resource recovery of biosolids. The Kāpiti Coast District Council is in a favourable position to be a leader with municipal biosolids beneficial use in New Zealand. This is due to high quality Grade ‘A’ equivalent biosolids being produced from its sludge treatment systems which allow various beneficial use options to be a possibility.

There are a number of international emerging biosolids treatment and/or disposal technologies that are currently in full scale production. Most are only sustainable for large quantities of biosolids which provide the quantities of scale which justify the capital investment. Nationally, there is a number of emerging biosolids treatment and/or disposal technologies that are currently being trialled to try and best utilise biosolids as a resource. In particular, there are several variants of the biosolids gasification process being developed, with similar aims of significantly reducing the biosolids volume, as well as producing valuable by-products such as chemicals, fertilisers, and electricity. It was decided that these options be investigated further as a possibility in the future when they become available, once findings from pilot plant trials and any scaled up processes are known.

The preferred biosolids disposal/'beneficial use' option was for the Kāpiti Coast District Council to pursue the option to blend biosolids with topsoil required for Kāpiti's M2PP expressway project with NZTA. The reason for this is due to its financial attractiveness, ability to enable the Council to meet planned carbon emissions reduction targets, future flexibility if and when alternative biosolids resource recovery options become available, and a relatively low CAPEX required for implementation.

While the logistics and formalities associated with the option of biosolids application to expressway land is finalised, it was recommended that the status quo should remain: disposal at the Otaihanga Landfill (as long as the landfill consent variation to increase the allowable height is accepted) with the standby option of disposal at the Silverstream Landfill.

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REFERENCES

NZWWA (2003) *'Guidelines for the safe application of biosolids to land in New Zealand'*, NZWWA, Wellington.

KCDC (2012) *'Carbon and Energy Management Plan',* Kāpiti Coast District Council

Councils of the Wellington Region (2012) *'Waste Management and Minimisation Plan 2011-2017'*, Carterton District Council, Hutt City Council, Kāpiti Coast District Council, Masterton District Council, Porirua City Council, South Wairarapa District Council, Upper Hutt City Council, Wellington City Council

Hill Laboratories (2013) *'Soil Testing for General Agriculture'*, <http://www.hill-laboratories.com/page/pageid/2145845702/Soil%20test%20for%20General%20agriculture#Guides>

MERA (2012) *'Forecast Population Growth' (February 2012 MERA customised Kāpiti Coast District projections)',* Monitoring and Evaluation Research Associates Ltd

NNFCC (2011) *'Review of Technologies for Gasification of Biomass and Wastes'*, National Non-Food Crops Centre

PNCWA (2012) *'Gasification of Sludge and Biosolids – A Review of Technology Fundamentals and the Current Commercial Status'*, Pacific Northwest Clean Water Association

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