Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.
Hydrothermal deconstruction of single-use personal protective equipment: process design and economic performance

Xing Xin a, Faisal Javid a, William A. Anderson b, José G.B. Derraik c, Trudy Sullivan d, Yvonne C. Anderson e, f, Saeid Baroutian a, *

a Department of Chemical and Materials Engineering, The University of Auckland, Auckland, New Zealand
b Department of Chemical Engineering, University of Waterloo, Waterloo, Canada
c Department of Paediatrics: Child & Youth Health, Faculty of Medical and Health Sciences, University of Auckland, Auckland, New Zealand
d Department of Preventive and Social Medicine, University of Otago, Dunedin, New Zealand
e enAble Institute, Faculty of Health Sciences, Curtin University, Bentley, WA, Australia
f Telethon Kids Institute, Perth Children’s Hospital, Nedlands, WA, Australia

ARTICLE INFO

Keywords:
Hydrothermal deconstruction
COVID-19
Process modelling
PPE
Wet oxidation

ABSTRACT

Increased demand for single-use personal protective equipment (PPE) during the COVID-19 pandemic has resulted in a marked increase in the amount of PPE waste and associated environmental pollution. Developing efficient and environmentally safe technologies to manage and dispose of this PPE waste stream is imperative. We designed and evaluated a hydrothermal deconstruction technology to reduce PPE waste by up to 99% in weight. Hydrothermal deconstruction of single-use PPE waste was modelled using experimental data in Aspen Plus. Techno-economic and sensitivity analyses were conducted, and the results showed that plant scale, plant lifetime, discount rate, and labour costs were the key factors affecting overall processing costs. For a 200 kg/batch plant under optimal conditions, the cost of processing PPE waste was found to be 10 NZD/kg (6 USD/kg), which is comparable to the conventional practice of autoclaving followed by landfilling. The potential environmental impacts of this process were found to be negligible; meanwhile, this practice significantly reduced the use of limited landfill space.

1. Introduction

Personal protective equipment (PPE) are items used to counter infectious, toxic, contagious, electrical, and radiological exposure (Mahmood et al., 2020). Amidst the ongoing global COVID-19 pandemic, in healthcare facilities and domestic households, PPE such as gloves, goggles, isolation gowns, surgical masks, face shields, and filtering facepiece respirators (FFRs) have been commonly used (Islam et al., 2020). Moreover, governments worldwide have imposed stringent policies for the mandatory use of PPE items, contributing to a marked increase in PPE used and subsequently disposed of (Prata et al., 2020). This PPE waste stream poses a threat to terrestrial and aquatic environments, making its disposal problematic for global waste management organisations (Wang et al., 2021). Globally, studies have already reported widespread occurrence of various types of PPE across aquatic bodies and landforms (Fadare and Okoffo, 2020; Rakib et al., 2021).

Single-use PPE are primarily comprised of synthetic plastic polymers and rubbers, including polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), polystyrene (PS), polyurethane (PUR), nitrile butadiene rubber (NBR), polyisoprene (IR), latex (cis-1,4-polyisoprene), and spandex. Not only are these plastics produced from non-renewable petroleum-based chemicals, they also offer high durability against physical or chemical degradation (Cherubini et al., 2009). Polyolefins such as PE and PP (widely used in PPE materials) are chemically stable while also flexible and resistant to weathering degradation (Ammala et al., 2011). Plastic additives such as phthalates, bisphenol A and S, tetramethylthiuram disulfide, and polychlorinated diphenyl ethers have often been linked to immunotoxicity, obesity, breast cancer, insulin resistance, diabetes, metabolic disorders, and endocrine disruption in humans and various other organisms (Giuilivio et al., 2016; Godswill and Godspel, 2019). These compounds are widely incorporated into PPE plastics to extend their shelf-life, slowing down their rate of biodegradation.

Solid waste management techniques to treat PPE waste currently
considered a sustainable method in many regions (Li et al., 2022).

Hazardous emissions such as particulate matter and unintentionally
mass composition of PPE waste and the properties of PPE materials assumed as unconventional components in Aspen Plus model. 

Fully sterilises the contaminated PPE, there is minimal change in waste incineration. However, even though autoclaving of PPE waste success-
fuly sterilises the contaminated PPE, there is minimal change in waste volume, so the influx of waste at landfill disposal sites is not reduced (Thind et al., 2021). Furthermore, landfill disposal of PPE waste may result in marine and land contamination (Kutralam-Muniasamy et al., 2022). Due to the pandemic surge in waste volume and reduced avail-
ability of landfill sites, disposing of PPE waste in landfills is no longer considered a sustainable method in many regions (Li et al., 2022).

Hydrothermal deconstruction, also referred to as wet oxidation, is a thermochemical technique that disintegrates and reduces complex organic waste material, including PPE waste, that is environmentally safe (Anthraper et al., 2018). Hydrothermal deconstruction targets the oxidation of complex organic molecules to form short-chained carboxylic acids under high temperature (150–350 °C) and pressure (20–175 bar) conditions, resulting in waste reduction and solubilisation (Javid et al., 2021a, 2021b). Contrary to existing waste management technol-
ologies, hydrothermal deconstruction is a ‘green’ technology that is readily scalable and cost-efficient and does not emit hazardous gaseous emissions, including persistent organic pollutants or dioxins, nitrogen oxides (NOx) and mercurial emissions (Anthraper et al., 2018). Addi-
tionally, hydrothermal deconstruction of organic waste can generate valuable buy-products, such as volatile fatty acids (predominantly acetic acid and ammonia-nitrogen), which can be re-utilised. The excellent performance of this technology (solid reduction > 85%) has been re-
ported in the treatment of municipal sludge (Baroutian et al., 2015) and pharmaceutical waste (Javid et al., 2022). The reaction kinetics that occur under hydrothermal deconstruction are complex and poorly characterised. Previous studies on sludge classified the reaction pathway into three stages: insoluble organic content being solubilised through hydrolytic depolymerisation; oxidative reactions converting these hy-
drolysis products into small molecules such as acetic acid, formic acid, acetone and ash; finally, these products being further oxidised to CO2, water and other gases (Prince-Pike et al., 2015).

In this study, we designed a hydrothermal deconstruction process as an alternative to autoclaving and landfilling single-use PPE waste. To the best of our knowledge, this is the first study to focus on the economic aspects of the hydrothermal deconstruction of PPE waste. The process design and economic analyses were conducted using Aspen Plus soft-
ware for process simulation with validation based on experimental data. An environmental impact assessment was also carried out to examine the potential environmental impacts of this process. This research can provide valuable insights and assist in the design and scale-up of hy-
drothermal deconstruction of PPE waste.

2. Methodology

2.1. Quantification and composition of single-use PPE waste

In order to gain an understanding of the types and quantity of single-
use PPE waste generated in hospitals, PPE waste was collected (3 April 2020 – 30 June 2020) from Taranaki Base Hospital (New Plymouth, New

| Waste type            | Amount, item | Weight, kg |
|-----------------------|--------------|------------|
| PPE                   |              |            |
| Gowns                 |              |            |
| Level 2 isolation gowns (2H3XLY) | 1707 | 161 |
| Level 2 isolation gowns (2F3XLB) | 1332 | 229 |
| No-cuff gowns         | 2349         | 247        |
| Ultracold gowns       | 14           | 2          |
| Coveralls full suit isolation gown | 1 | 0.2 |
| Masks and other face coverings | | |
| Level 2 surgical masks (RHS919B) | 323 | 1 |
| Level 2 surgical masks (A-5001) | 1293 | 4 |
| Filtering facepiece respirators (1860S) | 96 | 1 |
| Filtering facepiece respirators (9320 A-) | 10 | 0.1 |
| Filtering facepiece respirators (1870 -+) | 2144 | 19 |
| Face masks with eye shield | 60 | 1 |
| Face masks without eye shield | 13 | 0.1 |
| Face shields          | 445          | 14         |
| Goggles               | 35           | 2          |
| Gloves                |              |            |
| Latex gloves          | 619          | 3          |
| Head coverings        |              |            |
| Haircaps              | 60           | 9          |
| Non-PPE               |              |            |
| Paper tissues         | 162          | 0.03       |
| Cloth wipes           | 179          | 1          |
| Hazard Bags           | 44           | 0.4        |
| Total                 | 10,886       | 694.8      |

comprise incineration and autoclaving followed by landfiling. Although incineration can effectively disinfect and reduce PPE waste, it results in significant carbonaceous emissions (1074 kg CO2e/t) and also generates hazardous emissions such as particulate matter and unintentionally produces persistent organic pollutants (Ma et al., 2020). Due to these toxic emissions, New Zealand has restricted medical waste incineration under the Resource Management Act 1991 (Smith and Lopipero, 2001). Autoclaving to de-contaminate PPE waste followed by landfill disposal is a comparatively better waste management technique compared to incineration. However, even though autoclaving of PPE waste success-

- References of material properties
  - (Rana et al., 2012)
  - (Annah et al., 2016)
  - (Vitchuli et al., 2013)
  - (Chen et al., 2021)
  - (Roy et al., 1997)
  - (Zakaria et al., 2011)
  - (Yang et al., 2016)
  - (Annah et al., 2016)
defined as nonconventional solid components in Aspen Plus in terms of composition was used in the Aspen Plus modelling to define the input a weight basis (Table S1 in Supplementary data). The overall mass stream of PPE waste. Table 2 also shows the properties of PPE materials dismantled into pieces, and the material compositions were obtained on separation, solid and liquid separation, and water recycling. Table 3 also outlines the summary of the main equipment units and assumptions in each stage. The design’s processing conditions, including reaction time, temperature and pressure, were based on the experimental results (Table S2 in Supplemental data) using a lab-scale hydrothermal reactor (Javid et al., 2022). The PPE waste was shredded to reduce all material, the individual fragments approximately 1 cm across, before being loaded into the hydrothermal reactor. The key stage, hydrothermal deconstruction, was a batch operation including the steps of preheating, reaction, and cooling. A batch reactor was chosen for this study due to its easy operation and low cost for high-pressure reactions (Sawai et al., 2014).

After the reaction, the outlet stream at a subcritical condition (300 °C and 100 bar) needs to be cooled down. Heat recovery is frequently employed to decrease energy consumption and processing costs for industrial plants (Saari et al., 2016). As shown in Fig. 1, a multi-stage shell and tube heat exchanger and a heat storage tank were employed for heat recovery. This design recovers heat from the outlet stream of the reactor, and the thermal energy is stored in a high-pressure tank for the next batch. Because wet oxidation is an exothermic process, after starting up and increasing the reaction temperature to 300 °C, the reactor will be adiabatic and can self-sustain the operation with no auxiliary heat. This study proposed basic parameters for the multi-stage shell and tube heat exchanger and heat storage. A detailed calculation shall be conducted to determine the stage number of heat exchange at the plant construction stage. Heat loss in the heat exchanger and storage is ignored as compensation for the heat generated in wet oxidation. It should be mentioned that the process design in Fig. 1 is a preliminary study, and details of equipment and pipelines in each step are not considered.

Liquid and gas separation occurred in a flash drum at 40 °C and 1 bar, then gas products were discharged. The remaining solids were separated by a mechanical filter and transported to a landfill. The liquid after solid separation was stored in a reservoir before being pumped back into the hydrothermal reactor for the next batch. It was assumed 0.1 wt% of water was lost due to evaporation with the off-gas.

The operation procedure for each batch can be described in five steps: (1) PPE waste is shredded and loaded in the reactor; (2) subcritical water (285 °C, 100 bar) and pressurised oxygen (20 °C/100 bar) are injected into the reactor; (3) reaction temperature is gradually elevated and maintained at 300 °C for 90 min, because the reaction is exothermic (Slavik et al., 2015); (4) the outlet stream from the reactor flows through the multi-stage heat exchanger and the temperature decreases to 40 °C; meanwhile water from the reservoir flows through the heat exchanger to a heat storage tank, and the temperature increases to 285 °C; and (5) the cooled outlet stream of the reactor flows through a flash tank and filter to separate gas and solid, respectively.

| Processing stage          | Main equipment                                      | Assumptions in Aspen modelling |
|---------------------------|-----------------------------------------------------|--------------------------------|
| Size reduction            | Shredder                                            | PPE materials were reduced to |
|                           |                                                     | fragments ~1 cm across         |
| Hydrothermal deconstruction| High-pressure reaction vessel                       | Yield reactor was used to     |
|                           |                                                     | simulate the reaction at 300 °C|
|                           |                                                     | and 100 bar                    |
| Heat exchange             | Multi-stage shell and tube heat exchanger           | Temperature of heat            |
|                           |                                                     | exchanger outlet stream was    |
|                           |                                                     | set at 40 °C                   |
| Liquid and gas separation | Flash drum                                           | Two-phase flash drum was set   |
|                           |                                                     | at 40 °C and 1 bar, gas        |
|                           |                                                     | products were discharged       |
| Solid and liquid separation| Mechanical filter                                   | Solid separation rate was set  |
| Water recycling           | Water reservoir and pump                            | at 100 wt%                     |

2.2. Process description

The entire process included six stages as shown in Table 3: size reduction, hydrothermal deconstruction, heat exchange, liquid and gas separation, solid and liquid separation, and water recycling. Table 3 also outlines the summary of the main equipment units and assumptions in each stage. The design’s processing conditions, including reaction time, temperature and pressure, were based on the experimental results (Table S2 in Supplemental data) using a lab-scale hydrothermal reactor (Javid et al., 2022). The PPE waste was shredded to reduce all material, the individual fragments approximately 1 cm across, before being loaded into the hydrothermal reactor. The key stage, hydrothermal deconstruction, was a batch operation including the steps of preheating, reaction, and cooling. A batch reactor was chosen for this study due to its easy operation and low cost for high-pressure reactions (Sawai et al., 2014).

After the reaction, the outlet stream at a subcritical condition (300 °C and 100 bar) needs to be cooled down. Heat recovery is frequently employed to decrease energy consumption and processing costs for industrial plants (Saari et al., 2016). As shown in Fig. 1, a multi-stage shell and tube heat exchanger and a heat storage tank were employed for heat recovery. This design recovers heat from the outlet stream of the reactor, and the thermal energy is stored in a high-pressure tank for the next batch. Because wet oxidation is an exothermic process, after starting up and increasing the reaction temperature to 300 °C, the reactor will be adiabatic and can self-sustain the operation with no auxiliary heat. This study proposed basic parameters for the multi-stage shell and tube heat exchanger and heat storage. A detailed calculation shall be conducted to determine the stage number of heat exchange at the plant construction stage. Heat loss in the heat exchanger and storage is ignored as compensation for the heat generated in wet oxidation. It should be mentioned that the process design in Fig. 1 is a preliminary study, and details of equipment and pipelines in each step are not considered.

Liquid and gas separation occurred in a flash drum at 40 °C and 1 bar, then gas products were discharged. The remaining solids were separated by a mechanical filter and transported to a landfill. The liquid after solid separation was stored in a reservoir before being pumped back into the hydrothermal reactor for the next batch. It was assumed 0.1 wt% of water was lost due to evaporation with the off-gas.

The operation procedure for each batch can be described in five steps: (1) PPE waste is shredded and loaded in the reactor; (2) subcritical water (285 °C, 100 bar) and pressurised oxygen (20 °C/100 bar) are injected into the reactor; (3) reaction temperature is gradually elevated and maintained at 300 °C for 90 min, because the reaction is exothermic (Slavik et al., 2015); (4) the outlet stream from the reactor flows through the multi-stage heat exchanger and the temperature decreases to 40 °C; meanwhile water from the reservoir flows through the heat exchanger to a heat storage tank, and the temperature increases to 285 °C; and (5) the cooled outlet stream of the reactor flows through a flash tank and filter to separate gas and solid, respectively.

![Fig. 1. Preliminary process design for the hydrothermal deconstruction of PPE waste using oxygen as oxidiser.](image-url)
were obtained from the experimental data (Table S2 in Supplementary data). The COD value (Chemical Oxygen Demand) of the outlet stream of hydrothermal deconstruction reactor was simulated to be 4805 mg/L in 2022. This study also modelled PPE waste as a non-conventional solid, should be noted that PR-BM and NRTL models are commonly used to model biopolymers as non-conventional solids in Aspen Plus (Shi et al., 2022). This study also modelled PPE waste as a non-conventional solid, but the model was focused on simulating the physical properties and phase behaviour of the produced chemical mixtures.

Model compounds and their mass distribution as shown in Table 4 were obtained from the experimental data (Table S2 in Supplementary data). The COD value (Chemical Oxygen Demand) of the outlet stream of hydrothermal deconstruction reactor was simulated to be 4805 mg/L in the Aspen model. In comparison, the experimental validation showed a value of 5193 mg/L, indicating a good agreement between the Aspen model and experiments.

In order to dispose of the PPE waste collected, reactor capacity was assumed to be 5 kg/batch. The annual throughput was estimated at 3650 kg of PPE waste based on 2 batches per day (equivalent to 730 batches per year). The processing time was assumed to be 4 h for each batch, including preparation, operation, cleaning, and maintenance.

Four scenarios were constructed to compare the economic performance. Scenario 1 uses a reactor that is a scaled-up version of the laboratory set-up. Pure oxygen is used, and unconsumed oxygen after the reaction is discharged with the gaseous products. Scenario 2 has a heat exchanger and a heat storage tank for heat recovery, as illustrated in Fig. 1. Scenario 3 implements heat recovery and oxygen reuse. It is assumed the long-time reaction (90 min) in this study is thermodynamically controlled, therefore, the amount of oxygen is sufficient for 6 cycles (El-Shafey et al., 2012). A gas compressor and gas tank are employed for oxygen reuse. Scenario 4 employs heat recovery and air as the oxidant gas. The experimental results (Table S2 in Supplementary data) verified that replacing oxygen gas with air can achieve the same level of solids reduction at a working pressure of 125 bar and 300 °C. Scenario 4 uses an air compressor to supply pressurised air to the reactor.

### 2.4. Economic analysis

An economic analysis was undertaken that included estimates for total capital investment (TCI) costs, operating expenses (OPEX), and processing costs, with sensitivity analyses performed on key variables. This method was used for the hydrothermal deconstruction process and also for autoclaving followed by landfill disposal (conventional method).

Table 5 shows the assumptions used to analyse the economic performance of a chemical process plant. As shown, TCI comprises fixed capital investment (FCI) – which includes direct and indirect costs based on total purchased equipment (TPE) costs – and working capital (WC). The TPE percentages for the direct and indirect costs were estimated using the Aspen Process Economic Analyzer or from the vendor quotation by Eq. (1). TPE is the sum of total purchased equipment cost by Eq. (2).

\[
C_i = C_0 \times \left( \frac{S_i}{S_0} \right)^n
\]  
(1)

\[
TPE = \sum_{i=1}^{n} C_i
\]  
(2)

where \(C_i\) was the estimated cost of new equipment with \(S_i\) capacity, \(C_0\) was the cost of initial equipment with \(S_0\) capacity, and \(n\) was the scaling factor, which was set as 0.66 for fluid-solid equipment (Peters et al., 1968). TPE was the cost of total purchased equipment, \(T\) was the number of purchased equipment.

OPEX for a chemical process plant typically includes land use, maintenance, utilities (electricity and cooling water), and labour. Other costs considered in this study were the transportation of clinical waste from hospital to the plant, oxygen gas, and landfilling fees of solid residues. The Aspen Plus model was used to estimate utility and oxygen consumption. The breakdown details of FCI and OPEX for the four scenarios illustrated in Fig. 1 are provided in Table S3 and Table S4 in Supplementary data.

Annual techno-economic assessment was used to estimate the processing cost expressed as NZD per processed PPE waste (Fivga and Dimitriou, 2018). The annualised TCI was calculated by Equation (3), assuming to be borrowed and repaid over the plant’s lifetime at the specified loan interest rate. The processing cost was calculated using Eq. (4). A sensitivity analysis was conducted to investigate the influence of

### Table 4

Product distribution of hydrothermal deconstruction in Aspen model.

| Model compounds     | Distribution, wt% |
|---------------------|-------------------|
| Reaction water      | 13.83             |
| Acetic acid         | 6.15              |
| Propionic acid      | 0.04              |
| Ammonia             | 0.01              |
| Carbon monoxide     | 7.16              |
| Carbon dioxide      | 72.09             |
| Hydrogen            | 0.51              |
| Solid residue       | 0.21              |

### Table 5

Assumptions used to analyse the economic performance of a chemical process plant.

| Assumption                              | Value                      |
|-----------------------------------------|----------------------------|
| Basic assumptions                       |                            |
| Plant lifetime                          | 15 years                   |
| Annual plant operating time             | 2920 h                     |
| Plant operator                          | 2                          |
| Discount rate                           | 10%                        |
| Inflation rate                          | 2%                         |
| NZD - USD exchange rate (2021)          | 0.65                       |
| Total capital investment (TCI)          | FCI + WC                   |
| Fixed capital investment                | Direct cost + Indirect cost|
| Direct cost                             | TPE                        |
| Purchased equipment installation        | 39% of TPE                 |
| Instrument and controls                 | 26% of TPE                 |
| Piping                                  | 31% of TPE                 |
| Electrical system                       | 10% of TPE                 |
| Buildings                                | 29% of TPE                 |
| Yards improvement                       | 12% of TPE                 |
| Service facility                        | 55% of TPE                 |
| Indirect cost                           | 32% of TPE                 |
| Engineering and supervision             | 34% of TPE                 |
| Construction expenses                   | 4% of TPE                  |
| Legal expenses                          | 19% of TPE                 |
| Contractors’ fee                        | 37% of TPE                 |
| Contingency                             | 15% of FCI                 |
| Working capital                         |                            |
| Operating expenses                      |                            |
| Land use                                | 5% of TCI                  |
| Maintenance                             | 5% of FCI                  |
| Electricity price                       | 0.31 NZD/kWh               |
| Cooling water price                     | 4.79 NZD/T                 |
| Oxygen price                            | 56.23 NZD/kg               |
| Transport of clinical waste price       | 3.89 NZD/kg                |
| Landfill of general waste price         | 2.09 NZD/kg                |
| Labour price                            | 45.15 NZD/h                |

* TCI - total capital investment; OPEX - operating expenses; FCI - fixed capital investment; TPE - total purchased equipment; WC - working capital; WC - working capital.
operating expenses on the processing cost.

\[ ATCI = TCI \times r \times (1 + r)^N \frac{1}{(1 + r)^N - 1} \]  

\[ \text{Processing cost} = \frac{ATCI + \text{Annual operating costs}}{\text{Annual processed PPE waste}} \]  

where \( ATCI \) is the annualised \( TCI \), \( r \) is the discount rate, and \( N \) is the lifetime of the plant.

2.5. Environmental impacts analysis

The potential environmental impacts (PEI) of the PPE deconstruction process were assessed using the Waste Reduction Algorithm developed by the US Environmental Protection Agency (Young and Cabezas, 1999). The Waste Reduction Algorithm is a quantification model considering eight potential environmental impacts: human toxicity by ingestion (HTPI), human toxicity by inhalation/dermal exposure (HTPE), terrestrial toxicity potential (TTP), aquatic toxicity potential (ATP), global warming potential (GWP), ozone depletion potential (ODP), photochemical oxidation potential (PCOP), and acidification potential (AP). The potential environmental impacts (PEI) index of a system (\( I \)) is described by Eq. (5):

\[ I = \sum_i \alpha_i I_i = \sum_i \alpha_i \sum_j M_j \sum_k x_{k,j} \phi_{k,i} \]  

where \( I_i \) is the PEI index associated with environmental impact category \( i \), \( \alpha_i \) is the weighting factor for the category \( i \), \( M_j \) is the mass flow rate of stream \( j \), \( x_{k,j} \) is the mass fraction of component \( k \) in stream \( j \), and \( \phi_{k,i} \) is the specific PEI of component \( k \) associated with environmental impact category \( i \). This algorithm is a convenient tool for design engineers to evaluate the environmental friendliness of a chemical process at an early design stage (Young and Cabezas, 1999).

The system boundary for the hydrothermal deconstruction plant was designated with a dashed line, as shown in Fig. 2. The PEI indexes in this study were calculated on a processing basis, PEI/kg of processed PPE waste. A system with lower PEI index values represents a more environmentally desirable process. Approaches to decreasing the PEI index values are discussed in this study.

3. Results and discussion

3.1. Energy and mass balance

This study used four scenarios to compare economic performance, as
shown in Fig. 3. Scenario 1 in Fig. 3(A) uses a reactor that is a scaled-up version of the laboratory set-up. It consumes 118 kWh of electricity and make-up water (1 L) is required due to the evaporation loss. Excess oxygen (72 kg) is used in one batch, and un consumed oxygen is discharged with the gaseous products. Fig. 3(B) illustrates scenario 2 with heat recovery to achieve self-sustaining operation without supplemental heating. Other features in terms of mass flows and energy consumption are the same as in scenario 1.

Fig. 3(C) demonstrates scenario 3 with heat recovery and oxygen reuse. Based on the Aspen modelling, 72 kg of pure oxygen is sufficient for 6 batches. A gas compressor and gas tank are employed for the oxygen reuse, and 20 kWh of electricity is consumed in one batch for gas compression. Water condensation in the gas compressor was ignored in this study. Scenario 4 illustrated in Fig. 3(D) implements heat recovery and using air as the oxidant gas. A higher working pressure is used to provide enough oxygen from the air, resulting in a higher energy consumption from the pump and compressor.

| Table 6 |
| --- |
| Cost comparison of hydrothermal deconstruction of PPE waste in the four scenarios. |
| Scenario comparison | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 |
| Description | No heat recovery | Heat recovery | Oxygen reuse | Air |
| Plant capacity, kg/batch | 5 | 5 | 5 | 5 |
| Operation times, batch/year | 730 | 730 | 730 | 730 |
| Annual throughput, kg/year | 3650 | 3650 | 3650 | 3650 |
|功率消耗 | 429,170 | 756,294 | 988,312 | 988,312 |
| OPEX, NZD | 3313,241 | 3310,526 | 873,729 | 383,911 |
| Processing cost, NZD/kg | 923 | 934 | 275 | 141 |

| Table 7 |
| --- |
| Cost comparison of changes in scenario 4 (scale-up and part-time operation). |
| Scenario | Scenario 4a | Scenario 4b | Scenario 4c | Scenario 4d |
| Scale-up factor for scenario 4 | 2 | 10 | 20 | 40 |
| Plant capacity, kg/batch | 10 | 50 | 100 | 200 |
| Operation times, batch/year | 730 | 730 | 730 | 730 |
| Annual throughput, kg/year | 7300 | 36,500 | 73,000 | 146,000 |
| TCI, NZD | 1034,575 | 1150,520 | 1204,376 | 1260,753 |
| OPEX, NZD | 410,223 | 596,956 | 821,859 | 1266,867 |
| Processing cost, NZD/kg | 75 | 20 | 13 | 10 |

**3.2. Economic analysis**

The estimated costs for each of the four process scenarios are presented in Table 6 in terms of total capital investment (TCI) cost, operating expenses (OPEX), and processing cost. The TCI cost increased from scenario 1 to scenario 3 as more unit operations were employed to recover heat and reuse oxygen. Scenarios 3 and 4 had the same TCI cost since the equipment units were the same. The OPEX value was slightly lower in scenario 2 compared to scenario 1, indicating energy consumption was not a major contributor to the operation expenses. The OPEX value markedly decreased when oxygen reuse was applied in scenario 3, and further reduced when air was introduced in scenario 4, indicating that oxygen cost is a significant contributor to OPEX.

The processing cost in scenario 2 was slightly higher than in scenario 1, but the cost decreased significantly in scenarios 3 and 4, with scenario 4 having the lowest processing cost. Nevertheless, the processing cost in scenario 4 was still too high to make the process economically feasible compared with the common practice, landfilling.

Table 7 shows the changes in cost for scenario 4 when the plant scale was increased by two times to 40 times (scenarios 4a to 4d) and the operation time was decreased. The annual throughput, TCI and OPEX increased across each scenario. On the other hand, processing costs decreased from 75 NZD/kg (49 USD/kg) in scenario 4a to 10 NZD/kg (6 USD/kg) in scenario 4d. A larger plant scale could therefore contribute to lower processing costs, although investment risk would be increased due to increased TCI. A large-scale plant would be more suitable for a high-population region, e.g. Auckland, which generates much more waste.

In addition, Table 7 presents the economic performance of scenario 4d for part-time operations. When the annual operation times were decreased from 584 batch/year to 18 batch/year, the processing cost was elevated from 10 NZD/kg (7 USD/kg) to 86 NZD/kg (56 USD/kg). Comparing scenario 4d-4 with scenario 4, it is noted that part-time operation of a large plant performed better than a full-time operation of a small plant in terms of the processing cost.

**3.3. Sensitivity analysis**

Process scenario 4 was selected as an example since it presented the lowest process cost across the four basic scenarios. Fig. 4 shows six factors affecting the processing cost. The baseline values for each factor (factor changes at 0%) are presented in Table 5. As can be seen in Fig. 4, the labour rate, discount rate, and plant lifetime all impact the processing cost. A short plant lifetime, a high discount rate or a high labour rate led to an increased processing cost. The electricity price, transportation price and landfill price marginally affected the processing cost, indicating scenario 4 would be robust to the fluctuation of these prices.

**3.4. Comparison with conventional practice**

A conventional approach to treat medical waste is disinfection by autoclaving followed by landfill disposal. Fig. 5 shows the comparison...
between the optimal hydrothermal deconstruction approach (scenario 4d) and the autoclaving-landfilling approach. It was assumed that PPE waste (146,000 kg/year) would be transported from a hospital to a processing site for either disinfection by autoclave or hydrothermal deconstruction, with the remaining solids sent to a landfill for final disposal. TCI, OPEX and the processing cost of autoclaving-landfilling approach were calculated following the methods described previously.

TCI of autoclaving-landfilling was 907,751 NZD (590,038 USD) less than hydrothermal deconstruction due to the simple and low-cost equipment used for autoclaving. The OPEX values of both approaches were similar due to the same costs of labour and clinical waste transportation, which were the main contributors to operation costs. The autoclaving-landfilling approach led to 146,000 kg/year of landfill waste, and the overall processing cost was 8 NZD/kg (5 USD/kg). Meanwhile, the hydrothermal deconstruction approach achieved 94% mass reduction of landfill waste at a processing cost of 10 NZD/kg (6 USD/kg). The landfill fees in New Zealand have increased by 42% in 2021, and will continue to increase gradually given the government encourages minimising waste disposal in landfills across the country. Hydrothermal deconstruction is an attractive alternative to landfilling. A large-scale plant (e.g. Scenario 4d) will be competitive in terms of the processing cost when the technology becomes mature in industry and landfill fees further increase.

3.5. Potential environmental impacts

The environmental impacts would be negligible for a small-scale plant such as a 5 kg/batch hydrothermal deconstruction system. However, a large-scale plant such as scenario 4d could pose potential impacts on the environment due to gaseous emissions. The hydrothermal deconstruction off-gas is mainly composed of used air with trace amounts of carbon dioxide, carbon monoxide, and hydrogen. Off-gas cleaning technologies should be used to reduce the potential environmental impacts. Catalytic conversion can be used to clean up flue gas by oxidising carbon monoxide and other reducing gases via a catalyst-loaded filter (Li et al., 2012). Monoethanolamine (MEA) based absorption processes can be used to capture carbon dioxide and obtain pure carbon dioxide as a commodity (Li et al., 2016).

Fig. 6 shows the potential environmental impacts of a large-scale hydrothermal deconstruction process (scenario 4d). A higher value indicates posing more environmental impacts. Off-gas emissions without any gas cleaning led to the highest scores except GWP (global warming potential). The individual PEI of PCOP (photochemical oxidation potential) contributed the most to the total value, and the second-highest PEI was HTPE (human toxicity potential by exposure). The trace vaporisation of ammonia and acetic acid to the off-gas were responsible for these two potential environmental impacts (Petrescu and Cormos, 2015). Overall, it is noted that the total value was as low as 0.006 PEI/kg.

Catalytic conversion markedly decreased the PCOP and HTPE values, but the GWP value increased due to the greater amount of carbon dioxide. Hence, applying carbon dioxide capture after catalytic conversion further decreased the total PEI value and the environmental impacts were minimised. However, carbon dioxide capture’s high investment and intensive energy consumption could undermine its economic feasibility (Yun et al., 2020), especially at these relatively small scales.

3.6. Safety and social aspects of the hydrothermal process

Processes that involve materials and chemicals handling or conversion should undergo preliminary hazards analysis and incorporate inherently safer design principles throughout the development and implementation cycles. Table 8 shows the potential hazards that may occur in a hydrothermal process which need to be mitigated during the
A hydrothermal deconstruction technology, as a promising alternative to the conventional practice by autoclaving and landfilling, can reduce PPE waste by 99% in weight. Economic analysis of the process scenarios indicated that using compressed air as the oxidiser and a large-scale plant can substantially improve the economic performance and wider applicability of this technology, particularly because the supply of pure oxygen would not be required. A 5 kg/batch hydrothermal deconstruction plant would require approximately 988,312 NZD (642,403 USD) for total capital investment and 383,911 NZD (249,542 USD) for annual operating expenses. Sensitivity analysis showed that plant lifetime, discount rate, and labour rate were strong contributors to the processing cost, while electricity, transportation, and landfill prices were weak factors. The processing cost dramatically decreased with the increase in the plant scale, and a 200 kg/batch hydrothermal deconstruction process achieved economic feasibility equivalent to conventional autoclaving-landfilling processes. The assessment by the waste reduction algorithm indicated this process would pose negligible impacts on the environment. Off-gas cleaning by catalytic conversation and carbon dioxide capture could further reduce the discharge of pollutants and their potential environmental impacts.

### Table 8

| Identified hazards | Cause and potential consequence | Mitigation |
|--------------------|---------------------------------|------------|
| **Materials**      | Handling infectious PPE waste may cause contamination | Establishing clear standard operating procedures including the wear of PPE for workers of any unit |
| **Overpressure**   | The hydrothermal reactor operates at 100 bar and 300 °C. There will be a BLEVE (boiling liquid expanding vapour explosion) hazard if vessel containment is lost. | Pressure monitoring and relief system design and analysis |
| **Temperature runaway** | Hydrothermal deconstruction is an exothermic reaction, leading to the potential hazard of temperature runaway. | Temperature monitoring system design and analysis |
| **Rotating equipment** | Hazards typically associated with rotating equipment (e.g. shredder, pumps, compressor) | Establishing standard operating procedures, and enclosed processing areas |

### Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### Acknowledgement

This research was financially supported by the New Zealand Ministry of Business, Innovation and Employment via the MBIE COVID-19 Innovation Acceleration Fund and Medical Assurance Society Foundation. The authors acknowledge the Ministry of Health for the supply of PPE items for this study and the support and assistance of Taranaki District Health Board. The opinions presented are those of the author(s) and do not necessarily represent an official view of the Ministry of Health. The authors acknowledge Mr Geoff Ray for his technical assistance.

### Declaration of Competing Interest

The authors declare no conflict of interest in the publication of this study.

### Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.psep.2022.08.060.

### References

Ammala, A., Bateman, S., Dean, K., Petinakis, E., Sangwan, P., Wong, S., Yuan, Q., Yu, L., Patrick, C., Leong, K.H., 2011. An overview of degradable and biodegradable polyolefins. Prog. Polym. Sci. 36, 1015-1049.

Amsbey, F., Wang, L., Shahzad, G., 2016. Thermogravimetric and calorimetric characteristics during co-pyrolysis of municipal solid waste components. Waste Manag. 56. https://doi.org/10.1016/j.wasman.2016.06.015.

Anthaper, D., McLaren, J., Baroutian, S., Munir, M.T., Young, B.R., 2018. Hydrothermal deconstruction of municipal solid waste for solid reduction and value production. J. Clean. Prod. 201, 812-819.

Baroutian, S., Smit, A.-M., Andrews, J., Young, B., Gapes, D., 2015. Hydrothermal degradation of organic matter in municipal sludge using non-catalytic wet oxidation. Chem. Eng. J. 260, 846-854. https://doi.org/10.1016/j.cej.2014.09.063.

Chen, R., Zhang, D., Xu, X., Yuan, Y., 2021. Pyrolysis characteristics, kinetics, thermodynamics and volatile products of waste medical surgical mask rope by thermogravimetry and online thermogravimetry-Fourier transform infrared-mass spectrometry analysis. Fuel 295, 120632. https://doi.org/10.1016/j.fuel.2021.120632.

Cherubini, F., Bird, N.D., Cowie, A., Jungmeier, G., Schlamadinger, B., Woess-Gallwas, S., 2009. Energy-and greenhouse gas-based LCA of biofuel and bioenergy systems: key issues, ranges and recommendations. Resour. Conserv. Recycl. 53, 434-447.

El-Shafey, E.-S.I., Al-Lawati, H., Al-Sumri, A.S., 2012. Ciprofloxacin adsorption from aqueous solution onto chemically prepared carbon from date palm leaflets. J. Environ. Sci. 24, 1579-1586.

Fadare, O.O., Okoffo, E.D., 2020. Covid-19 face masks: a potential source of microplastic fibers in the environment. Sci. Total Environ. 737, 140279.

Fivga, A., Dimitriou, I., 2018. Pyrolysis of plastic waste for production of heavy fuel substitute: a techno-economic assessment. Energy 149, 865-874. https://doi.org/10.1016/j.energy.2018.02.094.

Giulivo, M., de Alda, M.L., Capri, E., da Barcelo, D., 2016. Human exposure to endocrine disrupting compounds: Their role in reproductive systems, metabolic syndrome and breast cancer. A review. Environ. Res. 151, 251-264.

Godwill, A.C., Godsel, A.C., 2019. Physiological effects of plastic wastes on the endocrine system (Bisphenol A, Phthalates, Bisphenol S, PBDEs, TBBPA). Int. J. Bioinformat. Comput. Biol. 4, 11-29.

Husafvel, R., Pajunen, N., Paalysyaho, M., Paavola, I.-L., Inkinen, V., Heinikann, K., Dahl, O., Ekroos, A., 2014. Social metrics in the process industry: background, theory and development work. Int. J. Sustain. Eng. 7, 171-182. https://doi.org/10.1080/19397083.2013.806166.

Islam, S.M., Safiq, M.B., Bodrud-Doza, M., Mamun, M.A., 2020. Perception and attitudes toward PPE-related waste disposal amid COVID-19 in Bangladesh: an exploratory study. Front. Public Heal. 8, 699.

Javid, F., Ang, T.N., Hanning, S., Svinskis, D., Burrell, R., Taylor, M., Wright, L.J., Baroutian, S., 2021a. Hydrothermal deconstruction of local anesthetics (bupivacaine and lignocaine) in pharmaceutical waste. J. Environ. Chem. Eng. 9, 106273.

Javid, F., Ang, T.N., Hanning, S., Svinskis, D., Burrell, R., Taylor, M., Wright, L.J., Baroutian, S., 2021b. Hydrothermal deconstruction of two antibiotics (ampicillin and metronidazole) in pharmaceutical waste. J. Environ. Chem. Eng. 9, 106273.
