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SPREP
Secretariat of the Pacific Regional Environment Programme

PacWastePlus
PACIFIC WASTE MANAGEMENT

This initiative is supported by **PacWastePlus**-a 72 month project funded by the European Union (**EU**) and implemented by the Secretariat of the Pacific Regional Environment Programme (**SPREP**) **to sustainably and cost effectively improve regional management of waste and pollution.**

TECHNOLOGY OPTIONS:

SAFE DESTRUCTION OF HEALTHCARE WASTE

OTHER THAN TRADITIONAL, HIGH-TEMPERATURE INCINERATION

SEPTEMBER 2022

This report seeks to assist Pacific Island Countries (PICs) and Timor-Leste to select alternative technologies for the treatment of healthcare waste other than traditional incineration or landfilling.

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Acknowledgment: SPREP's PacWastePlus Programme commissioned the services of MRA Consulting Group to undertake desktop research to generate a decision-making tool to assist with the selection of Healthcare Waste (HCW) treatment technologies. The diverse context of the Pacific region has been considered during the research. Research was undertaken via a desktop-based review of publicly available resources and equipment supplier specification.

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Our vision: A resilient Pacific environment sustaining our livelihoods and natural heritage in harmony with our cultures.

PacWastePlus Programme

The Pacific – European Union (EU) Waste Management Programme, PacWastePlus, is a 72-month programme funded by the EU and implemented by the Secretariat of the Pacific Regional Environment Programme (SPREP) to improve regional management of waste and pollution sustainably and cost-effectively.

About PacWastePlus

The impact of waste and pollution is taking its toll on the health of communities, degrading natural ecosystems, threatening food security, impeding resilience to climate change, and adversely impacting social and economic development of countries in the region. The PacWastePlus programme will generate improved economic, social, health, and environmental benefits by enhancing existing activities and building capacity and sustainability into waste management practices for all participating countries.

Countries participating in the PacWastePlus programme are: *Cook Islands, Democratic Republic of Timor-Leste, Federated States of Micronesia, Fiji, Kiribati, Nauru, Niue, Palau, Papua New Guinea, Republic of Marshall Islands, Samoa, Solomon Islands, Tonga, Tuvalu, Vanuatu*.

KEY OBJECTIVES

Outcomes & Key Result Areas

The overall objective of PacWastePlus is “to generate improved economic, social, health and environmental benefits arising from stronger regional economic integration and the sustainable management of natural resources and the environment”.

The specific objective is “to ensure the safe and sustainable management of waste with due regard for the conservation of biodiversity, health and wellbeing of Pacific Island communities and climate change mitigation and adaptation requirements”.

Key Result Areas

- Improved data collection, information sharing, and education awareness
- Policy & Regulation - Policies and regulatory frameworks developed and implemented.
- Best Practices - Enhanced private sector engagement and infrastructure development implemented
- Human Capacity - Enhanced human capacity

Learn more about the PacWastePlus programme by visiting

EUROPEAN UNION | SPREP Secretariat of the Pacific Regional Environment Programme | PacWastePlus PACIFIC WASTE MANAGEMENT

https://pacwasteplus.org/

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Acronyms

Terminology	Definition
$k	Thousand dollars
$M	Million dollars
°C	Degrees Celsius
ASME	American Society of Mechanical Engineers
CO	Carbon monoxide
C_xH_x,	Various hydrocarbons of different chain length
H_2	Hydrogen gas
H_2O	Water
HCW	Healthcare waste
HDPE	High-density polyethylene
HEPA	High efficiency particulate air filter
hr	Hour
kcal	Kilocalories
kg	Kilogram
kWh	Kilowatt hour
L	Litre
MHz	Megahertz
min	Minute
MRA	MRA Consulting Group
N_2	Nitrogen gas
NO_x	Nitrogen oxides
OECD	Organisation for Economic Co-operation and Development
OH&S	Occupational Health and Safety
PICs	Pacific Island countries
POPs	Persistent Organic Pollutants
PPE	Personal protection equipment
psig	Pounds per square inch pressure
PVC	Polyvinyl chloride
SO_x	Sulfur oxides
SPREP	Secretariat of the Pacific Regional Environmental Program
SWAP	Committing to Sustainable Waste Actions in the Pacific
tpa	Tonnes per hour
US EPA	United States Environmental Protection Agency
USD	United States Dollars
UV	Ultraviolet
V	Volt

Executive Summary

This study has relied primarily on desktop research to generate a decision-making tool to assist with the selection of Healthcare Waste (HCW) treatment technologies. The tool can be used to inform planning decisions within the Pacific context, although specific contextual considerations (such as geographical, financial and socio-political requirements) need to be applied by those using the tool. The diverse context of the Pacific region has been considered during the research.

Research was undertaken via a desktop-based review of publicly available resources and equipment supplier specification. A high-level discussion of treatment technology identified the various approaches to waste disinfection and management focussing on non-incineration treatment technologies.

Feasible technology options to the Pacific context were identified through a suitability analysis. These options were analysed against technological, legal, economic, and environmental considerations.

Healthcare waste management technologies included in the detailed evaluation were:

- Microwave treatment;
- Steam disinfection;
- Pyrolysis;
- Friction heat treatment; and
- Non-chlorinated chemical disinfection.

The resulting specification tables (Section 4) seek to inform decision-making within Pacific islands seeking to improve healthcare waste management.

1. Introduction

1.1 Background

The healthcare sector faces unique challenges in the safe and environmentally responsible management of waste. The improper treatment of HCW can pose serious hazards at all stages of its collection, handling, transportation, and disposal.

This report aims to assist the Secretariat of the Pacific Regional Environmental Program (SPREP), as part of the EU-funded PacWastePlus Programme, in providing guidance to Pacific Island countries (PICs) and Timor-Leste in choosing technology to treat HCW.

Previous studies have provided a generic overview of HCW treatment, without focus on aspects that may be important in the Pacific context. Further, they have generally presented incineration as being similar with non-incineration technologies. This has made informed decision-making for treatments beyond incineration and landfilling difficult.

1.2 Current practices

Current practices in PICs and Timor-Leste have often relied upon a "disposal" based approach (either landfilling or burning) to manage wastes that are infectious, hazardous, and sometimes culturally sensitive (e.g., human remains). Table 1 summarises some of the advantages and disadvantages to this approach to HCW management.

Table 1 Overview of current HCW management practices for PICs and Timor-Leste

Current practice	Advantages	Disadvantages
Landfill disposal	• Generally required even if waste has been treated/ disinfected • Lower air emissions than incineration	• Non-treated wastes are highly hazardous during handling and disposal • Generation of hazardous leachates • Requires expensive sanitary controls to prevent groundwater contamination • May lead to adverse health impacts to waste pickers that are active at landfills
Incineration	• Reduces waste volume • Residue is unrecognisable • Destruction of pathogens • Low infrastructure or energy requirements • Used to treat wide variety of waste types	• Hazardous air emissions (heavy metals, particulates, dioxins and furans)[1] due to poor operation • Potentially hazardous solid residuals (requiring controlled disposal) • May not comply with Stockholm Convention[2] • Poor community perception • High costs associated with fuel usage • May require significant repair and maintenance activities beyond the capacity of local hospitals and clinics. • Short life span, in many cases less than five (5) years.

[1] National inventory of the sources of dioxin emissions have found HCW incinerators to be a leading source. Dioxins have been linked to cancer, immune disorders, diabetes, birth defects and other health issues (Hays & Aylward, 2003).

[2] The Stockholm Convention aims to eliminate the production (intentional or unintentional) of Persistent Organic Pollutants (POPs), which includes dioxins and furans.

As governments strengthen regulations to protect the environment and public health, landfill and incineration practices are expected to become more expensive. These practices will still likely have a place in the future management of HCW, such as the landfill disposal of disinfected material. Although, there are opportunities to achieve better practice standards that reduce the harm to the environment while ensuring minimal risks to human health.

1.3 Classification of healthcare waste

One of the major difficulties in the management of HCW is the diverse variety of waste types, ranging from non-hazardous general rubbish to regulated wastes. Table 2 provides and overview of the common types of HCW and examples.

One advantage of conventional disposal-based management is that it can be applied to a wide variety of HCW categories (although not without associated environmental impacts). There is no non-incineration technology that can treat all categories of HCW. Comingling or mixing different waste categories combines all associated risks and applies them to the mixed volume. For example, if 1 kg of infectious material is mixed with 9 kg of general waste, all 10 kg of mixed waste must be treated as potentially infectious. Comingling wastes can also cause downstream risks as hazardous chemical may remain unchanged following disinfection or create harmful emission during treatment.

It is recommended for facilities to conduct a waste audit prior to selecting a treatment technology to quantify:

- Composition – the proportions of each HCW category of the entire volume; and
- Generation rate – the volume of waste generated over time.

An audit may also identify opportunities for waste minimisation and segregation that reduces the volume of material that require treatment. Every healthcare facility is unique in the waste that it produces, hence strategic management and treatment should be tailored to the specific requirements of the facility.

Figure 1 gives an estimate of the typical composition of HCW, although the proportions of each sub-category are expected to vary significantly (Chartier, 2014).

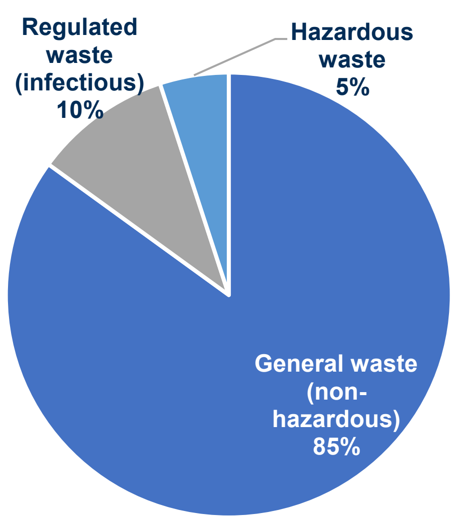

Figure 1 Typical waste composition of healthcare facilities

Table 2 Classification and definitions of common HCW categories

Classification	Category	Definition	Examples
General waste (non-hazardous)	Recyclable	Free from risks and can be recycled through further processing and resource recovery.	Cardboard and paper, food waste, metal, glass
	Non-recyclable	Free from risks and can be disposed via conventional waste management practices.	Plastic packaging, bulky items, reception waste
Regulated waste	Infectious/ biohazardous	Capable of producing infectious disease.	Waste contaminated with blood and other bodily fluids, cultures, and stocks of infectious agents from laboratory work, or waste from patients with infections (e.g., swabs and bandages)
	Pathological	Subset of infectious waste consisting of recognisable human or animal body parts.	Human tissues, organs, fluids, limbs, and contaminated animal carcasses
	Sharps	Comprising of a point or edge capable of cutting, piercing or penetrating skin.	Syringes, needles, disposable scalpels, and blades
Hazardous waste	Chemical	Any solid, liquid, or gaseous waste material that, if improperly managed or disposed of, may pose substantial hazards to human health and the environment.	Solvents and reagents used for laboratory preparations, disinfectants, sterilant and heavy metals contained in medical devices (e.g., mercury in broken thermometers) and batteries
	Pharmaceutical	Expired, unused and contaminated drugs and vaccines	Vials, containers, capsules, tablets and connecting tubing
	Cytotoxic	Chemicals toxic to cells (i.e., mutagenic, teratogenic or carcinogenic)	Cancer treatment drugs and their metabolites
	Radioactive	Material contaminated by radionuclides	Radioactive diagnostic material or radiotherapeutic materials

1.4 Waste Management Hierarchy

HCW treatment (i.e., converting regulated and hazardous wastes into non-hazardous material) is a component of a larger HCW management system. Figure 2 broadly classifies each aspect of the waste management system and ranks them by their hierarchy of importance.

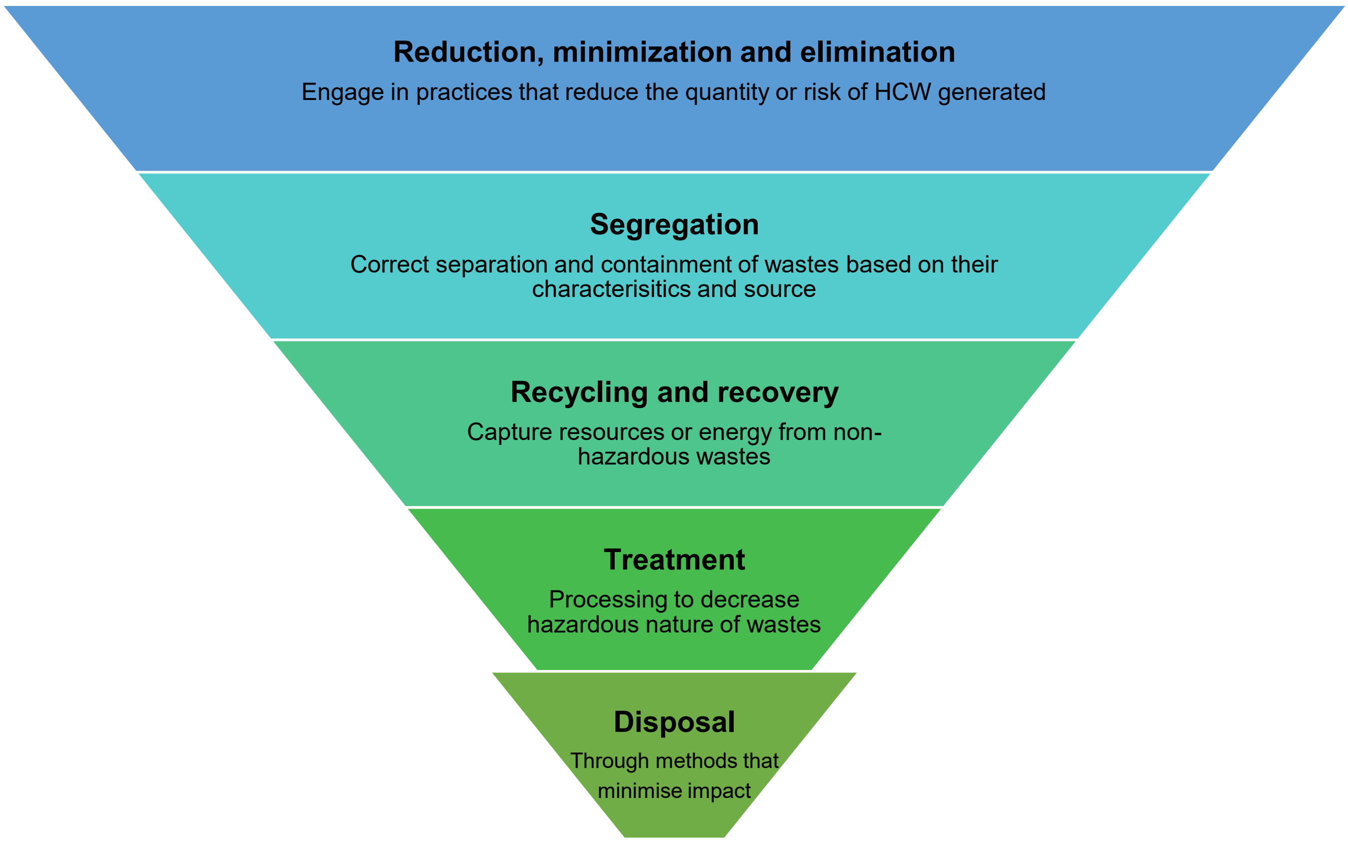

Figure 2 HCW management waste hierarchy

A systematic approach to materials management should be applied to HCW strategic planning, instead of only focusing on the treatment or disposal stages. Planning should include collection, transportation, storage, contingency plans and health and safety considerations.

Only by addressing all stages of waste generation can volumes be reduced or eliminated. For example, purchasing staff should consult with other departments to understand problems arising from the volume or composition of medical supplies and use this information to inform purchasing decisions.

Waste segregation is important because it reduces the volume of material requiring treatment (hence decreasing costs), prevents the contamination of non-hazardous wastes and creates opportunities for resource recovery.

At a minimum, facilities should aim to have separate collections for infectious, hazardous, radioactive, and general waste. This requires the separation of materials at their point of generation in containers appropriate to the waste type (e.g., labelled bags for infectious waste or rigid, leak-proof containers for sharps).

Improper disposal (including landfilling, dumping and open burning of non-treated wastes) should be minimised, even if that means replacement with a lower preference treatment method that do not recover or recycle materials.

2. Research Methodology

This study has relied primarily on desktop research to generate a decision-making recommendation to assist with the selection of HCW treatment technologies. The tool can be used to inform planning decisions within the Pacific context, although specific contextual considerations (such as geographical, financial, and socio-political requirements) need to be applied by those using these recommendations. The diverse context of the Pacific region has been considered during the research.

This report has primarily relied following resources in the desktop-based review:

- SPREP reports, information and audit data;
- International convention guidelines;
- The Pacific Data Hub (pacificdata.org);
- The World Business Council for Sustainable Development;
- Online resources related to HCW management technology;
- Information of publicly listed companies; and
- Industry examples of HCW technology applications.

A full list of sources can be found in Section 8.

2.1 Research approach

The following methodology was used to develop the resources in this report:

1. Broad research of the HCW technology market to find a wide range of available options (refer Section 3);
2. The application of a selection criteria to initially assess their suitability to PICs and Timor-Leste (refer Section 3.6); and
3. Detailed evaluation of suitable technologies using a range of focus area (refer Section 4).

The primary output of this report are decision-making recommendations that provides information to compare potential technology options.

2.2 Using the decision-making recommendation

The following steps are recommended for decision-makers wishing to evaluate technologies suited to their specific context.

1. Conduct baseline data collection, including:
   - Legal requirements (national and international)
   - HCW audit data (volumes and composition)
   - Availability of utilities (water, electricity, fuel)
   - Available space and security for treatment technology
   - Budget for capital, operation and maintenance costs
   - Existing HCW management practices (incineration or landfilling)
   - Operator availability and prior training
   - Existing waste segregation practices

2. Determine the advantages and disadvantages of deploying technology "on-site" (dedicated to a particular HCW generator) or "off-site" (a centralised/ regionalised treatment plant).

Criteria for decision making may include:

- Transport and handling logistics (distance, service providers, etc.)
- Regulatory/ legal requirements for transporting hazardous materials
- Cost-benefits and financial considerations
- Facility planning and capacities
- Maintenance and operation capacity
- Environmental and health impacts (e.g., risk of exposure and greenhouse gas emission)
- Public acceptance

3. Calculate the technology treatment capacity required. If waste audit data is not available, volumes should be estimated from Table 3 (WHO, 2017). There is large variability in the volume of waste generated at a single type of facility and thus a facility assessment of waste is highly recommended before selecting a treatment technology.
4. Use context-specific information to assess eligible technologies outlined in Section 4.
5. Publish bidding documentation and evaluation criteria for the procurement of eligible technology.
6. Final evaluation of received bids, incorporating detailed financial analysis such as annual projected cash flows or net present value.

Facilities should not rely solely on supplier data but should request a list of current users of the technology from the supplier. Decision-makers should seek to interview users to get their feedback on technology performance, such as microbial inactivation efficacy, reliability, staff acceptance and other relevant considerations.

Table 3 Waste generation rates estimated by facility size (WHO, 2017)

Facility	Infectious waste generation rate
Hospital	0.693 kg/bed/day
Clinic	0.07 kg/patient/day
Basic health unit	0.01 kg/patient/day

Note: there are two methods to calculate the average infectious waste generation waste for a healthcare facility.

1. **For facilities with overnight patient care:**

   Number of beds x Average bed occupancy rate x Infectious waste generation rate (kg/bed/day)
   = Average infectious waste generation rate (kg/day)

2. ***For day-clinics (i.e., no overnight patient care):***

   Average number of patients treated per day x Infectious waste generation rate (kg/patient/day)
   = Average infectious waste generation rate (kg/day)

3. Technology Overview

This section provides an overview of common, non-incineration approaches to HCW treatment. Figure 3 categorises technologies into four major categories: low-heat treatment, high-heat treatment, chemical, and other techniques. The following sections provide a summary of each approach.

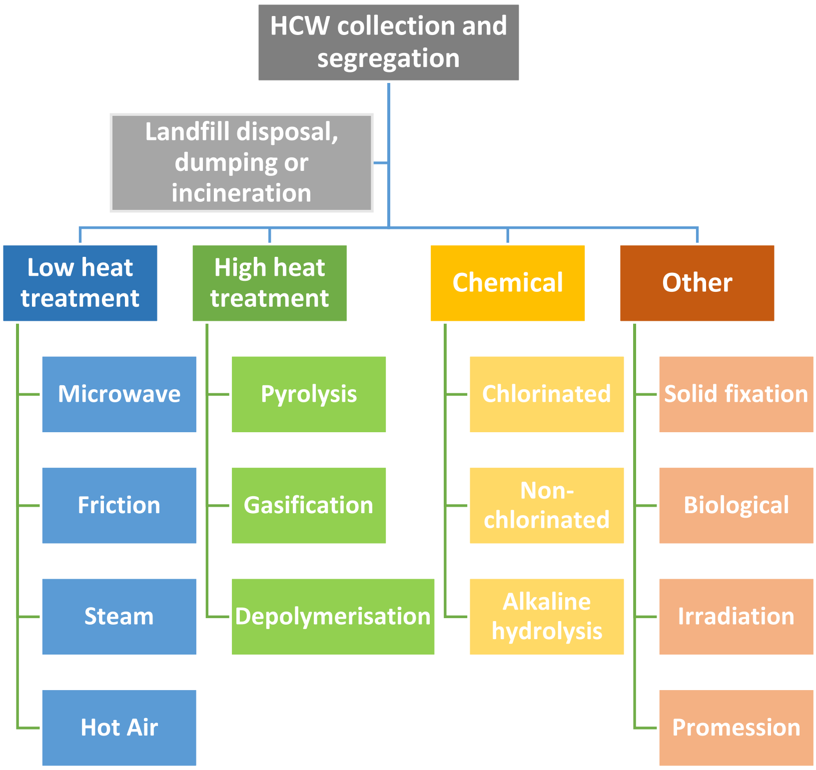

Figure 3 Common HCW treatment techniques

3.1 Treatment Capabilities

Each non-incineration HCW technology option has waste streams it is designed to accept, while others should be excluded from treatment due to risk to the equipment, operator health, or the environment. Table 4 summarises the treatment capabilities of each HCW treatment technology option.

As a rule of thumb, the following wastes may require dedicated disposal arrangements as they are commonly not treatable by conventional HCW technology:

- Volatile and semi-volatile organic compounds;
- Bulk chemotherapeutic wastes;
- Pressurised gas containers;
- Wastes containing heavy metals or radioactive material;
- Reactive chemicals or other hazardous chemical waste (unless specified otherwise).

It is recommended that these wastes are returned to the manufacturer/ supplier rather than disposed through conventional methods. Additional details regarding which wastes can and cannot be treated by HCW technology options is discussed in Section 4.

Table 4 Summary of technology options treatment capabilities

Technology Option	Infectious	Pathological	Sharps	Chemical	Pharmaceutical	Cytotoxic
Wet heat/ steam disinfection	x		x*			
Dry heat/ hot air disinfection	x		x*			
Microwave disinfection	x	x	x*			
Friction heat treatment	x	x	x			
Reverse polymerization	x	x	x			
Gasification	x	x	x	x^	x^	x^
Pyrolysis	x	x	x	x^	x^	x^
Chemical disinfection (chlorinated)	x*		x*			
Chemical disinfection (non-chlorinated)	x*		x*			
Alkaline hydrolysis	x	x				x
Solid fixation			x		x	x
Irradiation treatment	x		x*			
Promession		x				
Placenta pits		x				

***Note:** Waste shredding recommended/ required to remove all associated hazards

^Note: Dependent on the processing temperature used (temperatures between 500°C - 1,200°C required) and local regulations

3.2 Low-Heat Treatment

Low-heat treatment involves the application of enough thermal energy to destroy pathogens, without heating to a level that causes chemical breakdown or combustion. The temperature range for low-heat treatment is generally between 93°C - 177°C to ensure decontamination (Emmanuel, 2012).

Low-heat systems rely on either wet heat (injected steam or steam generated through microwaves) or dry heat (hot air created through convection or conduction). After incineration, steam disinfection is the most widely used HCW treatment technology used globally (Chartier, 2014). Shredding waste after disinfection can result in a 60 - 70% volume reduction, reduced puncture hazards from shards and renders waste unrecognisable.

Wet heat systems commonly rely on a steam **autoclave**, which can be further subdivided based on their method of air removal (i.e., gravity displacement, pre-vacuum, or pressure pulse) and integration of additional operating staged (e.g., shredded or drying). Chambers are designed to withstand the large pressure and temperature changes necessary to disinfect waste. Many variations on the autoclave system exist on the market, with a wide range of complexity and cost.

Microwave treatment operates using a similar principle to autoclaves, except moist heat is generated by microwaves. Smaller benchtop scale units can be operated in single batches, while larger scale continuous processing equipment can combine multiple processing stages. Water is added to the waste which is heated to steam by 2450 MHz microwave energy, typically supplied by 2 to 6 magnetrons with 1.2 kW outputs (Emmanuel et al., 2001)

Dry-heat systems use hot air without the addition of water or steam. Waste can be heated through conduction, convection, or thermal radiation (e.g., infrared). Systems have been traditionally used to disinfect medical equipment, although generally require higher temperatures and longer exposure times for waste treatment compared to steam-based processes.

A more novel low-temperature treatment method is **friction heating**. Heat is generated by high-speed rotors supplemented by resistance heaters. Treatment has a dual function of disinfecting and shredding waste, significantly decreasing waste volume (35% initial volume). Residual material also has a lower weight compared to steam-based systems.

3.3 High-Heat Treatment

High-heat thermal processes generally operate at temperatures ranging from 540°C - 8,300°C or higher, which caused the partial or complete destruction of waste. Heating relies on electrical resistance, induction, natural gas or plasma energy. The most prevalent high-heat treatment option is incineration, although this is associated with environmental impacts and low opportunities for energy recovery. Generally, high-heat treatment results in a 90 – 95% reduction in waste volume and require dedicated air-emission control systems.

Processes that are similar to incineration are **gasification** and **pyrolysis**, which both occur at high temperatures in the absence of oxygen. Gasification is partial oxidation (some oxygen is still present) of solid waste to generate a gas that can be used for heating or electricity generation. Pyrolysis occurs at lower oxygen levels and generates a liquid-state product. Unfortunately, the complete absence of oxygen is impossible in the treatment of HCW, hence dioxins and other air emissions can still be generated.

A less developed form of high-heat treatment is **reverse polymerization** (also known as depolymerisation) caused by high-energy microwaves. Significantly more power is required compared to low-temperature microwave treatment; systems use 14 magnetrons with 3 kW outputs (Emmanuel et al., 2001). The intense energy is enough to cause molecular level decomposition, while combustion is limited by a nitrogen atmosphere.

3.4 Chemical

A large variety of chemicals have been used in the disinfection of medical waste, such as dissolved chlorine dioxide, bleach (sodium hypochlorite), peracetic acid, or dry inorganic chemicals. Disinfection results of chemical systems are largely dependent on the type and concentration of disinfectant used. To enhance exposure of the waste to the chemical agent, chemical processes often involve internal shredding, grinding, or mixing.

Chlorine-based chemicals are effective in disinfecting waste, although have become less widely used due to environmental concerns and risks to operator safety. **Non-chlorine** systems come in a variety of solid, liquid and gaseous mediums, such as more recently developed ozone-based disinfection. These systems do not generate chlorine containing residuals or by-products. Some systems require proprietary reagents supplied by equipment providers. However, some systems allow effluents to be collected and reagents to be recycled.

A subset of non-chlorine treatment is **alkaline hydrolysis,** which converts pathological waste into a neutral, decontaminated, aqueous solution. Alkali (sodium or potassium hydroxide) is mixed with waste in a pressurized, heated container which initiates digestion. As well as a non-hazardous liquid by-product, the process also generates biodegradable mineral constituents (from bones and teeth) that can be crushed and recovered as sterile bone meal. Certain metals and concentrated acids cannot be treated via this method due to the generation of hydrogen gas or excessive reaction temperatures.

3.5 Other Treatment Options

3.5.1 Solid fixation

Disposal of untreated HCW to landfill should always be avoided. Although in scenarios where treatment options are not available, wastes should be entirely contained prior to disposal. Options for solid fixation include **encapsulation** and **inertisation.** The former involves filling an appropriate container (e.g., rigid plastic boxes or metal drums) with 75% waste and 25% a fixing medium such as sand, cement, or clay. Containers can then be sealed and disposed. The latter requires wastes to be shredded or crushed and mixed with cement. The mixture can then be formed into cubes or poured as a liquid directly onto a landfill.

This approach is most suited to the disposal of sharps and pharmaceutical wastes. Other wastes can also be disposed through this method, although care must be taken to minimise the potential for hazardous leachates. The main advantage of this approach is to reduce the risk of contact for landfill operators and scavengers.

3.5.2 Irradiation

Irradiation-based technologies rely on the high frequency radiation (gamma, x-ray or ultraviolet) to disinfect waste. Systems commonly use either **electron beams, Cobalt-60,** or **UV** diodes which can rupture the cell walls of infectious pathogens. This approach does not physically alter the waste, which would still require shredding to be rendered unrecognisable

These technologies require strict occupational risk prevent (such as fixed shielding) to prevent operator exposure. While some (such as electron beams) have no residual radiation after the treatment has ended, other systems may produce radioactive by-products.

3.5.3 Biological

Biological systems range from developmental **enzyme digestors** to low-tech **placenta pits**, although carry out the similar function of decomposing organic/ pathological waste. Advanced systems use additive enzymes and controlled environments to increase the rate of decomposition, while low-tech systems allow degradation to occur naturally.

Biological activity can decontaminate pathogens, although the exact time required is largely dependent on local conditions (Chartier, 2014). Care must be taken to ensure liquid leachate or excessive odours are unable to escape from the system. Most treatment technologies are entirely self-contained and have dedicated air emission control system (such as HEPA filters). Although since biological systems are typically designed and constructed locally, considerations need to reflect the potential impacts of leachate and odour (more details discussed in Section 4.6)

The handling and disposal of placentas (regardless of the approach used) should be sensitive to the cultural sensibilities, traditions and religion of the local community.

3.5.4 Promession

Promession is a newly developed technology with similarities to alkaline hydrolysis in the treatment of anatomical waste. Instead of the application of alkali and heat to disintegrate organic material, promession involves cryogenic freeze-drying using liquid nitrogen followed by mechanical agitation. The resulting dry powder has a lower weight and volume compared to untreated waste.

Systems lack the ability to treat a wide range of wastes. The reliance on liquid nitrogen and mechanical equipment also results in high operating costs.

3.6 Suitability Analysis

Each of the technologies discussed were evaluated against five selection criteria (Table 6). The aim was to conduct an initial suitability assessment for deployment in the Pacific context. The assessment used a traffic-light colour system outlined in

Table 5 Traffic-light ranking legend

(green)	**Favourable or positive outcome**
(yellow)	**Acceptable outcomes**
(red)	**Outcomes that should be avoided or minimised**

These were applied to the following criteria:

- Alignment with the waste hierarchy – ability to achieve the objectives summarised in Section 1.4;
- Expertise required to operate the technology – a judgement of the relative operating and maintenance complexity;
- Potential for operation to require regulatory control – a risk rating regulatory interventions (e.g., international law, environmental protection acts, work health and safety laws) based on previous deployment in other countries;
- Status as an Environmentally Sound Technology – technologies capable of reducing environmental damage through minimising emissions and enabling recycling/ recovery from process residuals (OECD, 1997);[3] and
- Potential residual risk to human health and the environment – a preliminary risk assessment using the risk matrix shown in Appendix B.

More details of each rating can be found in Appendix A.

[3] A detailed definition for Environmentally Sound Technologies can be found in the OECD (1997) "Glossary of environment statistics, studies in methods", no. 67. Organisation for Economic Co-operation and Development

Table 6 Summarised selection categories applied to HCW treatment technology options

Category	Technology Option	Sub-category	Alignment with waste hierarchy	Expertise required to operate the technology	Potential for operation to require regulatory control	Status as an Environmentally Sound Technology	Potential residual risk to human health and the environment
High Heat Treatment	Reverse polymerisation		Energy Recovery	Advanced	Low risk	Demonstrated	3C - Major/ Remote
	Gasification	Entrained flow Moving bed Fluidised bed	Energy Recovery	Advanced	Medium risk	Demonstrated	3B - Hazardous/ Remote
	Pyrolysis	Plasma Induction Laser	Energy Recovery.	Advanced	Medium risk	Demonstrated	3B - Hazardous/ Remote
Low Heat Treatment	Dry heat disinfection	Conduction Convection Thermal radiation	Treatment (Potential recycling)	Minimal	Low risk	Demonstrated	2D - Minor/ Improbable
	Wet heat disinfection	Autoclave Vacuum autoclave	Treatment (Potential recycling)	Minimal	Low risk	Demonstrated	2C - Major/ Improbable
	Friction heat treatment		Treatment (Potential recycling)	Moderate	Low risk	Demonstrated	2D - Minor/ Improbable
	Microwave disinfection		Treatment (Potential recycling)	Moderate	Low risk	Demonstrated	2C - Major/ Improbable
Chemical	Chlorinated disinfection	Sodium hypochlorite Chloride dioxide	Treatment/ Disposal	Minimal	High risk	Not Demonstrated	4B - Hazardous/ Occasional
	Non-chlorinated disinfection	Gas (ozone) Liquid (peracetic acid) Solid (calcium oxide)	Treatment/ Disposal	Minimal	Medium risk	Potential	4C - Major/ Occasional
	Alkaline hydrolysis		Treatment/ Disposal	Moderate	Medium risk	Potential	4C - Major/ Occasional
Other	Solid fixation	Encapsulation Inertisation	Disposal	Minimal	Medium risk	Not Demonstrated	4C - Major/ Occasional
	Irradiation treatment	Electron beam Cobalt-60 UV	Treatment (Potential recycling)	Advanced	Low risk	Demonstrated	5D - Minor/ Frequent
	Promession		Treatment/ Disposal	Moderate	Medium risk	Potential	3C - Major/ Remote
	Placenta pit		Disposal	Minimal	Medium risk	Potential	2C - Major/ Improbable

4. Comparative Evaluation

This section provides detailed information on specific focus areas for each technology option identified in Section 3, so as to allow one to evaluate the feasibility of implementation of the technology in the context of the Pacific environment and one's specific needs.

These include:

- Microwave treatment;
- Steam disinfection;
- Pyrolysis;
- Friction heat treatment; and
- Non-chlorinated chemical disinfection.

Additional details are provided for solid fixation and placenta pits which are viable, non-technological alternatives to direct burning or landfilling.

The detailed assessments focus on technologies that have a proven track record of successful implementations in medical settings.

The comparison is structured into four major sections: Technological, Legal, Economic and Environmental. Under each of these sections, different focus areas have been identified to assist in the comparison of potential technology options.

It should be noted that:

- Cost estimates are indicative and would require further investigation during technology selection and procurement; and
- Some considerations are mutual across some technologies (e.g., recommendations for collection practices). These have been listed under each relevant technology to assist quick comprehension of each technology's requirements.

4.1 Microwave Treatment

Table 7 Specification table for microwave treatment

Section	Focus Area	Microwave disinfection
	Technology overview and relation to waste management hierarchy	**Treatment (potential recycling):** treated wastes typically disposed, although potential for resource recovery for metals (through magnet separation) and shredded plastics. **Batch Treatment**: benchtop scale units generally operate in a 45 min - 1 hr treatment cycle. Waste is loaded into the unit by a reusable, fully enclosed, microwavable container. Operators can select the unit function based on the type and quantity of waste. Steam or water is added to the chamber under vacuum, which is then maintained at a setpoint temperature through microwave heating. **Continuous/ Semi-Continuous Treatment:** larger treatment plants consisting of multiple unit operations such as automatic hopper loading, shredders, conveyors, steam generators, microwave generators and computer controls. Operates similar to a batch treatment system, although with less operator handling and automated shredding.
	Examples of countries where technology has been successfully used	Deployed in multiple countries internationally (e.g., USA, Germany, France) including developing island nations (e.g., Dominican Republic). International technology suppliers can supply equipment globally.
	Acceptable feedstocks (i.e., types of waste accepted and their condition)	**Designed to treat:** infectious waste. Co-shredding waste decreases the risks of sharps. Pathological waste can be treated, although requires consideration of cultural/ legal/ religious customs. **Cannot treat:** large anatomical parts, cytotoxic, volatile/ semi volatile organic compounds, heavy metals, radioactive or pharmaceutical waste
	Requirements for separation, collection and storage of feedstocks	• Source separation should ensure no hazardous chemicals are included in feed streams • Infectious material should be collected in clearly labelled plastic bags (which are placed in the unit in their entirety) • Minimum approach to waste collection requires a "three-bin" system: infectious waste, sharps, and general waste. • Waste storage prior to treatment should be lockable and isolated from the general public. Maximum storage times for infectious waste is 24 hr - 48 hr.
	HCW treatment capacity (per unit time)	**Batch-wise microwave**: 1 kg/hr to 210 kg/hr **Continuous microwave**: 100 kg/hr to 600 kg/hr
	Process outputs and their associated reuse/ disposal options	**Solid output:** disinfected HCW with reuse or recycling options dependent on waste type **Liquid output**: condensed steam **Gaseous output**: Nil
	Technology footprint and geographical requirements (i.e., climate and elevation)	**Batch-wise microwave**: generally, between a benchtop size to 2 m^3 **Continuous microwave**: large range of sizes, including systems entirely enclosed in mobile shipping containers to stationary plants with >40m^2 footprints. **Geography:** systems are suited to warm, moist climates with low elevations (reduces heating requirements)

Section	Focus Area	Microwave disinfection
	Logistical requirements (i.e., power/ water access, reagents, storage and sitting of equipment)	Technology deployment should consider: • Requirements for grinding/ shredding waste to be unrecognizable, decrease sharps risks and decrease residual waste volume • Access to a sanitary sewer for purging of condensed steams • Stable 220 - 400 V power supply (dependent on unit size) • Access to water (tap quality)
	Technological and processing complexity (i.e., maintenance constraints, training requirements and technical expertise)	**Operation**: Low complexity due to computer-aided controls – waste type and weight are used to calculate the processing temperature and cycle time. Systems typically manned by a single operator. Operators should be trained to identify non-compliant feed material, OH&S and record keeping procedures, routine maintenance task and contingency plans (e.g., fires or spills) **Maintenance**: high complexity and expertise required. Systems may include moving parts (e.g., shredders) that require regular maintenance. Vital computer and electrical components will need technical knowledge to repair and maintain.
	Scalability	Large variability in treatment capacities and throughput (e.g., batch or continuous systems) allows technology options to be scaled to the treatment requirements of a particular setting.
	Technology lifespan, durability and resilience	**Approximately 10+ years** Shredder components and air filters typically require the most frequent replacement, with a lifespan of about 1.5 years.
	Potential need for regulation to protect the environment	Wastewater discharge must comply with sewer discharge requirements. Few other legal barriers due to lack of emissions.
	Potential need for regulation to protect operator health and safety	Workplace OH&S policy required to protect operators from heated, moving, and hazardous elements. A microwave energy detector can be employed to monitor leakage and can be integrated into standard maintenance procedures.
	Potential impact of international conventions	No intervention of international conventions (e.g., compliant with the Stockholm Convention due to lack of incineration by-products). Technology is well established and recognised in other international jurisdictions.
	Capital expenditure (i.e., equipment purchase cost, ancillary services and infrastructure/ civil engineering requirements)	**Batch-wise microwave:** $50k to $200k **Continuous microwave:** $100k to $600k+
	Transport and installation cost	**Batch-wise/ small scale:** Transport and installation costs should be included **Continuous/ medium scale**: Systems can often be loaded for shipment in a standard 20-ft container with "plug and run" connectivity (to electricity and water supply). Shipping costs vary annually, although estimates from the USA to Pacific Islands are $2,500 to $4,000 USD.
	Operational expenditure (i.e., labour, maintenance, replacement parts, utilities, material handling, storage etc.)	**Operating cost**: $0.10 to $0.42 per kilogram of waste **Annual maintenance cost**: $200-$1k (Kollu et al., 2022)
	Process emissions and by-products	**Solid by-product**s: disinfected residuals (non-hazardous, although non-shredded sharps can represent a puncture hazard) **Liquid by-products:** condensed steam disposed to sewer **Gas by-products**: Nil - continuous operation systems typically employ HEPA air filters to prevent airborne pathogens. Elimination of hazardous emissions and effluent is contingent on the correct feedstock control to prevent hazardous chemicals.

Section	Focus Area	Microwave disinfection
	Water and electricity consumption	**Batch treatment:** 3 kg/cycle = 45 mins, 0.9 kWh and 0.5L water 20 kg/cycle = 45 mins, 3.5 kWh and 2.5L water **Continuous treatment (with integrated shredding):** 100 kg/hr = 20 kWh 500 kg/hr = 100 kWh (WHO, 2019)
	Risks to environment	Low risk to the environment due to lack of emissions under normal operating conditions. Risk of poor waste segregation resulting in chemical waste contaminating air, condensate or treated waste.
	Risks to human health	Low risks to human health due to sterilisation of wastes. Independent studies have found air emissions in worker's personal airspace did not exceed health limits. Shredding decreases sharps risk during final disposal.
	Benefits to the environmental and human health	Improvement on current disposal/ incineration practices due to reduced harm to the environment and human health, primarily through the reduction of airborne emissions and the safe sterilisation of infectious material.

4.2 Steam Disinfection

Table 8 Specification table for steam disinfection treatment

Section	Focus Area	Steam disinfection
	Technology overview and relation to waste management hierarchy	**Treatment (potential recycling):** treated wastes are typically disposed, although potential for resource recovery. **Vacuum autoclave:** the simplest autoclave systems consist of a sealing metal chamber designed to withstand high pressures. Autoclaves generally have an external steam jacket for additional heating (systems without external heating are known as a retort). Air is evacuated from the chamber due to its insulating properties. Systems are classified according to their method of air evacuation: gravity-displacement, pre-vacuum, or pressure-pulse. **Advanced autoclave**: expands upon basic autoclave design by integrating additional mechanical processing stages to improve heat transfer and render waste unrecognisable. This can include fragmenting, shredding, drying, mixing or compaction.
	Examples of countries where technology has been successfully used	Deployed extensively in the Oceanic region (e.g., Australia and New Zealand) and Pacific Islands (e.g., Nuku'alofa hospital, Tonga). Multiple technology suppliers located in the Oceanic/ Pacific region.
	Acceptable feedstocks (i.e., types of waste accepted and their condition)	**Designed to treat:** infectious waste. Co-shredding waste decreases the risks of sharps. **Cannot treat:** large anatomical parts, cytotoxic, volatile/ semi volatile organic compounds, heavy metals, radioactive or pharmaceutical waste
	Requirements for separation, collection and storage of feedstocks	• Source separation should ensure no hazardous chemicals are included in feed streams • Infectious material should be collected in clearly labelled plastic bags (which are placed in the unit in their entirety) • Minimum approach to waste collection requires a "three-bin" system: infectious waste, sharps, and general waste. • Waste storage prior to treatment should be lockable and isolated from the general public. Maximum storage times for infectious waste is 24 hr - 48 hr.

Section	Focus Area	Steam disinfection
	HCW treatment capacity (per unit time)	**Vacuum autoclave:** 5 kg/hr to 3,000 kg/hr **Advanced autoclave:** 5 kg/hr to 2,000 kg/hr (WHO, 2019)
	Process outputs and their associated reuse/ disposal options	**Solid output:** disinfected HCW with reuse or recycling options dependent on waste type **Liquid output**: condensed steam **Gaseous output**: Nil
	Technology footprint and geographical requirements (i.e., climate and elevation)	**Vacuum autoclave:** generally, between a benchtop size to over 20 m^3 **Advanced autoclave**: large range of sizes dependent on treatment stages, but can range from 3.5 m^3 to over 20 m^3 **Geography:** systems are suited to warm, moist climates with low elevations (reduces heating requirements)
	Logistical requirements (i.e., power/ water access, reagents, storage and sitting of equipment)	Technology deployment should consider: • Requirements for grinding/ shredding waste to be unrecognizable, decrease sharps risks and decrease residual waste volume • Access to a sanitary sewer for purging of condensed steams • Stable 220 - 400 V power supply (dependent on unit size) • Access to water (soft/ demineralised water may be required per manufacturer recommendation) • Temperature resistance waste bags or bins should be employed to fully contain untreated waste • Treated wastes will be heavier due to condensed steam, impacting final disposal costs. • Waste loading configuration (e.g., multi-level racks) can improve steam exposure and disinfection
	Technological and processing complexity (i.e., maintenance constraints, training requirements and technical expertise)	**Operation:** System operation should be calibrated to the expected waste profile of the clinical setting. Different temperatures, pressures and contact times are required depending on waste feedstock characteristics. Time-temperature parameters are well established to reach high disinfection rates. Operators should be trained to identify potential high-risk wastes and adjust operating parameters accordingly. Operators should also be trained to identify non-compliant feed material, OH&S and record-keeping procedures, routine maintenance tasks and contingency plans (e.g., fires or spills). Advances systems typically have higher degrees of automation and computer-aided control, requiring less operator intervention although higher maintenance complexity. All systems are typically manned by a single operator. **Maintenance:** most systems have a low maintenance complexity due to a lack of moving parts or complex computer controls. Annual tests should ensure heating capabilities and instrument accuracy (e.g., thermocouples and pressure gauges). Advanced systems integrating mechanical processing will require regular maintenance.
	Scalability	Large variability in treatment capacities and throughput (depended on the size of the autoclave/ retort) allows technology options to be scaled to the treatment requirements of a particular setting.
	Technology lifespan, durability and resilience	**Approximately 10 years** Regular validation tests using biological indicators should be conducted to ensure system performance.
	Potential need for regulation to protect the environment	Wastewater discharge must comply with sewer discharge requirements. Few other legal barriers due to lack of emissions.
	Potential need for regulation to protect operator health and safety	Minor risk of odour nuisance, requiring systems to be adequately ventilated. Workplace OH&S policy required to protect operators from heated/ hazardous elements. Operators can employ chemical or biological indicators to monitor the rate of disinfection.

Section	Focus Area	Steam disinfection
	Potential impact of international conventions	No intervention of international conventions (e.g., no incineration by-products complies with Stockholm Convention). Technology is well established and recognised in other international jurisdictions. Pressure chambers should be constructed to meet international pressure vessel standards (e.g., ASME Section VII) rated between 1 and 2 bar gauge pressure (or higher).
	Capital expenditure (i.e., equipment purchase cost, ancillary services and infrastructure/ civil engineering requirements)	**Vacuum autoclave:** $5k to $200k **Advanced autoclave:** $200k to $900k+
	Transport and installation cost	**Vacuum autoclaves:** Low-complexity systems can be designed and constructed in-situ, decreasing transportation requirements. Transport and installation costs for high-complexity vacuum autoclaves is expected to be below $2,500 USD. **Advanced autoclave:** largely dependent on the number and type of ancillary process units, although expected to be below $5,000 USD.
	Operational expenditure (i.e., labour, maintenance, replacement parts, utilities, material handling, storage etc.)	**Operating cost**: $0.13 to $0.36 per kilogram of waste. Autoclavable bags are about $18 - $163 per 100, depending on size, thickness, and whether they have temperature strips. **Annual maintenance cost**: $12k Comparison analysis have found that autoclave operational costs can be more than 2 times the operational costs of microwave treatment at the same capacity (Kollu et al., 2022). Comparative analysis tailored to the Pacific region has not been conducted, hence results may vary.
	Process emissions and by-products	**Solid by-products**: disinfected residuals (non-hazardous, although non-shredded sharps can represent a puncture hazard) **Liquid by-products**: condensed steam disposed to sewer **Gas by-products**: Nil - air evacuated from the treatment chamber must be filtered (HEPA) and steam condensed. Elimination of hazardous emissions and effluent is contingent on the correct feedstock control to prevent hazardous chemicals.
	Water and electricity consumption	**Vacuum autoclave:** 40 kg/cycle = 50 mins, 7 kWh and 200L water 800 kg/cycle = 60 mins, 56 kWh and 1,800L water **Advanced autoclaves** will have higher cycle times and energy consumption but generally use less water. (WHO, 2019)
	Risks to environment	Low environmental impacts due to lack of emissions under normal operating conditions. Risk of poor waste segregation resulting in chemical waste contaminating air, condensate or treated waste.
	Risks to human health	Low risks to human health due to sterilisation of wastes. There is some risk that barriers to direct steam exposure or heat transfer (e.g., insufficient air evacuation, overloaded chamber, bulky waste material, waste in multiple bags or sealed heat-resistance containers etc.) may compromise disinfection rates. Independent studies have found air emissions in workers' personal airspace did not exceed health limits. Shredding decreases sharps risk during final disposal.
	Benefits to the environmental and human health	Improvement on current disposal/ incineration practices due to reduced harm to the environment and human health, primarily through the reduction of airborne emissions and the safe sterilisation of infectious material.

4.3 Pyrolysis

Table 9 Specification table for pyrolysis treatment

Section	Focus Area	Pyrolysis
	Technology overview and relation to waste management hierarchy	**Energy Recovery:** ability to convert latent chemical energy in waste into heat or electricity. Pyrolysis is a form of high-temperature incineration that occurs at temperatures between 200 to 700ºC. The reaction is endothermic, meaning it requires energy input (compared to combustion which is exothermic). It also occurs only in the absence of oxygen, requiring a controlled inert atmosphere of nitrogen. Processes are generally characterised by their method of heating, which include: **Plasma pyrolysis**: plasma arc torches or electrodes converting electrical energy into thermal energy **Induction pyrolysis:** electromagnetic induction through a conductive metal creates heat due to resistance **Natural gas pyrolysis:** combustion of natural gas to reach high temperatures Some pyrolysis processes also have controlled oxidation units can combust resulting gas streams to produce heat or electricity. **Note:** some advanced pyrolysis technologies are relatively new in their development and commercialization, hence lack a proven track record of performance and emission characteristics. Technology procurement should seek to prioritise well established systems. (Chartier, 2014)
	Examples of countries where technology has been successfully used	Limited international deployment, primarily concentrated in the USA.
	Acceptable feedstocks (i.e., types of waste accepted and their condition)	**Designed to treat:** high calorific waste streams (above 2,000 kcal/kg) containing infectious, pathological, chemical, pharmaceutical, cytotoxic and low-level radioactive material. **Cannot treat:** waste with excessive moisture content (above 30%) or proportions of non-combustible material (above 5%). Source separation must also prevent the following: pressurised gas containers, silver salts, radiographic waste and wastes containing heavy metals or excessive chlorinated hydrocarbons.
	Requirements for separation, collection and storage of feedstocks	• Infectious material should be collected in clearly labelled plastic bags (which are placed in the unit in their entirety) • Minimum approach to waste collection requires a "three-bin" system: infectious waste, sharps, and general waste. Collection and storage of hazardous materials must adhere to local and international regulatory requirements. Hazardous waste bins should be placed in dedicated areas to prevent risk of cross-contamination. • Waste storage prior to treatment should be lockable and isolated from the general public. Maximum storage times for infectious waste is 24 hr - 48 hr.
	HCW treatment capacity (per unit time)	45 kg/hr to over 1,400 kg/hr
	Process outputs and their associated reuse/ disposal options	**Solid output:** varies based on temperature of pyrolysis reaction (such as ash, coke, elemental metal, glassy residual). Some systems allow for recovery of metals. **Liquid output:** nil **Gaseous output:** syngas (H_2, CO, C_xH_x, H_2O and N_2) used to generate electricity or steam
	Technology footprint and geographical requirements (i.e., climate and elevation)	Between 20 m^3 to 150 m^3 **Geography:** pyrolysis systems are best suited as a large-scale, continuous operation plant at a regional treatment centre. The location of a regional treatment plant should consider geographical and transport logistics between major HCW generation sources. Transport and storage requirements should be minimised due to the potentially hazardous nature of HCW. An offsite treatment location also decreases the risk of power instability to hospitals.

Section	Focus Area	Pyrolysis
	Logistical requirements (i.e., power/ water access, reagents, storage and sitting of equipment)	Technology deployment should consider: • Stable of 480 V, three-phase power supply • Access to water (tap quality) • Inert atmospheres require nitrogen gas supply • Controlled oxidation units require compressed air supply (100 psig) • Systems require an air emission control system for exhaust gases • Potential requirement for water treatment unit for cleaning gas scrubbing water (internal recycling or prior to discharge)
	Technological and processing complexity (i.e., maintenance constraints, training requirements and technical expertise)	**Operation:** Systems are typically designed with automated waste loading and operation, requiring minimal operator intervention. Operators need to be trained in daily cleaning and preventative protocols, identification of non-compliant feed material, OH&S and record-keeping procedures. Operators should also be able to recognise potential technical issues that require maintenance intervention. **Maintenance:** Due to the relatively novel status of pyrolysis waste treatment technology, maintenance is expected to require specialised personnel. Additionally, some designs may be prone to unreliability or failures due to their lack of extensive commercial history. Therefore, maintenance requirements are expected to be significant and highly complex for pyrolysis systems.
	Scalability	Large variability in treatment capacities due to range of design options. Large regional treatment facilities can be scaled to national HCW generation rates (dependent on transportation logistics).
	Technology lifespan, durability and resilience	**Unknown** (due to relatively novel status of technology deployment) Systems that use plasma arc torches need regular replacement.
	Potential need for regulation to protect the environment	Due to the ability to treat a wide range of waste types, some jurisdictions may require special permits or adherence to certain regulations (e.g., acceptable air emission limits). Technology performance and emission characteristics should be well established and compared to local regulatory requirements.
	Potential need for regulation to protect operator health and safety	Workplace OH&S policy required to protect operators from heated, moving, and hazardous elements. Regular toxicity tests should be conducted of solid residual waste to ensure safe handling.
	Potential impact of international conventions	Potential intervention of the Stockholm Convention due to the generation of dioxins. Supplier specifications and verification should ensure robust air emission control systems result in low risk of atmospheric pollution.
	Capital expenditure (i.e., equipment purchase cost, ancillary services and infrastructure/ civil engineering requirements)	Approximately $800k to $3.5M (Emmanuel et al., 2001)
	Transport and installation cost	Shipping and commissioning costs are estimated between $10,000 to $50,000 USD
	Operational expenditure (i.e., labour, maintenance, replacement parts, utilities, material handling, storage etc.)	**Operating cost:** high operating costs due to consumption of electricity or consumables (e.g., natural gas). Systems should aim for continuous operation to decrease the heating requirements and heat-stresses to components. Exact operational costs largely dependent on local energy prices and the type of pyrolysis heating. Air emission control systems may also need regular regeneration/ replacement of gas scrubbing components. **Annual maintenance cost:** unknown
	Process emissions and by-products	**Solid by-products:** inert residuals that can be disposed to a regular landfill. Solid residuals from systems required to treat high proportions of chlorinated hydrocarbons (e.g., PVC) have been shown to contain high concentrations of dioxins, furans and other toxic substances. **Liquid by-products:** nil **Gas by-products:** exhaust gases vented after cleaning

Section	Focus Area	Pyrolysis
	Water and electricity consumption	Requires energy input of approximately 0.3 - 0.55 kWh/kg of waste treated. Systems are able to recover up to 80% of the input heat as hot water or steam. Water consumption varies based on technology design. Some gas scrubbing systems recirculate water during continual operation. Otherwise, waste consumptions rates can be over 2,000 L/hr. (Emmanuel et al., 2001)
	Risks to environment	Due to the inability to completely restrict oxygen in HCW feedstocks (either as pockets of trapped air or chemically bonded oxygen in waste), pyrolysis still generates low quantities of NO_x, SO_x, dioxins, and furans (at levels much lower than incineration). Systems are typically fitted with pollution control devices to clean exhaust streams. Higher reaction temperatures decrease the risks of harmful air emissions. Independent studies have found air emissions from advanced pyrolysis units are three orders of magnitude below US EPA limits. (Emmanuel et al., 2001)
	Risks to human health	Low risks to human health due to sterilisation of wastes. Independent studies have found air emissions in workers' personal airspace did not exceed health limits. Pyrolysis generates flammable liquids/ gases and operates at high temperatures, representing a physical risk to operator safety and potential explosion hazards. Even though reaction temperatures are high, chamber surfaces can be maintained at room temperature through proper insulation. Some systems also rely on high-power electrical currents to generate heat, which can be a risk to operators during cleaning or maintenance. Proper system operation, OH&S protocols and automatic system controls must be in place to decrease occupational risks.
	Benefits to the environmental and human health	Improvement on current disposal/ incineration practices due to significant reduction to environmental and human health risks. Energy recovery can offset the use of fossil fuels, further benefiting the environment and social outcomes.

4.4 Friction Heat Treatment

Table 10 Specification table for friction heat treatment

Section	Focus Area	Friction heat treatment
	Technology overview and relation to waste management hierarchy	**Treatment (potential recycling):** Treated wastes typically disposed, although potential for resource recovery**.** Systems utilize both moist and dry heat to disinfect waste. High speed rotors simultaneously shred and heat waste due to friction, converting the moisture in the waste into steam. Systems are further heated to above 135ºC through resistance heaters, resulting in an overall volume and weight reduction.
	Examples of countries where technology has been successfully used	Deployed internationally across Europe, America, Africa, and Asia with ability to supply to Oceanic/ Pacific region. One system operational in Australia.
	Acceptable feedstocks (i.e., types of waste accepted and their condition)	**Designed to treat:** infectious and pathological waste. Well suited to treat sharps. **Cannot treat:** cytotoxic, volatile/ semi volatile organic compounds, heavy metals, radioactive or pharmaceutical waste
	Requirements for separation, collection and storage of feedstocks	• Source separation should ensure no hazardous chemicals are included in feed streams • Infectious material should be collected in clearly labelled plastic bags (which are placed in the unit in their entirety) • Minimum approach to waste collection requires a "three-bin" system: infectious waste, sharps, and general waste. • Waste storage prior to treatment should be lockable and isolated from the general public. Maximum storage times for infectious waste is 24 hr - 48 hr.
	HCW treatment capacity (per unit time)	10 kg/hr to 600 kg/hr (WHO, 2019)
	Process outputs and their associated reuse/ disposal options	**Solid output:** disinfected and pulverised HCW with potential used as refuse-derived fuel **Liquid output**: condensed steam **Gaseous output**: Nil
	Technology footprint and geographical requirements (i.e., climate and elevation)	0.5 m^3 (10kg/hr) to above 30 m^3 (500 kg/hr) Equipment should have solid, concrete foundation footing **Geography**: systems are suited to warm, moist climates with low elevations (reduces heating requirements)
	Logistical requirements (i.e., power/ water access, reagents, storage and sitting of equipment)	Technology deployment should consider: • Access to a sanitary sewer for purging of condensed steams • Stable 400 V power supply • Access to water (soft/ demineralised water may be required per manufacturer recommendation)
	Technological and processing complexity (i.e., maintenance constraints, training requirements and technical expertise)	**Operation:** System operation is aided by computer controls and can be manned by a single operator. Operators should also be trained to identify non-compliant feed material, OH&S and record-keeping procedures, routine maintenance tasks and contingency plans (e.g., fires or spills). **Maintenance:** Regular maintenance requirements include daily cleaning, regular checks (e.g., rotors, blades, filters, sensors, gaskets, valves etc.) and the addition of oil. Technical maintenance capabilities are required for electrical components and servicing of moving parts.
	Scalability	Large variability in treatment capacities and throughput allows technology options to be scaled to the treatment requirements of a particular setting.
	Technology lifespan, durability and resilience	**Approximately 10+ years** Rotor blades and filters typically require the most frequent replacement, with a lifespan of about 1.5 years.

Section	Focus Area	Friction heat treatment
	Potential need for regulation to protect the environment	Independent studies found chlorine levels in a friction-heat system's wastewater were above Italian regulatory limits, potentially due to the nature of feed material. Technology selection should consult regulatory wastewater discharge requirements prior to procurement. Few other legal barriers due to minimal emissions. (Emmanuel, 2012)
	Potential need for regulation to protect operator health and safety	Workplace OH&S policy required to protect operators from heated/ hazardous elements. Technologies commonly employ automatic safety features (e.g., power supply cut-off) to improve operator safety.
	Potential impact of international conventions	No intervention of international conventions (e.g., no incineration by-products complies with Stockholm Convention).
	Capital expenditure (i.e., equipment purchase cost, ancillary services and infrastructure/ civil engineering requirements)	\$110k to \$160k for systems with capacities below 30 kg/hr (Emmanuel, 2012)
	Transport and installation cost	Small scale units - transport and installation costs should be included Systems can often be loaded for shipment in a standard 20-ft container with “plug and run” connectivity (to electricity and water supply). Shipping costs vary annually, although estimates from the USA to Pacific Islands are \$2,500 to \$4,000 USD.
	Operational expenditure (i.e., labour, maintenance, replacement parts, utilities, material handling, storage etc.)	**Operational cost:** >\$0.13/kg (Emmanuel, 2012) Lower HCW storage, transportation, and disposal costs due to decreased waste weight and volume
	Process emissions and by-products	**Solid by-products**: disinfected residuals (non-hazardous) **Liquid by-products**: condensed steam disposed to sewer **Gas by-products**: Nil - air evacuated from the treatment chamber must be filtered (HEPA) and steam condensed. Systems should have exhaust venting for vapor discharge. Elimination of hazardous emissions and effluent is contingent on the correct feedstock control to prevent hazardous chemicals.
	Water and electricity consumption	13 kg/cycle = 50 mins, 12 kWh and 15L water 60 kg/cycle = 50 mins, 40 kWh and 90L water (WHO, 2019)
	Risks to environment	Low environmental impacts due to lack of emissions under normal operating conditions. Steam and vapours generated during the treatment cycle pass through heat exchangers and filters to condense steam and filter air before being released. Risk of poor waste segregation resulting in chemical waste contaminating air, condensate or treated waste
	Risks to human health	Low risks to human health due to sterilisation of wastes. Systems have high disinfection rates through combined wet and dry heating. High-speed rotors not only shred material and generate heat, but also rupture pathogen cell membranes resulting in their complete destruction. Independent studies have found air emissions in workers' personal airspace did not exceed health limits
	Benefits to the environmental and human health	Decreased waste volume and weight results in a lower transportation carbon footprint compared to untreated waste. Improvement on current disposal/ incineration practices due to reduced harm to the environment and human health, primarily through the reduction of airborne emissions and the safe sterilisation of infectious material.

4.5 Non-chlorinated Chemical Disinfection

Table 11 Specification table for non-chlorinated chemical disinfection

Section	Focus Area	Chemical disinfection
	Technology overview and relation to waste management hierarchy	**Treatment/ Disposal:** Treated wastes are disposed with few opportunities for resource recovery. Due to environmental and health concerns related to toxic by-products from chlorine-based systems, this evaluation has focused on non-chlorine options. Options are highly varied and sometimes lack well-established commercial precedence. Examples of systems include: **Gas-disinfectant:** ozone **Liquid-disinfectant:** alkali **Solid-disinfectant:** calcium oxide (reacts to form calcium hydroxide) Systems are generally entirely self-contained and integrate multiple processing stages (e.g., shredded and mixing) to ensure complete contact of the disinfecting agent. Selection of the type of disinfectant used should take into consideration the common pathogens to be disinfected, the availability of chemicals and their hazards.
	Examples of countries where technology has been successfully used	Technology does not have an extensive implementation history, with most deployments occurring in the US. No chemical disinfection systems have been used in the Oceanic/ Pacific region.
	Acceptable feedstocks (i.e., types of waste accepted and their condition)	**Designed to treat:** infectious waste. Systems are better suited to treat liquid wastes, although solids treatment is possible with adequate shredding, disinfectant concentrations, and contact time. Waste shredding is required, although excessive proportions of sharps will accelerate the deterioration of shredder blades. **Cannot treat:** cytotoxic, volatile/ semi volatile organic compounds, heavy metals, radioactive or pharmaceutical waste**.** Contact between strong caustic disinfectants and various chemicals (including metals) may cause fires.
	Requirements for separation, collection and storage of feedstocks	• Source separation should ensure no hazardous chemicals are included in feed streams • Infectious material should be collected in clearly labelled plastic bags (which are placed in the unit in their entirety) • Minimum approach to waste collection requires a "three-bin" system: infectious waste, sharps, and general waste. • Waste storage prior to treatment should be lockable and isolated from the general public. Maximum storage times for infectious waste is 24 hr - 48 hr.
	HCW treatment capacity (per unit time)	20 kg/hr to 900 kg/hr (Emmanuel, 2012)
	Process outputs and their associated reuse/ disposal options	**Solid output:** disinfected and shredded HCW (disposal required due to potential toxicity) **Liquid output**: filtered effluent with characteristics dependent on disinfectant used (disposed to sewer). **Gaseous output**: Nil
	Technology footprint and geographical requirements (i.e., climate and elevation)	Footprints are generally up to 15 m^2. **Geography:** location should consider transportation costs and accessibility of raw disinfectants.

Section	Focus Area	Chemical disinfection
	Logistical requirements (i.e., power/ water access, reagents, storage and sitting of equipment)	Technology deployment should consider: • A consistent and cost-appropriate supply of chemical reagents • Requirements for grinding/ shredding waste to ensure sufficient disinfectant contact area • Access to a sanitary sewer for disposal of filtered effluent • Stable 220 - 400 V power supply (dependent on unit size) • Access to water (tap quality) • Adequate ventilation to prevent the concentration of irritant vapours • A separate, well-ventilated storage area for disinfectants
	Technological and processing complexity (i.e., maintenance constraints, training requirements and technical expertise)	**Operation:** Correct operator training is critical to ensure hazard identification and mitigation, correct handling procedures of hazardous substances, disinfectant dosing rates, personal protection measures, identification of non-compliant feed material, routine maintenance tasks and contingency plans (e.g., fires or spills). Systems can be manned by 1-2 operators. **Maintenance:** Regular maintenance requirements include daily cleaning, regular checks (e.g., rotors, blades, filters, sensors, gaskets, valves etc.) and the addition of oil. Technical maintenance capabilities are required for electrical components and servicing of moving parts.
	Scalability	Low scalability compared to other technology options due to restrictions to safe handling of raw disinfectants and treated HCW.
	Technology lifespan, durability and resilience	**Approximately 10 years** Rotor blades and filters typically require the most frequent replacement, with a lifespan of about 1.5 years. The selection of chemical disinfectants should take into consideration their stability and shelf life. Some remain stable for several years in a range of environmental conditions, while others degrade quickly.
	Potential need for regulation to protect the environment	It is recommended that supplier information and independent reviews are consulted regarding the effluents from chemical treatment systems. Wastewater characteristics will depend on the type and concentration of disinfectant used. Regulatory wastewater discharge limits must be consulted to ensure compliancy. Transportation, handling, and storage of raw disinfectants must also comply with environmental protection laws.
	Potential need for regulation to protect operator health and safety	Systems must comply with local OH&S regulations regarding the storage, transportation, and handling of toxic chemicals (disinfecting agents). Workplace OH&S policy is required to protect operators from heated/ hazardous/ toxic elements, including adequate PPE and ventilation. The treatment area should be equipped with eye-wash stations and emergency showers. Hazard training should inform operators of the risks involved and proper handling procedures.
	Potential impact of international conventions	Systems employing chlorine-based disinfectants are at risk of generating dioxins and other substances controlled under the Stockholm Convention. Equipment selection should ensure that any potential emissions from a non-chlorine system is not at risk of similar restrictions. The transboundary movement of raw disinfectants must comply with international shipping and customs requirements. Port regulations at both the country of supply and acceptance should be consulted regarding shipping hazardous chemicals (such as storage, labelling, insurance and licensing requirements).
	Capital expenditure (i.e., equipment purchase cost, ancillary services and infrastructure/ civil engineering requirements)	$100k to $450k for low pressure systems (Emmanuel, 2012)
	Transport and installation cost	Small scale units - transport and installation costs should be included Systems can often be loaded for shipment in a standard 20-ft container with “plug and run” connectivity (to electricity and water supply). Shipping costs vary annually, although estimates from the USA to Pacific Islands are $2,500 to $4,000 USD.

Section	Focus Area	Chemical disinfection
	Operational expenditure (i.e., labour, maintenance, replacement parts, utilities, material handling, storage etc.)	**Operational cost**: $0.12 to $0.52 per kilogram of waste Operational costs are largely variable due to a range of prices for raw disinfectants. Operational costs are expected to be higher for chemical treatment compared to microwave or autoclave systems to treat the same volume of waste. (Emmanuel, 2012)
	Process emissions and by-products	**Solid by-products**: disinfected residuals require disposal to landfill. Care should be taken to minimise the risk of toxic leachates from disposed waste. **Liquid by-products**: all liquid effluents should be controlled and disposed as per manufacturer specifications. This often requires a sanitary sewer or dedicated wastewater treatment due to potential biocide and toxic properties. Some systems recycle disinfectants, removing the generation of liquid by-products. These systems are generally preferred due to their low emissions. **Gas by-products**: Vapours and exhaust gases evacuated from the treatment chamber must be filtered (HEPA). Designs should ensure that there is no release of airborne pathogens during waste shredding. Safeguards should be taken to prevent occupational exposures to the chemical disinfectant through fugitive emissions, accidental leaks or spills from storage containers, discharges from the treatment unit, volatilized chemicals from treated waste or liquid effluent, etc.
	Water and electricity consumption	Water and electricity consumption vary dramatically based on the type of disinfected used (e.g., solid disinfectants that require water to dissolve) and type/ number of ancillary processes (e.g., shredding or heating). Individual supplier specifications should be consulted.
	Risks to environment	Reactions between disinfecting agents and components of the waste stream have the potential to generate toxic vapours. By-products are dependent on the type of disinfectant used, although most have the potential to cause adverse environmental impacts.
	Risks to human health	All disinfectants have the potential to cause operator harm during handling and treatment. At a minimum, irritation to eyes and the respiratory tract can be caused through direct contact or by aerosols/ vapours. Concentrated disinfectants (such as alkali) are corrosive enough to cause permanent scarring, blindness or even death. Reactions between disinfecting agents and components of the waste stream have the potential to generate excessive heat or fires. Operators must be trained in identifying non-compliant feed material. Some chemical disinfectants do not have a full range of disinfecting capabilities. Bacterial spores, mycobacteria, parasites, and some viruses may be resistant to certain disinfectants. Operators must have knowledge of the expected pathogens in the feed material to reduce the risk of infection from treated wastes.
	Benefits to the environmental and human health	Non-chlorine systems have the advantage of not generating dioxins or other chlorine-containing by-products. Improvement on current disposal/ incineration practices due to reduction in airborne emissions. Although care must be taken regarding other by-products of chemical treatment and weigh their impacts against current practices.

4.6 Improved Disposal Practices

Table 12 Specification table (limited scope) for improved disposal practices solid fixation and placenta pits

Section	Focus Area	Solid fixation	Placenta pit
	Technology overview and relation to waste management hierarchy	**Disposal**: No potential for resource recovery. **Encapsulation**: filling containers (e.g. HDPE or metallic drums) with waste, adding an immobilising agent (e.g. plastic foam, sand, cement or clay) and sealing. Sealed containers are then disposed to landfill. **Inertisation**: direct mixing of shredded waste with cement and lime. Liquid slurry can be poured directly into landfill cells or formed into a solid (cube or pellets) for disposal. The fixation of HCW decreases health and environmental risks inherent in direct disposal to landfill, particularly in areas where landfill waste picking/ scavenging is commonly practiced.	**Disposal**: No potential for resource recovery. A placenta pit is a low-resource disposal option for placenta waste. An audit of Peru hospitals found placenta represented 8% of the overall waste generated (Diaz et al., 2008). When carried out safely, placenta pits can have beneficial environmental and health outcomes compared to landfill or incineration disposal. Although care must be taken to respect cultural and religious norms.
	Examples of countries where technology has been successfully used	Practice is common and extensively practiced globally, with variations to the type of ancillary processing or fixation method.	Practice is common and extensively practiced globally (particularly developing countries).
	Acceptable feedstocks (i.e., types of waste accepted and their condition)	**Designed to treat:** predominately tailored to sharps, although suitable for low quantities of chemical or pharmaceutical waste. **Cannot treat**: excessive infectious or pathological waste, bulky items or radioactive material	**Designed to treat:** placenta waste and small quantities of other pathological waste (e.g., blood) **Cannot treat:** all non-organic waste, including infectious, chemical, pharmaceutical, cytotoxic and radioactive waste
	Requirements for separation, collection and storage of feedstocks	• Minimum approach to waste collection requires a "three-bin" system: infectious waste, sharps and general waste. • Waste storage prior to disposal should be lockable and isolated from the general public. Maximum storage times for infectious waste is 24 hr - 48 hr. • Collection and storage of hazardous materials must adhere to local and international regulatory requirements. Hazardous waste bins should be placed in dedicated areas to prevent risk of cross-contamination.	• Source separation should ensure only eligible, organic waste is disposed (including plastic bags/ containers used to transport waste) • Placenta material should be safely deposited in the pit in a manner that minimises operator exposure. • Placenta storage prior to disposal should be minimised, with pits located close to areas of generation. • Waste should not be treated with disinfecting chemicals that can destroy microorganisms responsible for degradation.
	HCW treatment capacity (per unit time)	Limited by processing/ mixing/ transport capacity and available fixing agents.	Limited by the size and available of active pits.
	Process outputs and their associated reuse/ disposal options	**Solid outputs:** fixated waste requiring disposal to landfill **Liquid output:** nil **Gaseous output:** nil	**Solid output:** degraded organic material may require disposal to a controlled/ sanitary landfill dependent on level of microbial deactivation **Liquid output:** nil **Gaseous output**: nil

Section	Focus Area	Solid fixation	Placenta pit
	Technology foot print and geographical requirements (i.e., climate and elevation)	Minimal footprint required - shredders can be constructed under 4 m^2. A mixing pit can be employed to mix shredded waste with fixation substances. **Geography:** solid fixation requires access to landfill disposal; hence transport distances and logistics should be considered.	Pit dimensions should be tailored to the average birth rate of the specific setting. A maximum of 5 L of space is required per placenta if all the bloody liquids are collected. **Geography:** pits should be located as away from publicly accessible or hygienically sensitive (e.g., kitchens) areas. At least 1.5 m from the bottom of the pit to the groundwater level is recommended. Construction should avoid areas of high-water tables or areas prone to flooding.
	Logistical requirements (i.e., power/ water access, reagents, storage and sitting of equipment)	Technology deployment should consider: • Requirements for grinding/ shredding waste for waste to be mixed with fixatives and to decrease residual waste volume • Stable 220 - 400 V power supply for waste shredder (dependent on unit size) • Access to water (tap quality) • Access to fixatives dependent on chosen method (e.g., metal, or plastic containers, clay, lime, cement, foam etc.)	Technology deployment should consider: • Monitoring of pit capacity and contingency planning for new pits to be constructed. • Marking and record keeping of sealed pits (including location and final date of sealing). • The time required to destroy pathogenic microorganisms is dependent on temperature, pH, moisture, and complex chemical/ biological reactions. There is lacking research for the recommended length required, although a minimum of 2 years is used as a rule-of-thumb. • Pits should always be closed and locked when not in use.
	Technological and processing complexity (i.e., maintenance constraints, training requirements and technical expertise)	**Operation:** Low complexity with pre-defined operation parameters (e.g., fixative to waste ratios). Operators should be trained to identify non-compliant feed material, OH&S and record keeping procedures, routine maintenance task and contingency plans (e.g., fires or spills). **Maintenance:** Low complexity required for cement mixers and waste shredders (e.g., replacement of blades, lubrication of moving parts).	Minimal operational and maintenance intervention required. Pits should be constructed to ensure their stability and to prevent excessive water ingress.
	Capital expenditure (i.e., equipment purchase cost, ancillary services and infrastructure/ civil engineering requirements)	Low capital investment required. Dependent on disposal requirements, a waste shredder and concrete mixer can be purchased for under $5,000.	Due to the risk of liquid waste leaching into soil and infiltrating groundwater, the bottom of the pit should be sealed with concrete to slow down ingress of liquids. Walls can remain unsealed, although should be reinforced. Construction can utilise standard concrete rings (1 m diameter) as the top slab, creating a watertight seal to prevent surface water infiltration. The lid should have a lockable hatch and gas vent to prevent pressure build up. It is recommended that two pits are constructed at the same time, to allow the immediate filling of the second after the closure of the first. Total cost estimated between $1,000 to $2,000.

Section	Focus Area	Solid fixation	Placenta pit
	Operational expenditure (i.e., labour, maintenance, replacement parts, utilities, material handling, storage etc.)	Largely dependent on the availability and type of fixative and consumable supplies. Typical mixing proportions for HCW inertisation are: 65% shredded waste, 15% lime, 15% cement and 5% water.	Minimal operational costs to manage and maintain pits. Ash or charcoal can be added to pits to reduce odour.
	Process emissions and by-products	**Solid by-products**: solid fixated waste requires disposal to landfill **Liquid by-products**: risks of hazardous liquid leachates resulting from disposed waste. Landfills should have adequate leachate management to prevent contamination of groundwater or surrounding surface water. **Gas by-products**: potential generation of infectious vapours/ aerosols during waste shredding or mixing with concrete (requires appropriate operator PPE and a well-ventilated operating area).	**Solid by-products:** degraded biological waste (potentially requiring final disposal to landfill). **Liquid by-products:** liquid leachate with the risk of infectious contamination of groundwater. **Gas by-products:** methane and other gases resulting from biological degradation (generation rates expected to be low and not a risk to the environment or human health if appropriately vented).
	Water and electricity consumption	Risk of hazardous leachates formed from fixated wastes. This method of disposal should only be used for small proportions of hazardous chemicals. If bulk hazardous wastes need to be disposed, they should be returned to the manufacturer or taken to a controlled/ sanitary landfill.	Risk of leachate contamination of groundwater. Pit location, design and construction should factor in risks of groundwater infiltration, such as situating pits away from areas with high water tables.
	Risks to environment	The handling and shredding of non-treated infectious/ pathological waste should be avoided. Pathogens can become easily airborne and risks infection. Only entirely enclosed systems with air emission controls should be used to prepare infectious material for disposal. Other OH&S risks must be minimised, such as mechanical moving parts and heavy lifting.	Risk of infection during waste handling/ disposal (requires appropriate transport containers and PPE). If pits are reopened after being sealed and emptied for reuse, enough time must be allowed to ensure full microbial deactivation (e.g., Infection risk during waste handling and when clearing out an aged pit. Odour mitigation strategies (such as distance from public areas and use of ash cover) should also be employed.
	Risks to human health	Largely dependent on the availability and type of fixative and consumable supplies. Typical mixing proportions for HCW inertisation are: 65% shredded waste, 15% lime, 15% cement and 5% water.	Minimal operational costs to manage and maintain pits. Ash or charcoal can be added to pits to reduce odour.
	Benefits to the environmental and human health	Improvement on direct disposal of HCW to landfill, especially in the protection of landfill operators or waste pickers/ scavengers. Fixation and placenta pits also do not generate air emissions comparable to waste incineration.	

5. Timor-Leste Case Study

Timor-Leste was selected as a case study to demonstrate the decision-making processes for HCW treatment technologies presented in Section 2.2. The research outcomes of Section 4 have been used to determine recommendations for Timor-Leste hospitals.

Data regarding specific Timor-Leste hospitals have been sourced from the *Baseline Study for the Pacific Hazardous Waste Management Project - Healthcare Waste* (2014) prepared by ENVIRON Australia Pty Ltd for SPREP.

There are two limitations for this case study:

1. Only data from 2014 (or earlier) was available, therefore recommendations may not accurately reflect current hospital operations; and
2. Specific waste audit results for each of Timor-Leste healthcare facilities were not available.

Infectious waste generation rates have been estimated based on the hospital size and bed occupancy rates, although a dedicated waste audit would be required to validate this estimate and provide more clarity of the composition of waste generated.

These recommendations are not expected to be proscriptive or absolute as multiple technology options would be appropriate in each of the contexts presented.

Table 13 presents the outcomes of the Timor-Leste case study. Separate recommendations for HCW treatment have been made for each of the five major hospitals. An additional option has been presented for a consolidated regional treatment plant, capable of accepting HCW from multiple hospital/clinical sources.

There are a range of considerations made in the comparison of the two approaches, such as:

- Transport and handling logistics (distance, service providers, etc.)
- Regulatory/ legal requirements for transporting hazardous materials
- Cost-benefits and financial considerations
- Facility planning and capacities
- Maintenance and operation capacity
- Environmental and health impacts (e.g., risk of exposure and greenhouse gas emission)
- Public acceptance

A consolidated approach to HCW management takes pressure off individual hospitals and clinics, although requires more care regarding logistic requirements (transportation, dedicated staff, treated waste disposal etc.).

Table 13 Timor-Leste HCW treatment technology selection – case study

	Criteria	Guido Valadares National Hospital (Dili)	Baucau Referral Hospital	Maliana Referral Hospital	Suai Referral Hospital	Maubisse Referral Hospital	Consolidated Timor-Leste Treatment Facility
Background considerations	**Legal/ policy considerations**	There is no specific legislation or guidelines relating to healthcare waste management enforced nationally in Timor-Leste					
	Available space	Limited urban space concentrated by surrounding residential and commercial buildings. No dedicated storage facility.	Room for site expansion/ additional buildings.	Approximately 50% of hospital footprint currently utilised (room for expansion/ additional buildings).	Room for site expansion/ additional buildings. Caged area used to stockpile waste and sharps.	Room for site expansion/ additional buildings.	Not limited by footprint.
	Budget for capital, operational and maintenance costs	Budgets have not been estimated as part of the current project, as national financing or donor support is expected to aid the procurement and operation of HCW treatment technology. Currently, waste management practices in Timor-Leste are typically underfunded and lack dedicated resourcing.					
	Existing HCW management practices	Incineration (~500 kg/wk) with no formal disposal arrangement for ash. Complaints from neighbours due to fumes.	Open burning (~250 kg/wk). Onsite incinerator not operational.	Incineration (~100 kg/wk) with no formal disposal arrangement for ash.	Stockpiled or dumped off site (~75 kg/wk). Onsite incinerator not operational.	Landfill without treatment (~35 kg/wk). Onsite incinerator not operational.	No national consolidated approach to HCW management in place.
	Prior training	No known training programs in Timor-Leste relating to infection control or HCW management.					
	Operator availability and prior training	Staffing: Infection control - 2 Dedicated waste management - 4	Staffing: Infection control - 1 Dedicated waste management - 50	Staffing: Infection control - 1 Dedicated waste management - 2	Staffing: Infection control - 1 Dedicated waste management - 1	Staffing: Infection control - 1 Dedicated waste management - 20	Unknown
	Existing waste segregation practices	Evidence of correct segregation of waste types (use of colour-coded bins).	No separation of HCW and general waste (all mixed in an onsite dump).	Shortage of colour-coded bins for waste segregation.	Shortage of colour-coded bins for waste segregation.	No separation of HCW and general waste (all mixed in an onsite dump).	Various practices across 6 hospitals, 12 district health centres, 68 community health centres and 205 health posts.
Waste	**Number of Beds**	260	114	45	24	24	467
	Estimated bed occupancy rate	80%	70%	50%	40%	40%	71%
	Infection waste generation rate (kg/day)	144	55	16	7	7	228 (minimum)

	Criteria	Guido Valadares National Hospital (Dili)	Baucau Referral Hospital	Maliana Referral Hospital	Suai Referral Hospital	Maubisse Referral Hospital	Consolidated Timor-Leste Treatment Facility
	Expected waste composition	General hospital and surgical treatment facility waste compositions, including general waste, infectious waste, sharps and pharmaceuticals. Tertiary health care is typically provided overseas in countries such as Australia (WHO, 2017). Hence was originating from specialised services (e.g., chemotherapy/ radiology) are expected to be low.					
Recommendations	**General**	Separation of waste streams should prioritise segregation of infectious/ pathological waste, general waste, sharps and hazardous wastes. Once infectious material has been treated and sharps/ hazardous waste encapsulated, all material should be transported and disposed to a sanitary landfill by a trained waste service provider.					
	Sharps	**Shredding** (refer below)	**Encapsulation**				**Shredding** (refer below)
	Infectious/ pathological	**Advanced autoclave** (with internal shredding) with treatment capacity of 30 kg/hr (assuming 6-hour operation per day)	**Vacuum autoclave** with treatment capacity of 15 kg/hr (assuming 4 to 5-hour operation per day)	**Vacuum autoclave** with treatment capacity of 5 kg/hr (assuming 4 to 5-hour operation per day)	**Batch microwave** with treatment capacity of 5 kg/cycle (assuming 2 to 3 cycles per day).	**Batch microwave** with treatment capacity of 5 kg/cycle (assuming 2 to 3 cycles per day).	**Friction heat** with treatment capacity of 80 kg/hr (assuming 4 to 6-hour operation per day.

6. Conclusions

The complex and variable characteristics of HCW has created a large range of treatment technologies with unique advantages and disadvantages. No singular non-incineration HCW treatment technology can treat all potential wastes or be suited to all potential applications.

As such, facility management should first seek to understand the requirements, constraints, and objectives of implementing improved management practices.

This report has given an overview the approached to HCW treatment, followed by specifications and considerations tailored to deployment in the Pacific region.

These tools are intended to give guidance to PICs and Timor-Leste in the evaluation of non-incineration treatment options.

When considering technology options, it is recommended to:

- Be informed by locally collected data and observations of HCW generation and disposal characteristics (e.g., infection waste);
- Engage with suppliers and market competition in the procurement of treatment technology;
- Secure long term financial arrangements or aid funding which can help achieve high upfront costs.
- Ensure local communities are trained in the operation and maintenance of treatment equipment to decrease on-going operation costs and empower individuals to responsibly manage their wastes;
- Conduct regular testing of treated HCW to ensure consistent disinfection rates; and
- Collaborate with stakeholders across the healthcare sector (hospital management, landfill operators, government representatives, etc.).

Improved HCW management should also consider broader operational changes, such changing procurement practices to decrease waste generation and implementing source separation practices.

The goal of these systems should be to decrease risks to human health and the environment, improve operational efficiency and costs and suit the requirements of the local setting.

7. Glossary

Terminology	Definition
Alkaline hydrolysis	Chemical treatment process that reacts alkali (sodium or potassium hydroxide) with pathological waste in a pressurized, heated container to initiates digestion.
Autoclave	A machine used to carry out waste decontamination processes requiring elevated temperature and pressure.
Batch process system	A processing technique in which a series of process operations are carried out on a singular parcel of feedstock. Process steps are sequential, typically requiring all stages to be completed before a new parcel of feedstock is processed.
Biological treatment	A type of treatment that uses microorganisms to decompose and decontaminate waste.
Carcinogenic	Substances capable of promoting cancer in humans.
Chemical waste	Any solid, liquid, or gaseous waste material that, if improperly managed or disposed of, may pose substantial hazards to human health and the environment.
Chlorinated chemical disinfection	Chemical disinfection treatment that relies on chlorine-based chemicals (e.g., chlorine dioxide and sodium hypochlorite).
Continuous process system	A processing technique in which all processing stages are carried out continuously and the material being processed is not divided into identifiable portions.
Cytotoxic	Chemicals toxic to cells (i.e., mutagenic, teratogenic or carcinogenic).
Decontamination	The process of removing contaminants on an object or area, including chemicals, micro-organisms or radioactive substances.
Dioxins	A class of toxic organic compounds that typically result from the combustion of chlorine containing chemicals. Dioxins are persistent organic pollutants regulated by the Stockholm Convention.
Disinfection	The process of eliminating or reducing harmful microorganisms from inanimate objects and surfaces.
Dry or wet scrubbing	Air pollution control device that either use liquid (wet) or solid (dry) substances to clean flue gases. Scrubbing sprays are chosen to react with contaminants and neutralise pollutants.
Encapsulation	A disposal technique in which waste is entirely encapsulated in a container, which is disposed to landfill in its entirety.
Environmentally Sound Technology	Technologies capable of reducing environmental damage through minimising emissions and enabling recycling/ recovery from process residuals (OECD, 1997)
Friction heat treatment	A waste processing technique that uses high-speed rotos and resistance heaters to simultaneously disinfect and shred waste.
Furans	A class of toxic organic compounds consisting of a five-membered aromatic ring with four carbon atoms and one oxygen atom. Furans are persistent organic pollutants regulated by the Stockholm Convention.
Gasification	A high-temperature processing technique that converts organic material into gases without combustion.
Incineration	A waste destruction technique through burning/ combustion.
Inertisation	A disposal technique in which waste is physically bound within another substance (e.g., cement), also known as solidification.
Infectious/ biohazardous waste	Capable of producing infectious disease.
Irradiation	A waste processing technique in which high energy radiation sterilizes pathogens.
Leachate	Liquid formed due to the breakdown of waste or that has filtered through waste. Typically contains soluble or suspended pollutants.

Terminology	Definition
Microwave treatment	A waste processing technique which relies on high temperatures generated by microwaves to thermally disinfect waste.
Non-chlorinated chemical disinfection	Chemical disinfection treatment that relies on chlorine-based chemicals (e.g., ozone and calcium oxide).
Non-recyclable waste	Free from risks and can be disposed via conventional waste management practices.
Oxidation	A chemical reaction that takes place when a substance comes into contact with oxygen (including combustion).
Pathogens	A bacterium, virus, or other microorganism that can cause disease.
Pathological waste	Subset of infectious waste consisting of recognisable human or animal body parts.
Persistent Organic Pollutants	Toxic organic compounds that are resistant to environmental degradation through chemical, biological, and photolytic processes. Also known as “forever chemicals”.
Pharmaceutical	Expired, unused and contaminated drugs and vaccines.
Placenta	An organ that develops in the uterus during pregnancy.
Promession	A pathological waste disposal technique in which organic material is freeze-dried and pulverised.
Pyrolysis	The process of thermal decomposition of materials at elevated temperatures in an inert atmosphere.
Radioactive	Material contaminated by radionuclides.
Recyclable material	Free from risks and can be recycled through further processing and resource recovery.
Retort	Container or furnace used to carry out a chemical process.
Reverse polymerisation	The reduction of organic material through the application of microwave energy in an oxygen-depleted (nitrogen-rich) atmosphere.
Sharps	Comprising of a point or edge capable of cutting, piercing or penetrating skin.
Steam disinfection	The process of exposing microorganisms to saturated steam to denature/ destroy their cellular structure.
Sterilization	The processes of killing all microorganisms
Stockholm Convention	Multilateral environmental agreement that aims to eliminate or restrict the production and use of persistent organic pollutants.
Volatile and semi-volatile organic compounds	Polycyclic aromatic hydrocarbons that vaporize at room temperature

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Appendix A Selection Criteria

Table 14 Detailed selection criteria of identified HCW technology options

Category	Technology Option	Development stage	Alignment with waste hierarchy	Expertise required to operate the technology	Potential for operation to require regulatory control	Status as an Environmentally Sound Technology	Potential risk residual to human health and the environment
Medium/ High Heat Treatment	Reverse polymerization (high-intensity microwave)	**Commercial** Limited suppliers	**Energy Recovery** Potential co-application for resource recovery from other waste streams (e.g., tyres) with higher yields/ product quality than conventional pyrolysis.	**Advanced** Requires computer-aided process control to achieve the optimal processing temperature, O2/N2 ratios, energy input and processing times. Technicians are required to service high-powered microwave components. Pre-shredding and conveyors require continual maintenance.	**Low risk** Systems typically fitted with microturbines for electricity generation and/or flue gas scrubbing. Commercial technologies can be shown to meet local and international air quality control requirements.	**EST Demonstrated** More environmentally friendly than incineration due to lower by-product formation (e.g., dioxins and furans)	**3C - Major/ Remote** High energy and high temperature operation poses risks to process operators. The generation of flammable products can create uncontrolled fire risks or environmental damage. System controls and alarms can mitigate risks. Requires handling of chars (with heavy metal concentrate)
	Gasification	**Commercial** Limited suppliers	**Energy Recovery** Higher energy efficiency than incineration with potential co-application with other waste streams.	**Advanced** Typically requires computer-aided process controls to achieve optimal processing parameters. Feeds are more sensitive to non-homogenous waste streams when compared to incineration, requiring additional operator knowledge and control. Technicians are required to service processing, flue gas treatment and energy recovery equipment.	**Medium risk** Scientific studies have demonstrated the potential generation of POPs from gasification - chemicals which are regulated by the Stockholm Convention	**EST Demonstrated** More environmentally friendly than incineration due to lower by-product formation, although plastic fuels risk generation of POPs. Requires high treatment temperatures and gas scrubbing**.**	**3B - Hazardous/ Remote** High-temperature operation poses risk of fires/ explosions. Higher generation of char/ ash/ slag containing heavy metals poses health risks to operators. Risk of poor performance in gas capture releasing atmospheric pollutants.

Category	Technology Option	Development stage	Alignment with waste hierarchy	Expertise required to operate the technology	Potential for operation to require regulatory control	Status as an Environmentally Sound Technology	Potential risk residual to human health and the environment
Low Heat Treatment	Pyrolysis	**Commercial** Limited suppliers	**Energy Recovery** Higher energy efficiency than incineration with potential co-application with other waste streams.	**Advanced** Typically requires sophisticated systems (e.g., plasma burners) to generate temperatures required to achieve pyrolysis reaction. Highly technical operation and maintenance requirements.	**Medium risk** Usually fall under similar regulation to incineration systems.	**EST Demonstrated** Almost impossible to completely prevent oxygen in reaction chamber, resulting in the generation of dioxin/ furans/ by-products that need to be captured. Tests have shown these to be at acceptable levels	**3B - Hazardous/ Remote** High-temperature operation poses risk of fires/ explosions. Risk of poor performance in gas capture releasing atmospheric pollutants.
	Dry heat/ hot air disinfection	**Commercial** Limited suppliers	**Treatment (potential recycling)** Treated wastes typically disposed, although potential for resource recovery**.**	**Minimal** Low level of technical expertise required to operate most systems (1 operator required - clearly defined operating parameters). Low maintenance requirements.	**Low risk** Hot air treatment is an accepted technology in most countries.	**EST Demonstrated** Proven technology for similar laboratory/ clinical disinfection systems. Low odour generation although require higher temperatures and longer exposure times compared to wet heat systems.	**2D - Minor/ Improbable** High temperature/ pressure systems risk harm to operators.
	Wet heat/ steam disinfection	**Commercial** Suppliers available in Pacific Region	**Treatment (potential recycling)** Treated wastes typically disposed, although potential for resource recovery**.**	**Minimal** Low level of technical expertise required to operate most systems (1 operator required - clearly defined operating parameters). More advanced systems can utilise computer aided process controls.	**Low risk** Steam treatment is an accepted HCW treatment technology in most countries.	**EST Demonstrated** Low by-product formation, moderate energy and water requirements and proven track record contribute to EST status. May require controlled release or treatment of wastewaters**.**	**2C - Major/ Improbable** High temperature/ pressure systems risk harm to operators. Wastewaters risk contamination of local waterways. Risk of odours/ local air quality issues that may require gas capture.
	Friction heat treatment	**Commercial** Limited suppliers	**Treatment (potential recycling)** Treated wastes typically disposed, although potential for resource recovery**.**	**Moderate** Microwave systems typically have internal moving parts requiring continual maintenance	**Low risk** Low by-product generation and simplicity of technology represent low regulatory risk.	**EST Demonstrated** Systems require the capture and treatment of vapours/ steam/ wastewater released from the system.	**2D - Minor/ Improbable** High heat systems have a risk to operator health.

Category	Technology Option	Development stage	Alignment with waste hierarchy	Expertise required to operate the technology	Potential for operation to require regulatory control	Status as an Environmentally Sound Technology	Potential risk residual to human health and the environment
Chemical	Microwave disinfection	**Commercial** International suppliers capable of delivering to Pacific Region	**Treatment (potential recycling)** Treated wastes typically disposed, although potential for resource recovery.	**Moderate** Microwave systems typically have more moving parts and equipment compared to other low heat treatment systems. Requires 1 operator with some technical expertise.	**Low risk** Microwave treatment is an accepted HCW treatment technology in most countries.	**EST Demonstrated** Low by-product formation, moderate energy and water requirements and proven track record contribute to EST status. May require controlled release or treatment of wastewaters.	**2C - Major/ Improbable** High temperature/ pressure systems risk harm to operators. Wastewaters risk contamination of local waterways. Risk of odours/ local air quality issues that may require gas capture.
	Chemical disinfection (chlorinated)	**Commercial** International suppliers capable of delivering to Pacific Region	**Treatment/ Disposal** Treated wastes are disposed with few opportunities for resource recovery.	**Minimal** Low level of technical expertise required to operate most systems. Clearly defined operating parameters: dosing, contact time, pre-treatment and operating conditions.	**High risk** Potential for regulation under local and international laws due to chlorine pollution to air and water.	**EST Not Demonstrated** Environmental concerns related to the release of chlorine-containing wastewaters. Requires capture and treatment of process air emissions.	**4B - Hazardous/ Occasional** Risk of operator/ environmental exposure to hazardous toxic chemicals during operation, handling or storage. Treated material requires disposal, risking further hazard exposure.
	Chemical disinfection (non-chlorinated)	**Commercial** Some sub-category suppliers available in Pacific Region (e.g., alkaline hydrolysis)	**Treatment/ Disposal** Treated wastes are disposed with few opportunities for resource recovery.	**Minimal** Low level of technical expertise required to operate most systems. More advanced alkaline hydrolysis processing requires technical knowledge of dosing and conditioning time.	**Medium risk** Dependent on the type of chemical disinfectant chosen - potential air and water quality regulation.	**Potential EST** Dependent on the type of chemical disinfectant chosen and the handling/ final disposal of treated wastes.	**4C - Major/ Occasional** Chemical disinfectants are often hazardous and toxic, harmful to tissue and mucous membranes and cause harm to the environment.
Other	Solid fixation	**Commercial** Can be developed using on-island resources	**Disposal** No potential for resource recovery.	**Minimal** Very low technical expertise required.	**Medium risk** Potential to conflict with laws regulating disposal to landfills	**EST Not Demonstrated** Environmental concerns related to leaching of toxic/ hazardous liquids from encapsulated or inertized waste	**4C - Major/ Occasional** Risk of scavengers gaining access to encapsulated material. Risk of hazardous leachates.

Category	Technology Option	Development stage	Alignment with waste hierarchy	Expertise required to operate the technology	Potential for operation to require regulatory control	Status as an Environmentally Sound Technology	Potential risk residual to human health and the environment
	Irradiation treatment	**Development** Very limited commercial suppliers specific to waste treatment	**Treatment (potential recycling)** Treated wastes typically disposed, although potential for resource recovery**.**	**Advanced** Highly advanced radiation technology - requires high level of technical knowledge and fixed processing units.	**Low risk** Similar technology often utilised in other treatment applications (e.g., water treatment). Low environmental regulatory requirements.	**EST Demonstrated** Technology proven in similar (non-HCW) applications to produce low environmental risks (small amounts of ozone created)**.**	**5D - Minor/ Frequent** Residual radiation from treatment system requires strict OHS controls and guards to protect operator health.
	Promession	**Development** Very limited commercial suppliers available	**Treatment/ Disposal** Treated wastes are disposed with few opportunities for resource recovery.	**Moderate** Requires handling of cryogenic substances and maintenance of mechanical vibration equipment.	**Medium risk** Emerging nature of the technology lacking common place in regulatory frameworks.	**Potential EST** Lack of operational facilities mean its status as an EST is yet to be determined	**3C - Major/ Remote** Low temperatures and mechanical equipment represent a risk to operator safety
	Placenta pit	**Commercial** Can be developed using on-island resources	**Disposal** No potential for resource recovery	**Minimal** Very little active management.	**Medium risk** Risk of environmental regulation of open pits and risk of cultural taboo.	**Potential EST** Largely dependent on the construction and operation of facilities due to hazardous leachate risks.	**2C - Major/ Improbable** Risk of environmental contamination due to leaks/ leaching from containers.

Appendix B Risk Matrix

Table 15 Technology risk matrix

Risk probability	Risk Severity				
	Catastrophic A	Hazardous B	Major C	Minor D	Negligible E
Frequent 5	5A	5B	5C	5D	5E
Occasional 4	4A	4B	4C	4D	4E
Remote 3	3A	3B	3C	3D	3E
Improbable 2	2A	2B	2C	2D	2E
Extremely Improbable 1	1A	1B	1C	1D	1E

Table 16 Risk severity definitions

Severity	Health	Environment	Financial
Catastrophic	Death/ permanent total disability	Irreversible significant damage	Loss equal or excess of $10M
Hazardous	Permanent partial disability/ injuries/ illness that may result in hospitalisation of at least 5 people	Irreversible moderate damage	Loss equal or excess of $1M, less than $10M
Major	Permanent partial disability/ injuries/ illness that may result in hospitalisation of at least 1 people	Reversible significant damage	Loss equal or excess of $100k, less than $1M
Minor	Injury or illness resulting in one or more lost workdays	Reversible moderate damage	Loss equal or excess of $10k, less than $100k
Negligible	Injury or illness not resulting in a loss of workdays	Minimal damage	Loss less than $10k

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