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ORIGINAL ARTICLE

Additive manufacturing of recycled plastics: a 'techno-eco-efficiency' assessment

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Abstract

Plastic materials have been widely used to replace metals in functional parts due to their lower cost and comparable technical properties. However, the increasing use of virgin plastic material in consumer and industrial applications has placed a significant burden on waste management due to the volume of waste created and the potential negative effects of its end-of-life processing. There is a need to adopt circular economy strategies such as plastic recycling within industrial applications in order to reduce this significant waste management pressure. The present study used recycled polylactic acid (PLA) material as a feedstock for the 3D printing of a centrifugal semi-open pump impeller. The technical performance of 3D printed recycled PLA material and virgin PLA material was compared in this study. The environmental impacts for technically feasible impellers were assessed through the environmental life cycle assessment, while costs were evaluated by life cycle costing. The results were incorporated into a techno-eco-efficiency framework to compare the technical properties, environmental impacts, and costs. The social impacts of additive manufacturing and recycled feedstock material were also explored. The technical assessment results indicated that tensile strength, fatigue strength, density, and hardness decreased with recycled material content compared to virgin material. Microscopy of the fracture surfaces revealed the presence of slightly higher porosity and defects in recycled specimens, which could result in slightly lower technical properties. However, the recycled material was accepted for further ecological analysis as it offered higher pumping performance when compared to the original component and could reduce the burden on virgin material-based production and waste material disposal. Importantly, the results showed that 3D printed recycled PLA impellers are more eco-efficient when compared to 3D printed virgin PLA impellers.

Keywords Recycled plastics · Additive manufacturing · Mechanical characterisation · Eco-efficiency

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Abbreviations

ABS	Acrylonitrile butadiene styrene
AM	Additive manufacturing
EEA	Eco-efficiency assessment
GWP	Global warming potential
IMPLA	Injection moulded polylactic acid
NC	Normalised cost
PA	Polyamide
PLA	Polylactic acid
PS	Polystyrene
SLCA	Social life cycle assessment
VPLA	Virgin polylactic acid
ADP	Abiotic depletion potential
CE	Circular economy
ELCA	Environmental life cycle assessment
HIPS	High impact polystyrene
LCC	Life cycle costing
NEI	Normalised environmental impact
PC	Polycarbonate

PP Portfolio position
RPLA Recycled polylactic acid
UNEP United Nations Environment Program

1 Introduction

Plastic polymer materials are widely used in industrial and commercial applications due to their technical properties such as durability, corrosion resistance, high strength, light weight, and low maintenance when compared to metallic components [1, 2]. The production of plastic has reached a level of 381 million tonnes per year and 7.8 billion in total by 2015 [3]. However, the use of virgin plastic materials and the disposal of plastics in landfill or water bodies have caused significant environmental impacts such as eco-toxicity and greenhouse gas emissions (1.7 Gt CO_2-eq by 2015) due to their non-biodegradability [4]. The disposal of non-biodegradable plastic waste has increased to 80% of production at an alarming rate in recent years, while only 20% has been recycled [5]. The linear economy that starts from extraction and ends at disposal has depleted natural resources and posed negative environmental impacts such as greenhouse gas emissions, global warming, particulate matter emissions, and eco-toxicity [6]. If the current linear economic trajectory continues, the amount of plastic in oceans is expected to be more than the total biomass of fish by 2050 [4].

Recycling waste plastic into new or usable products can prevent both the material extraction and disposal stages in product life cycles, which could lead to a better circular economy (CE) [7, 8]. The five 'R' strategies, namely, recycling, remanufacturing, repairing, reusing, and refurbishing, can be considered to convert end-of-life products into new or usable products [9]. Figure 1 shows the life cycle stages of a conventional manufacturing scenario with CE strategies incorporated at different life cycle stages. These strategies reduce resource extraction and waste material disposal, thereby significantly avoiding the environmental impacts associated with manufacturing. These allow the plastic products to be recovered after a single life cycle and generate multiple life cycles for materials while maximising their utility and value [3].

Additive manufacturing (AM) or 3D printing has been found to offer higher material efficiency compared to subtractive manufacturing [10]. The use of additive manufacturing has increased by 32% during the last 5 years in the production of machine components [11–13]. Despite these benefits, AM also produces waste material in the form of support structures, failed prints, leftover raw materials, and disposable prototypes [14–16]. It is important to determine the contribution of AM to CE initiatives, such as the potential to use recycled feedstock. The metallic powder material that remains unused in the 3D printer can be recycled up to 95%, while waste metals from several applications can also be easily recycled to AM feedstock [17]. Similarly, the sustainability of recycling plastic waste and the feasibility of using recycled plastic material in AM should be investigated.

It has been found that the carbon footprint of recycled plastic is 3000 times lower when compared to virgin plastic materials [2]. However, the rate of recycling in the global plastic packaging industry still remains at 14% [3]. AM is a feasible manufacturing option to use recycled plastic material as filament feedstock [14]. Common plastic materials used in AM are acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), polyamide (PA/Nylon), and polycarbonate (PC). However, ABS, PA, and PC are petroleum-based and non-biodegradable.

PLA is a biopolymer made from plant materials such as corn starch, which is extensively used as a 3D printing filament feedstock material [18]. The virgin PLA material is available in pellet form, which can be used for filament extrusion and plastic injection moulding [19]. However, virgin PLA production increases the use of corn starch and sugar cane, which could affect the food security of some developing countries [20]. Since a large amount of PLA does not degrade under ordinary conditions, even with microbial action, the end-of-life disposal of commercial PLA parts has become a significant issue [21]. Furthermore, the disposal of waste PLA material also discards valuable raw materials, which could otherwise have been used as an alternative feedstock. Therefore, prolonging the life of PLA through

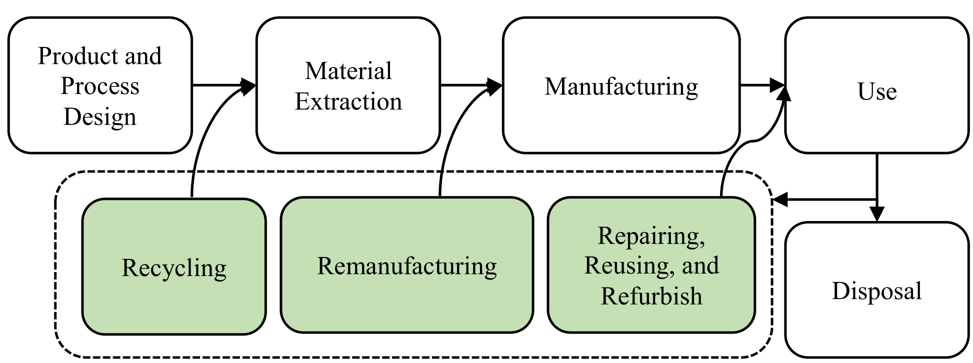


Fig. 1 Manufacturing life cycle stages, adapted from [9]

circular economy strategies, i.e. reuse, recycling, and recovery, is essential to reduce the pressure on virgin materials and minimise waste generation [11]. The waste PLA material could potentially be recycled into 3D printed filament, which could then be used to manufacture parts and reduce environmental impacts [14].

The feasibility assessment of waste plastic as a feedstock material for manufacturing in industrial applications has become a primary target of CE initiatives [22]. The technical properties of recycled plastic are significantly affected by the degree of degradation from multiple melt processing, contamination from other materials during waste collection, and external factors such as ultraviolet radiation [23]. Several studies have been conducted to improve the technical properties of recycled plastics. Mixing recycled plastic with virgin plastic material has become one of the most common approaches to achieving technical properties (97.5% tensile strength and 89.25% flexural strength) closer to virgin material [14]. In addition, recycled plastic materials have also been mixed with fillers [24], stabilisers, compatibilisers, and reinforcement fibres to improve their technical properties [25, 26].

The technical feasibility of recycled PLA material needs to be examined through mechanical characterisation tests such as density, viscosity, surface roughness, dimensional tolerance, tensile testing, fatigue testing, and functional application testing [14, 27]. The durability and service life of the functional parts made from recycled PLA material could also have a significant impact on the selection of recycled feedstock over virgin materials. However, technical data on recycled PLA material was very limited in previous studies. Table 1 presents several studies that have investigated the technical feasibility of recycled plastics, including PLA material. However, these technical assessments did not consider fatigue properties and the feasibility of functional applications of recycled PLA materials. Furthermore, the studies did not integrate the technical feasibility of recycled PLA material with the economic and environmental impact reduction of recycling plastic waste.

Environmental and economic impact assessments are important considerations in terms of circular economy as they quantify different approaches for end-of-life processing of plastic waste for comparison. Several studies have assessed the environmental impact of plastic waste recycling for AM through environmental life cycle assessment (ELCA) methods [14, 29, 30]. For example, Zhao et al. [14] studied the environmental impact of PLA in a closed-loop of 3D printing and recycling. The results show that environmental impacts associated with plastic recycling are significantly lower than other end-of-life processing methods such as incineration and landfill. Choudhary et al. [30] investigated the environmental and economic impacts of polyethylene terephthalate (PET) plastic waste recycling for 3D printing filament production through an ELCA and life cycle costing (LCC). The results show that recycled PET plastic reduces the environmental impacts and associated costs compared to virgin PET plastic. The study also reveals that the integration of renewable energy, such as solar photovoltaic systems, further improves the environmental performance of material recycling.

Implementing strategies to lower environmental impacts in manufacturing has the potential to increase the cost of production [31]. Hence, the environmental impact reduction per dollar invested should also be explored. Eco-efficiency assessment is a widely used integrative assessment framework that determines the environmental impact per dollar invested in the product. Eco-efficiency of plastic waste disposal of PET, polystyrene (PS), and PLA was studied in [32], which showed that PLA material has the highest eco-efficiency. An integrative framework of techno-eco-efficiency was proposed by Jayawardane et al. [26] for the sustainability assessment of additive manufacturing over subtractive manufacturing. The results show that additive manufactured composite material possesses higher eco-efficiency when compared to the subtractive manufactured component. Furthermore, this framework could be applied to assess the techno-eco-efficiency of recycled material feedstock in additive manufacturing.

Table 1 Previous studies on the technical feasibility of recycling PLA material

Material	Tests and results	Reference
PLA	The recycled PLA material was tested for mechanical properties, melt flow rate, and thermal properties through 10 cycles of re-extrusion. Recycled PLA showed acceptable properties as an additive in a material blend	[28]
PLA	The density and tensile properties of recycled PLA were slightly lower than virgin PLA	[6]
PLA	The recycled PLA was tested for tensile, shear, and hardness and exhibited lower properties than virgin PLA	[11]
PLA	The viscosity of recycled PLA deteriorated significantly, while mechanical properties reduced slightly over three cycles	[14]
PLA/cellulose	Recycled PLA blend of 30% wt. and blends of micro-cellulose were tested for technical properties. The recycled PLA blend showed better properties than 100% recycled PLA	[18]
PLA/lignin	The use of lignin fibres improved the tensile properties of PLA material by 7%	[24]
PLA/carbon fibre	Carbon fibre reinforcements improved the tensile, flexural, and impact properties of 73% recycled PLA	[25]

The increased use of additive manufacturing processes shifting from conventional processes could result in numerous social impacts, whereas waste recycling and the use of recycled feedstock materials could also impact society in many ways. Therefore, the social impacts of AM, waste recycling, and the use of recycled feedstock for AM should be systematically evaluated after assessing the technical, economic, and environmental impacts of AM. Even though the social impacts of manufacturing are significant, studies on the social impact assessment on manufacturing are very limited due to the difficulty in measuring relevant indicators. Several studies have evaluated the social impacts of manufacturing on the development of skills, changes to the intensity of work [33], job losses [34], and health and occupational hazards [35, 36]. The social impacts of material recycling and the use of recycled material feedstock have been analysed under the conservation of natural resources and reduction of landfill [37]. However, literature on the social impacts of recycled materials for AM feedstock is difficult to find. Table 2 presents a summary of the results from studies on the social impact assessment of AM and plastic recycling.

The aim of this study is to investigate the techno-eco-efficiency performance of recycled PLA material in comparison with virgin PLA material. The technical, economic, environmental, and social performance of recycled PLA material needs to be determined as a decision support tool for diverting plastic waste as a functional material to maximise utility and value in industrial applications.

2 Materials and methods

Post-manufacturing waste generated during virgin PLA filament manufacturing was used as the feedstock material for the recycled PLA 3D printer filament. The waste material was first separated from other contaminants and then shredded into particles of original pellet size (3 mm). Then the same filament extrusion method as the virgin filament production was used for the recycled material production. Figure 2 shows a process flow diagram of the conversion of

Table 2 Social impact assessments of AM and plastic recycling

Social impacts assessed	Method	Results	References
Level of employment	Social LCA (UNEP)	Skilled employment has increased with AM, while unskilled employment has decreased	[34]
Development of skills	SLCA, qualitative survey	AM aids the development of new skills such as product design optimisation, rapid prototyping, and rapid tooling	[33]
Intensity of work	SLCA, qualitative survey	AM decreases the intensity of work due to lower rework time, defects, and monitoring time	[33]
Occupational hazards	Material safety data	The chemicals and solvents used in AM can cause emissions and toxicity	[35]
	SLCA, quantitative survey	A reduction of occupational incidents (fatal and non-fatal) in AM	[33]
	Polymer weight correlation	The correlation to polymer weight was used to find the human toxicity potential (HTP) of fused deposition modelling AM	[36]
Conservation of natural resources	Energy and material consumption	Material consumption of AM is lower than SM, which contributed to the conservation of virgin material, while higher energy consumption was reported for AM compared to SM	[35]
Reduction of landfill	Diversion of landfill	Plastic waste could be diverted from landfill to construction aggregate to avoid landfill sites	[37]

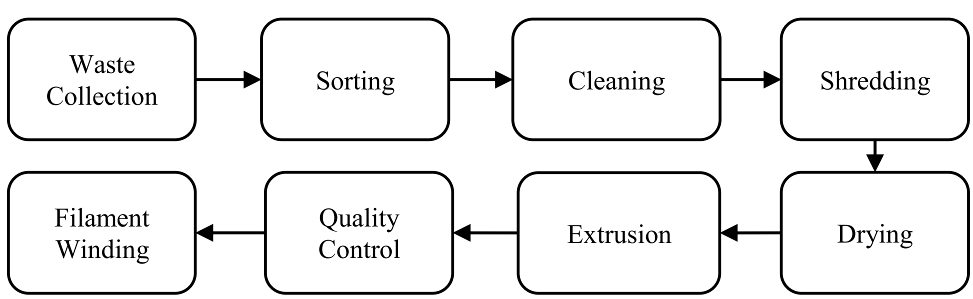


Fig. 2 Recycled filament manufacturing process

waste plastic material into recycled filament material for 3D printing applications.

A semi-open impeller in a centrifugal water pump was used as the functional part in this analysis based on the same criteria (complexity, solid-to-envelope ratio, application, functionality, and availability of performance test) used by Jayawardane et al. [38], with the chosen pump impeller design being taken from a *Grundfos Unilift KP 250* pump.

The techno-eco-efficiency framework (Fig. 3) by Jayawardane et al. [38] has been followed to compare the technical, economic, and environmental performance of pump impellers, which were made of virgin and recycled PLA materials. The technical feasibility of the materials included mechanical, built material, geometrical, morphological, and pump performance tests. The life cycle inventory (LCI) was developed only for technically feasible impellers. The environmental impacts have been quantified by the ISO 14040/44 ELCA method. The life cycle impact assessment (LCIA) was conducted using SimaPro LCA software for indicators selected through an expert survey. The economic value was calculated using the life cycle costing (LCC) method. The environmental impacts were normalised by dividing them by the gross domestic environmental impact per inhabitant (GDEI/Inh.), and then normalised values were multiplied by the relative weights assigned by experts. The costs were normalised by dividing them by the gross domestic product per inhabitant (GDP/Inh.). These normalised environmental impacts and normalised costs were incorporated into the eco-efficiency framework for determining the eco-efficiency portfolio. The eco-efficiency portfolio positions determined the eco-efficiency performance of 3D printed impellers made by recycled feedstock and virgin feedstock. The ELCA could help determine improvement strategies that could be used to improve the 3D printed impellers further.

2.1 Manufacturing

The virgin PLA (VPLA) and 100% recycled PLA (RPLA) 3D printer filament materials were sourced from *Aurarum Pty*, Melbourne, Australia. The injection moulded virgin PLA (IMPLA) material was sourced from *Jeewa Plastics*, Colombo, Sri Lanka. The 3D printed impellers and specimens for technical feasibility tests were manufactured using a *MakerBot Replicator Z18* 3D printer. The specimens for technical feasibility tests of the IMPLA material were made from a 5 mm plate using a computer numeric control (CNC) milling machine. Figure 4 a and b show the RPLA impeller, Fig. 4c and d show the VPLA impeller, and Fig. 4e shows the 3D printer.

The following specifications were set for 3D printing parameters for each configuration (Table 3).

Ideally, the 3D printer process parameters (Table 3) should be the same for both the VPLA and RPLA filaments. However, the disparity in melting temperature and viscosity between the VPLA and RPLA filaments required the use of slightly different process conditions in order to achieve 3D printed components of nominally similar quality. Therefore, the 3D printer process parameters were adjusted for the RPLA material in order to minimise the effects of process parameters on the technical feasibility of RPLA parts compared to VPLA parts. Namely, the nozzle temperature of the 3D printer for RPLA material was increased to 210 °C, the melt flow

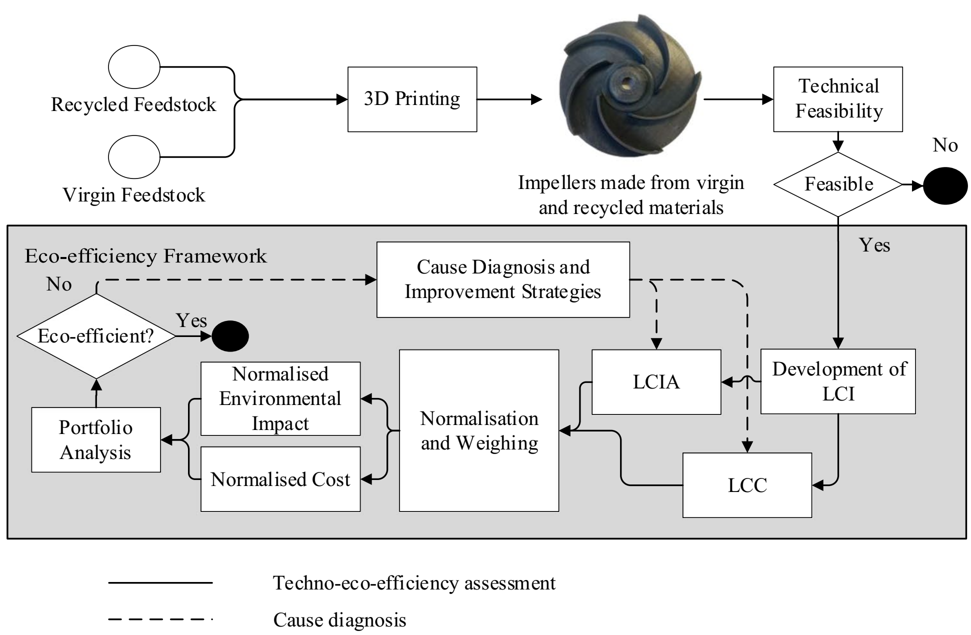


Fig. 3 Techno-eco-efficiency framework [26]

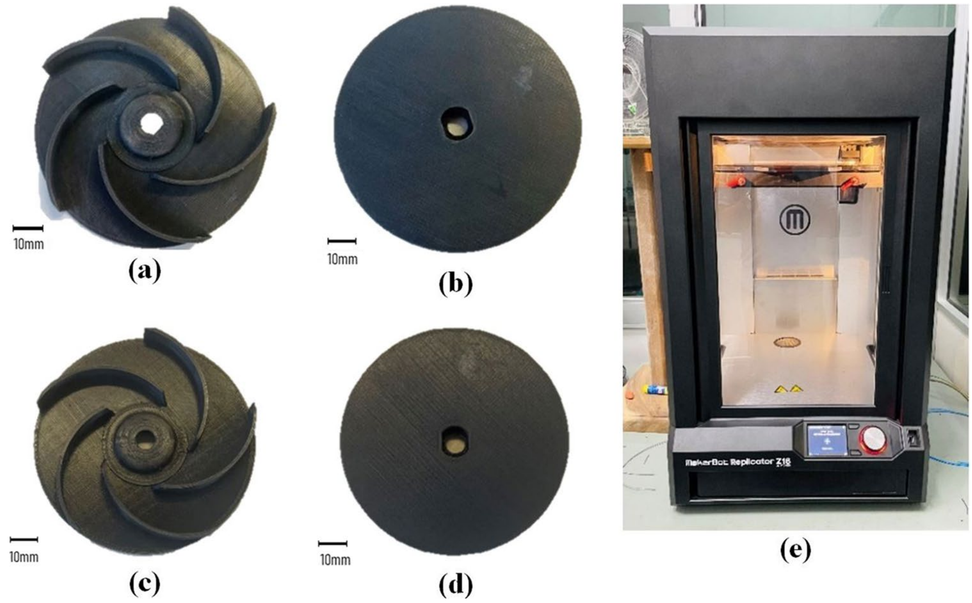


Fig. 4 RPLA impeller, front (**a**); RPLA impeller, rear (**b**); VPLA impeller, front (**c**); VPLA impeller, rear (**d**); and *MakerBot Replicator Z18* 3D Printer (**e**)

Table 3 Specifications for each PLA configuration

Material	VPLA filament	RPLA filament
Nozzle temperature	200 °C	210 °C
Bed temperature	60 °C	60 °C
Melt flow index	100%	110%
Nozzle size	0.4 mm	0.4 mm
Layer height	0.12 mm	0.12 mm
Print speed	60 mm/s	50 mm/s
Raster orientation	0°	0°
Roof and floor layers	4	4
Infill pattern	Cubic	Cubic
Infill density	100%	100%
Retraction (distance @ speed)	5 mm @ 40 mm/s	6 mm @ 50 mm/s

Melt flow index is a measure of ease of polymer flow. Retraction is the return movement of the 3D printer filament to avoid stringing

index was increased to 110%, and the print speed was reduced to 50 mm/s, in order to obtain uniform print extrusion without clogging [14, 39].

2.2 Technical feasibility assessment

The technical feasibility assessment was conducted in order to ensure the feasibility of the RPLA material for the functional application. Technical properties of the printed impeller and specimens were tested to study the mechanical, build material, geometrical, hydraulic performance, and morphological properties, as presented in Table 4.

Table 4 Technical feasibility properties and associated tests

Property	Test
Mechanical property	Tensile behaviour
	Fatigue testing behaviour
Build material property	Surface roughness
	Hardness
	Density
Geometric property	Dimensional tolerance
Hydraulic performance	Pump testing
Morphology	Microscopy of the fracture surface

2.2.1 Density

The density of a specimen is an important characteristic to determine the porosity of the specimen. Since 3D printed specimens have an inherently anisotropic nature due to the layered deposition of material, it is essential to measure the density through a standard method. The density of the 3D printed specimens was calculated by measuring specific gravity following the ASTM D792 standard, method A [40]. The specimens were first weighed in air and then weighed when immersed in distilled water at 23 °C. The density of RPLA and VPLA specimens was compared with the density of the injection moulded PLA (IMPLA) material.

2.2.2 Tensile testing

The tensile properties characterise the material's mechanical strength. Since the pump impeller considered in this study undergoes tensile loading, tensile testing has been considered. The tensile parameters of the PLA specimens, such as ultimate tensile strength (UTS), yield strength, strain at break, elastic modulus, and energy absorption, were tested using a *Testometric* Universal Testing Machine. The ASTM D638 type 1 standard specimens, as shown in Fig. 5, were printed from the same 3D printer. Four specimens of each configuration were tested at a 5 mm/min crosshead speed.

2.2.3 Fatigue testing

The fatigue failure by tensile loading has been considered in this study for the application of a pump impeller. Other failure modes including flexural loading, impact damage, and creep have not been considered in the analysis. According to ASTM D790, the fatigue tests were carried out using a specimen type identical to the tensile testing specimen. The fatigue properties of the PLA specimens were determined using the dynamic loading conditions of the *Testometric* Universal Testing Machine. The fatigue test was conducted by axially loading the test specimens with a stress ratio ($R = \sigma_{min}/\sigma_{max}$) of 0.1. A loading rate of 5 Hz was used in the experiment. Nine un-notched specimens were tested under load-controlled cyclic loading with three specimens for each stress level at 80% of ultimate tensile stress (UTS), 70% of UTS, and 60% of UTS. The number of cycles to failure and the stress levels were plotted as S–N curves using Basquin's model approximation. Equation 1 presents Basquin's model equation where S is the applied stress on the specimen and N is the number of cycles to failure, whilst A and B are material constants. The estimated fatigue life was determined by the number of cycles and pump speed (Eq. 2):

$$S = A \times N^B \tag{1}$$

$$Estimatedfatiguelife(h) = N/Pumpspeed(cycles/h) \tag{2}$$

2.2.4 Dimensional tolerance

The dimensional measurements of the 3D printed impellers were taken using a *Mitutoyo* digital vernier calliper (standard error of 0.01 mm). Measurements were obtained from the inner diameter (1), outer diameter (2), shroud thickness (3), and vane thickness (4) of the pump impeller (Fig. 6).

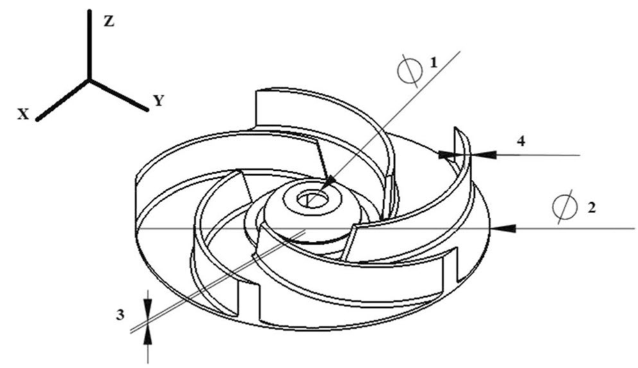


Fig. 6 Reference points for dimensional measurements

Five readings of each feature were measured, with mean values and standard deviations of the measurements being calculated.

2.2.5 Hardness

Following ISO 868 [41], the hardness of each PLA configuration was taken at 20 points of the tensile specimen beginning from the middle section using a handheld *CV DSDS001* Shore Durometer on the D scale. The average and standard deviation of the parameters were calculated.

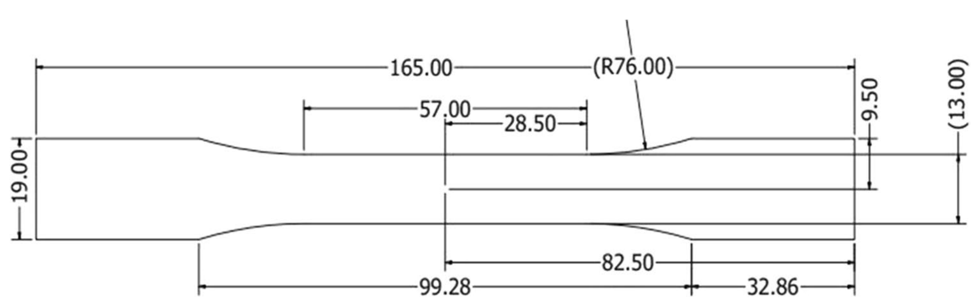
2.2.6 Surface roughness

The mean surface roughness (R_a) of the specimens was measured using a *Mitutoyo SJ-301* profilometer with a sampling length of 8 mm. The results for RPLA specimens were benchmarked with surface roughness measurements for the VPLA and IMPLA specimens. The measurements were obtained from 10 specimen points for each surface profile in order to determine consistency and standard deviation.

2.2.7 Hydraulic performance

The hydraulic performance of the impellers was tested by installing the impellers in a *Grundfos Unilift KP 250* pump to test the hydraulic performance of pumping. Figure 7 shows the water pump test rig, which was used to measure

Fig. 5 ASTM D638 Type I specimen used for tensile testing (dimensions shown in mm)



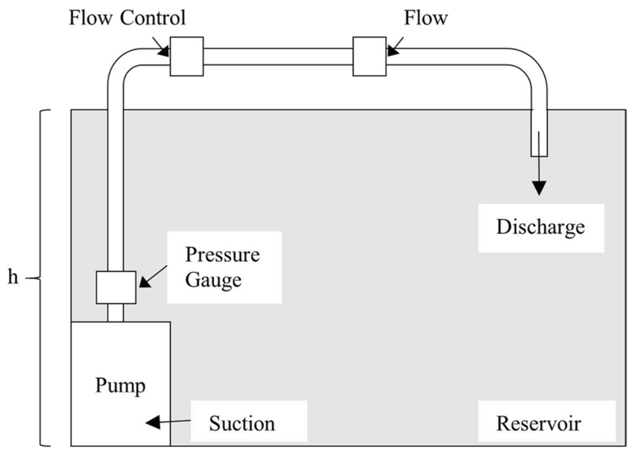


Fig. 7 Water pump test rig [26]

the parameters in Eq. 3 following the ISO 9901 standard on performance testing of pumps [42]. The pressure head (H) was obtained from the difference in heads at discharge and suction. The discharge head ($H_{d, n}$) was measured by a pressure gauge, while the suction head (H_S) was measured by the water level. The discharge flow rate ($Q^{\cdot}$) was calculated using a stopwatch and flow meter:

$$H = H_{d,n} - H_s \tag{3}$$

The results were plotted as H vs $Q^{\cdot}$ graphs in order to compare the hydraulic performance of the RPLA impeller, VPLA impeller, and the impeller from the original equipment manufacturer (OEM). The area under the H vs $Q^{\cdot}$ curve was used to determine the energy consumed by each impeller.

2.2.8 Surface morphology

The morphology of fracture surfaces was observed under a *ZEISS EVO 15* scanning electron microscope (SEM) under magnification ratios ranging from 50 to 250 at a voltage of 10 kV. The specimens were sputter-coated with silver (Ag) since the polymer specimen is non-conductive. The surface morphology was observed to identify defects and voids present in the 3D printed RPLA and VPLA materials. The surface of the IMPLA material was also observed for comparison.

2.3 Environmental life cycle assessment

The impellers which were found to be technically feasible were evaluated for sustainability. The first step was to assess the environmental impacts. The environmental impacts were assessed using an environmental life cycle assessment method in accordance with the ISO 14040/44 standard.

2.3.1 The goal

The goal of the study is to determine the environmental impacts of manufacturing pump impellers with RPLA and VPLA materials and their use in the industrial application of wastewater pumping with particles up to 10 mm. The functional unit (FU) is a pump impeller. The FU is used to conduct a mass balance to determine the inputs and outputs of the life cycle stages of the impeller.

2.3.2 The scope

The scope of the ELCA follows a source-to-service (S to S) approach where all the life cycle stages, from design to the delivery of service, are considered. Figure 8 presents the resource flow, which is within the scope of the ELCA.

2.3.3 Life cycle inventory

An LCI was created using the inputs and outputs of the life cycle stages, such as energy, materials, utility, labour, waste, and emission. The timeframe of the use stage was determined by the service life of each impeller. Table 5 presents the life cycle inventory developed for the functional unit.

2.3.4 Indicators and method

The *SimaPro* LCA software was used to calculate the environmental impacts of each impeller [43]. The Australian life cycle inventory database (AusLCI) in the *SimaPro* software was used to determine other inputs and outputs in the material processing and end-of-life processing stage for impact assessment. The environmental impacts that are relevant to the Australian manufacturing industry (Table 6) were determined by another consensus survey involving Australian manufacturing experts [26].

A mass manufacturing scenario in which AM machines are working 8 h per day for 5 years (lifetime of the AM machine) with an annual utilisation factor of 90% has been assumed in the calculation. Table 7 shows the production schedule with manufacturing time and batch size/production output (PO) of different manufacturing configurations of the pump impeller.

2.4 Life cycle costing (LCC)

Following the ELCA, the economic analysis was conducted to determine the unit cost of delivery of fluid during the service life of pump impellers made of RPLA and VPLA materials. A life cycle costing method was used to conduct an economic analysis using the same goal, scope, system boundary, and LCI as the ELCA, allowing ELCA and LCC results to be integrated. LCI inputs were

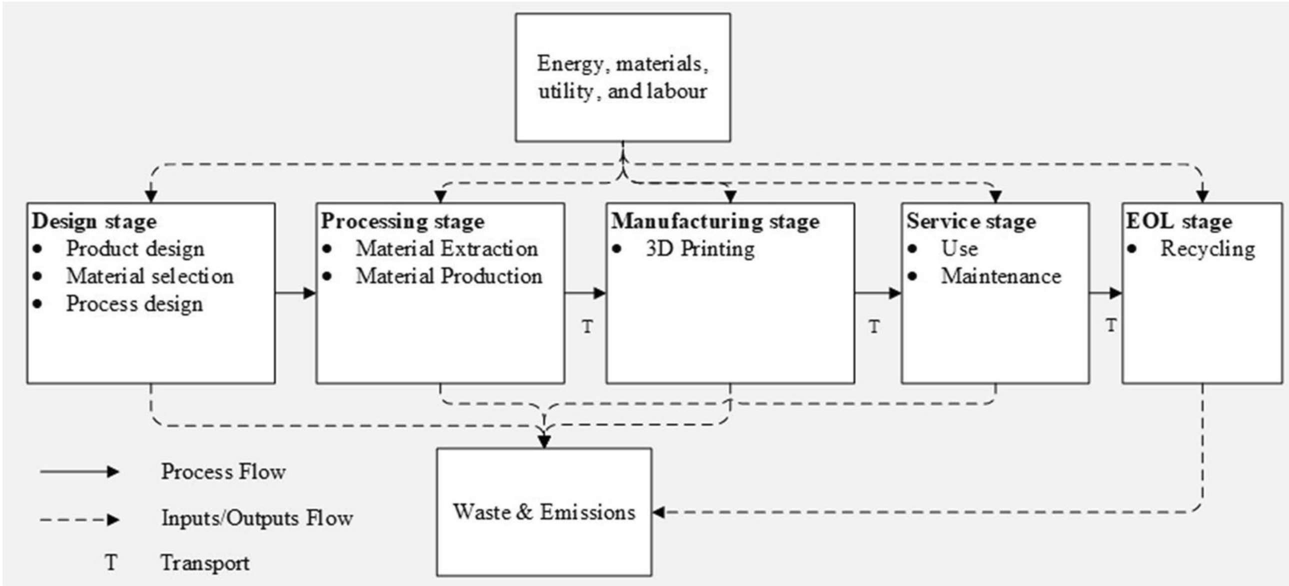


Fig. 8 The scope of ELCA [26]

Table 5 LCI of pump impellers

Stage	Material/process	RPLA	VPLA	3D printer
Design	**Energy (kWh)**			
	CAD modelling	10.00	10.00	
	Material selection	0.80	0.40	
Material processing	**Transportation (tkm)**			
	Sea			687.910
	Land	0.081	0.086	111.883
Manufacturing	**Primary materials (kg)**			
	PLA material	0.0238	0.0252	
	Material for machines (kg)			
	Steel			9.78
	Cast iron			5.87
	Aluminium			8.15
	Other plastics			6.52
	Copper			2.28
	Energy (kWh)			
	3D printing	0.717	0.659	
Use	**Energy (kWh)**			
	Use	35.45	41.14	

converted to cost values using Australia's market prices of these inputs. All cost values were inflated to the 2022 cost values using the inflation rate of Australia over 6 years. A two-step cost model was used following the methodology of Jayawardane et al. [26]. Firstly, the life cycle costs of 3D printed impellers were calculated. Secondly, the life cycle costs of pumping by 3D printed impellers were calculated.

2.4.1 LCC of impeller production

The life cycle cost of the impeller production ($LCC_{impeller, prod}$), including the life cycle stages from design to manufacturing, was determined as follows:

- Energy, utility, and labour costs in the design stage were calculated using relevant Australian energy cost figures.

Table 6 Environmental impact indicators and assessment methods

Indicator	Unit	Impact assessment method
Global warming potential (GWP)	t CO_2 eq	Australian indicator set with embodied energy V2.01
Eutrophication	kg PO_4^{3-} eq	
Land use	Ha a	
Water use	m^3 H_2O	
Cumulative energy demand (CED)	MJ	
Acidification potential	kg SO_2 eq	EPD (2013) V1.02
Abiotic depletion potential (ADP)	kg Sb eq	
Photochemical smog	kg NMVOC	ILCD 2011 midpoint + V1.08/ EU27 2010, equal weighting
Particulate matter	kg $PM_{2.5}$ eq	
Human toxicity	kg 1,4-DB eq	CML-IA baseline V3.03/EU25
Freshwater aquatic toxicity	kg 1,4-DB eq	
Marine toxicity	kg 1,4-DB eq	
Terrestrial toxicity	kg 1,4-DB eq	

CO_2 carbon dioxide, *NMVOC* non-methane volatile organic compound, *$PM_{2.5}$* particulate matter, *PO_4^{3-}* phosphate, *DB* dichlorobenzene, *Ha a.* hectare per year, *SO_2* sulphur dioxide, *Sb* antimony, *H_2O* water, *eq.* equivalent, *MJ* megajoule

Table 7 Production schedule of manufacturing scenario

	RPLA	VPLA
Total manufacturing time (h)	6.18	5.70
Batch size per annum/production output (PO)	425	461

Table 8 Capital cost and spare parts replacement costs

	3D printer (AUD)
Equipment costs[a]	9350
Transport cost	33
Extruder[a]	360
Build plate[a]	335

[a]MakerBot, USA

- Material processing costs included the raw material costs for RPLA and VPLA feedstock.
- Transportation costs were calculated from a supplier in Melbourne to a 3D printing facility in Perth.
- Manufacturing costs included the capital costs of machinery (Table 8), labour costs, and energy costs. These costs were apportioned based on the manufacturing time of each impeller (Table 7).

An inflation rate of 5.1% [44] and a discounting factor of 7% [45] were used in the LCC analysis to obtain the present value (PV) of the costs. The sum of PV was multiplied by the capital recovery factor (CRF). A CRF of 0.244 was determined by the equipment's operational time of 5 years and a discounting factor of 7%. It was then divided by the production output (PO) to obtain the $LCC_{impeller, prod}$ (Eq. 4). This cost was then converted to the price of the impeller (PI) using the value of the profit margin in the Australian pump market (35%) [46] (Eq. 5):

$$LCC_{Impeller,prod.} = (PV_{Capital} + PV_{Labour} + PV_{Energy} + PV_{O\&M}) \times CRF/PO \quad (4)$$

$$PI = LCC_{Impeller.prod.} \times (1 + PM) \quad (5)$$

2.4.2 LCC of pumping using 3D printed impellers

The service life (SL) is considered as the time period in LCC analysis. The life cycle cost of pumping using both RPLA and VPLA impellers over their SL ($LCC_{P, SL}$) was calculated. The fatigue life estimations of RPLA impeller and VPLA impeller were converted to SL to conduct the LCC analysis. The fatigue hours were converted to operating hours for pumping to determine the cost of energy consumed during these hours. It was considered that the pump operates for 4 h per day for 20 working days per month [47].

The energy consumed for pumping water using RPLA impeller and VPLA impeller was calculated for a fixed pressure head of 35 kPa. The energy consumption for both scenarios was multiplied by the current electricity price. The PV of energy costs over the impeller service life was then added to the PV of PI. The sum of PV was multiplied by the capital recovery factor (CRF) and divided by the service life of the impeller to obtain the $LCC_{P, SL}$ (Eq. 6). The study did not consider maintenance costs, and replacement costs of the pump impellers as similar costs are expected to incur in both scenarios [36]:

$$LCC_{P,SL} = \left(PV_{PI} + PV_{energy}\right) \times CRF/SL \tag{6}$$

2.5 Eco-efficiency assessment

The calculated values of life cycle costs and life cycle environmental impacts (LCEI) have been integrated using the eco-efficiency assessment framework to conduct a comparative eco-efficiency performance analysis. The following steps are used to calculate the eco-efficiency portfolio positions.

- The LCEI values are normalised by dividing with gross domestic environmental impact per inhabitant ($GDEI_i$/Inh) values (Eq. 7) to obtain the normalised environmental impacts (NEI_i) to convert all environmental impacts to the same unit [48, 49].
- The normalised values of environmental impacts were then multiplied by the corresponding weight to convert their values into one common unit, i.e. the number of Australians who produced the same amount of environmental impacts as the impeller [26]. These weights, which represent the level of importance of these environmental impacts, were ascertained by the feedback received from an expert survey [26] (also presented in the Appendix, Table 29). A single score of environmental impact (EI) was obtained by adding the normalised and weighed environmental impacts (Eq. 8):

$$NEI_i = \frac{LCEI_i}{GDEI_i/Inh} \tag{7}$$

$$EI = \sum_{i=1}^{11} NEI_i \times W_i \tag{8}$$

- The LCC values were then normalised by dividing with gross domestic product per inhabitant (GDP/Inh) value of Australia (AUD 75.250) [50] to obtain the normalised cost (NC) (Eq. 9), which is the number of Australians who produced the same GDP as the cost of the impeller [26]:

$$NC = \frac{LCC}{GDP/Inh} \tag{9}$$

- The portfolio position of environmental impact has to be determined to compare RPLA and VPLA impellers. This was done by dividing the EI of an impeller by the average value of EIs for all impellers considered for the comparative analysis. In the case of the portfolio position of cost, the NC of each impeller was divided by the average NCs of all impellers considered for this comparative eco-efficiency analysis (Eqs. 10–11) [26]:

$$PP_e = \frac{EI}{\sum EI/j} \tag{10}$$

$$PP_c = \frac{NC}{\sum NC/j} \tag{11}$$

- The environment–cost relevance ratio ($R_{E/C}$) was calculated as the ratio of mean EI and mean NC (Eq. 12), in order to determine the more influential parameter between EI and NC, which was used to determine the more influential parameter. The portfolio positions were revised (PP'$_e$, PP'$_c$) using the $R_{E/C}$ (Eqs. 13–14) and plotted in the graph of EI vs. NC (Fig. 9):

$$R_{E/C} = \frac{\sum EI_n/j}{\sum NC_n/j} \tag{12}$$

$$PP'_{e,n} = \frac{\left[\left(\sum PP_{e,n}\right)/j + \left[PP_{e,n} - \left(\left(\sum PP_{e,n}\right)/j\right)\right] \cdot \sqrt{\left(R_{E/C}\right)}\right]}{\left(\sum PP_{e,n}\right)/j} \tag{13}$$

$$PP'_{c,n} = \frac{\left[\left(\sum PP_{c,n}\right)/j + \left[PP_{c,n} - \left(\left(\sum PP_{c,n}\right)/j\right)\right] / \sqrt{\left(R_{E/C}\right)}\right]}{\left(\sum PP_{c,n}\right)/j} \tag{14}$$

The eco-efficiency value of a product is measured using the perpendicular distance above the diagonal line. If products are placed below the diagonal line, they are not eco-efficient and cause diagnosis, and improvement strategies should be implemented to improve the eco-efficiency. Since positions are revised with $R_{E/C}$, any changes to costs or environmental impacts of an impeller result in a change of EE portfolio positions of all impellers.

2.6 Social life cycle assessment (SLCA)

The social impacts of AM and recycled plastics for AM feedstock should be carefully assessed through several quantifiable indicators with the same goal, scope, and LCI as the ELCA and LCC. The findings of social, socio-environmental, and socio-economic aspects support the effective decision-making for the well-being of all stakeholders. The SLCA approach is a social impact assessment of the same product life cycle, which should be evaluated under the United Nations Environment Programme (UNEP) guidelines and methodological sheets for subcategories [51, 52]. The framework includes the assessment of social impacts on employees, local community, society, consumers, and other value chain actors. A quantitative approach has been used in this study using product-specific data on resource use/disposal and work hours. The social impacts on

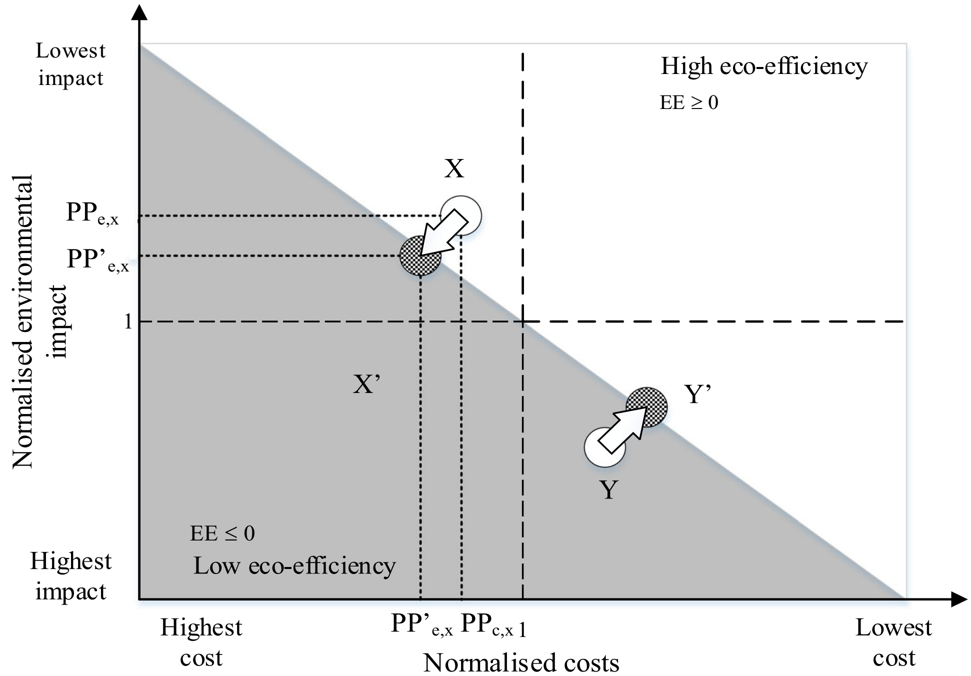


Fig. 9 EE portfolio and positions [26]

employees have been investigated under health and safety and employment level, while social impacts under local community and society have been investigated under conservation of natural resources and reduction of landfilling.

Health and safety The occupational and health hazard of AM and recycling for AM feedstock is an important indicator of social impacts on employees, which could be determined through the quantification of human toxicity potential (HTP). These include human toxicity by inhalation, ingestion, and dermal contact to employees in the mass manufacturing scenario of AM. Furthermore, plastic recycling for AM feedstock includes shredding plastic material into pellet size particles, which could lead to a higher concentration of particulate matter in manufacturing environments [33]. The method developed by Azapagic et al. [53] based on the correlation of polymer weight and HTP has been used in this study as follows (Eq. 15):

$$HTP = m_a \times TP_a \quad (15)$$

TP_a represents toxicity potentials to air, while m_a represents the mass of material emission to air. The TP_a for PLA material is 620 kg 1,4-DB eq./kg PLA. The HTP of each stage of the impeller life cycle is considered (Eq. 16) to calculate the HTP of the FU in line with the ELCA and LCC studies:

$$HTP = HTP_{Design} + HTP_{Processing} + HTP_{Mfg} + HTP_{Use} \quad (16)$$

However, the toxicity potential to the local community and society from other emissions (e.g. SO_x, NO_x, CO, $PM_{2.5}$) in the product life cycle has been quantified in the ELCA.

Employment level The level of employment was calculated (Eq. 17) from the number of hours of labour required in the mass manufacturing scenario previously considered in Sect. 2.3.4 for AM in comparison with SM/IM:

$$Employment\ level = \frac{No.\ of\ hrs.\ of\ labour\ in\ SM\ or\ IM - No.\ of\ hrs.\ of\ labour\ in\ A}{No.\ of\ hrs.\ of\ labour\ in\ SM\ or\ IM} \times 100 \quad (17)$$

Conservation of natural resources Conservation of natural resources is an intergenerational social impact indicator that affects the stakeholders of society in the SLCA model. The material and energy consumption calculations from Sect. 2.3.4 have been used to calculate the conservation of materials and conservation of energy (Eq. 18):

$$PP_e = \frac{EI}{\sum EI/j} \quad (18)$$

Reduction of landfill The waste management of plastic waste is an important social issue globally. Current waste management methods are landfilling, waste to energy, and recycling strategies.

If more industrial plastic could be recycled to manufacture feedstock material, the amount of landfill required to dispose of plastic waste could be reduced. The reduction of landfill is a social impact indicator that affects the local community. The reduction of landfill is calculated by the mass of the material that was recycled as feedstock of AM in the mass manufacturing scenario, which avoided disposal to the landfill sites. The reduction of landfill has been calculated (Eq. 19) in terms of the landfill required to carry 7000 tonnes of waste in Western Australia for 60 years [37]:

$$Reduction\ of\ landfill\ (ha) = \frac{Mass\ of\ material\ recycled}{7000\ t} \times 64\ ha \quad (19)$$

Other social impacts, including intensity of work, occupational accidents, and development of skills which have been found through literature review, have not been evaluated in this study due to the limited availability of product-specific primary data, expert judgement, and social context.

3 Results

3.1 Technical feasibility test results

The technical feasibility results of the standardised test specimens for recycled PLA (RPLA) material, virgin PLA (VPLA) material, and injection moulded PLA (IMPLA) material have been presented as follows for comparison.

3.1.1 Density

The density of the material specimens is presented in Table 9. A range of densities were observed for the RPLA material, which could be due to the high level of anisotropy. Mechanical characterisation tests, such as microscopy of the fracture surfaces, were investigated to analyse the cause of these variations. Furthermore, the density of the RPLA specimens was significantly lower than the density of the VPLA and IMPLA specimens.

Table 9 Density measurements

Material	Density
RPLA	1.09–1.14 g.cm^{-3}
VPLA	1.18 g.cm^{-3}
IMPLA	1.24 g.cm^{-3}

3.1.2 Tensile testing

Table 10 shows the results of the tensile tests for RPLA, VPLA, and IMPLA specimens. The average ultimate tensile stress of the recycled PLA material is 12% lower than the average ultimate tensile stress of the virgin PLA material. Furthermore, the ultimate tensile stress of the 3D printed recycled PLA material is 22% lower than the virgin injection moulded PLA material. The results were similar to the findings of Zhao et al. [14] where the recycled PLA specimens showed lower tensile properties. This was attributed to the porosity present in 3D printed specimens as observed by the lower density in the RPLA and VPLA specimens. In addition, the lower density for RPLA was expected to result in higher porosity which has a negative influence on ultimate tensile stress.

Figure 10 shows the comparison of the second strongest tensile stress–strain curves of the RPLA, VPLA, and IMPLA specimens under investigation. The stress–strain curve of the IMPLA specimen exhibits the highest result, whilst the stress–strain curve of RPLA shows the lowest result. The

Table 10 Tensile test results

Material	Test No	Yield strength (MPa)	Ultimate tensile stress (MPa)	Mean of UTS (MPa)	SD of UTS	Stress @ break (MPa)	Strain @ break (%)	Elastic modulus (GPa)
RPLA	1	52.01	59.10	56.7	2.22	51.39	4.31	1.878
	2	50.47	56.96			48.36	3.89	1.807
	3	49.22	53.72			45.56	3.75	1.733
	4	51.92	57.02			49.64	4.11	1.872
VPLA	1	58.06	64.12	63.38	2.17	59.63	3.58	2.253
	2	57.32	63.45			59.01	3.42	2.168
	3	59.13	65.55			59.00	3.55	2.079
	4	53.51	60.41			56.27	3.70	2.247
IMPLA	1	67.91	70.20	70.00	1.08	60.37	4.59	2.479
	2	65.57	68.90			59.25	4.45	2.385
	3	65.94	69.49			59.76	4.49	2.287
	4	68.16	71.42			61.42	4.79	2.471

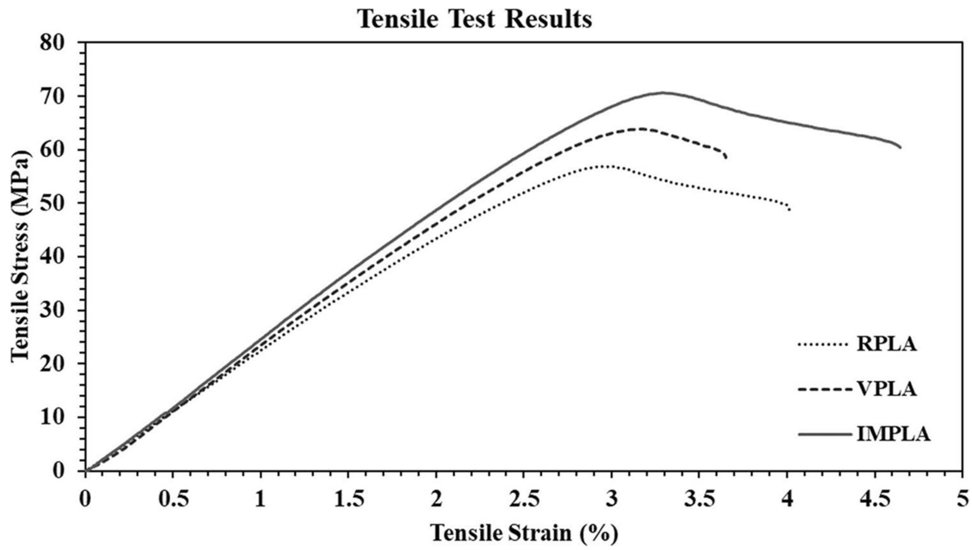


Fig. 10 Tensile test results

Table 11 Toughness results of the specimens

Material	Energy absorbed @ UTS (J.m^{-3})	Energy absorbed @ failure (J.m^{-3})
RPLA	92.01	149.65
VPLA	112.67	142.41
IMPLA	128.14	216.85

Table 12 Basquin's model values

Material	A	B
RPLA	61.98	− 0.1048
VPLA	75.72	− 0.1098
IMPLA	89.80	− 0.1144

curves initially show similar elastic moduli for all specimens, whilst the elastic modulus of the IMPLA specimen and VPLA specimen has increased closer to the ultimate tensile stress.

Table 11 shows the integrals of each stress–strain curve up to ultimate tensile stress and final failure. The integral shows the energy absorbed by the specimen which indicates that IMPLA has the highest toughness, while the RPLA has the lowest toughness.

3.1.3 Fatigue testing

The initial stress and number of cycles to failure curves were derived from the results of the fatigue tests. The logarithmic values of the fatigue test results and the linear trend line values

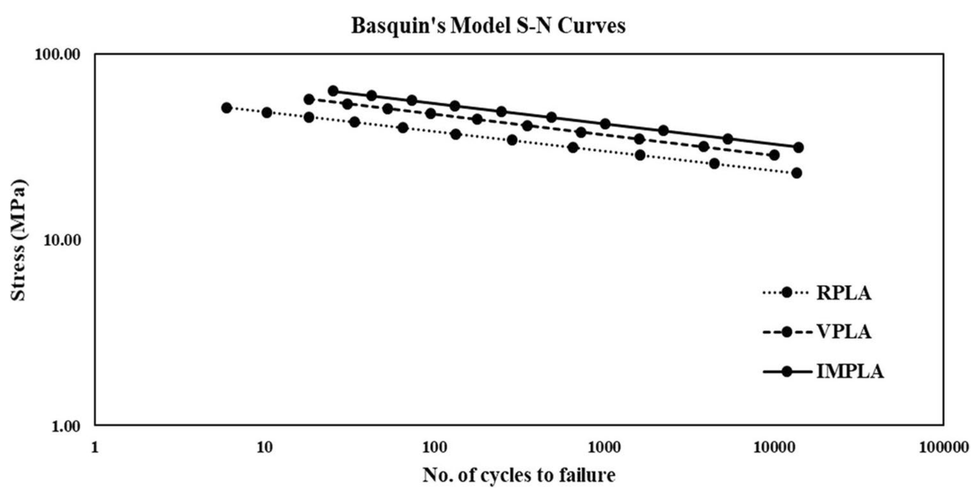


Fig. 11 Basquin's model S–N curves

were incorporated into Basquin's model approximation. Table 12 shows Basquin's model values obtained from the logarithmic model, whereas Fig. 11 shows Basquin's model curves plotted for RPLA, VPLA, and IMPLA specimens from the approximation.

The order of the fatigue strength remains similar to the order of the ultimate tensile stress. The rate of decrease of fatigue strength is also the same. The fatigue life estimation of the RPLA, VPLA, and IMPLA shows that RPLA specimens have a lower fatigue life for a given tensile stress on the impeller. The reduction of the fatigue life in RPLA specimens could be due to the lower ultimate tensile stress values found from the tensile test.

Fatigue life estimation The fatigue strength values for RPLA, VPLA, and IMPLA were used for the fatigue life estimation for the centrifugal open pump impeller in the wastewater application as presented in Table 13. It was assumed that the pump is operating in a steady-state condition and that a maximum pressure load of 10 MPa is acting on the impeller vanes by the water.

The RPLA specimen and VPLA specimen both indicated an estimated fatigue life lower than the standard lifetime of a pump impeller, namely, 1600 h. Hence, the estimated fatigue life of the RPLA and VPLA specimens was considered as the service life of the impellers.

3.1.4 Dimensional tolerance

Table 14 shows the dimensional measurements of the RPLA pump impellers. The dimensions of the inner diameter of the RPLA and VPLA impellers are slightly lower than the OEM impeller, while the dimensions of the external diameter of the RPLA and VPLA impellers are slightly higher than the OEM impeller. However, all dimension measurement values are within the acceptable tolerance levels of manufacturing, fitting, and clearance of the pump impeller for the selected water pump application.

3.1.5 Hardness

Table 15 presents the hardness values of the RPLA, VPLA, and IMPLA specimens. The RPLA specimens showed the lowest hardness value (80.4), while the IMPLA specimen showed the highest hardness value (84.7). This result was attributed to the porosity and defects present in specimens during 3D printing compared to injection moulding. Furthermore, the higher standard deviation (1.582) in hardness value for RPLA could explain the inconsistency of material properties in making RPLA.

3.1.6 Surface roughness

Table 16 presents the mean surface roughness of the vane and shroud of the three RPLA impellers. The results show that the surface roughness values of the three impellers are consistent for vane and shroud surfaces. The vane surface has a higher surface roughness due to the layered surface texture in the Z direction of 3D printing.

Table 13 Summary of fatigue results

Material	Fatigue strength (MPa) @ 10^6 cycles	No. of cycles to failure @ 10 MPa	Life estimation (hours) @ 10 MPa
RPLA	14.56	3.63E+07	208.50
VPLA	17.20	1.40E+08	584.57
IMPLA	19.70	4.81E+08	-

Table 15 Hardness measurement of the PLA specimens

Material	Average hardness (D scale)	Standard deviation (D scale)
RPLA	80.4	1.582
VPLA	81.5	0.243
IMPLA	84.7	0.166

Table 14 Dimensional measurements of the RPLA pump impellers

Impeller	Inner diameter (mm)	External diameter (mm)	Vane thickness (mm)	Shroud thickness (mm)	Height (mm)
RPLA I_1	7.48	90.63	1.48	1.76	12.64
RPLA I_2	7.45	90.79	1.51	1.69	12.78
RPLA I_3	7.52	90.70	1.46	1.71	12.83
VPLA I_1	7.55	90.65	1.50	1.68	12.66
VPLA I_2	7.49	90.51	1.49	1.70	12.91
VPLA I_3	7.84	90.72	1.46	1.73	12.82
OEM	8.00	90.00	1.55	1.21	13.00
Tolerance	0.55	0.79	0.09	0.55	0.36

I_x impeller number

Table 16 Mean surface roughness (R_a) of the impellers and specimens

Specimen	Shroud surface	Vane surface	Surface
RPLA I_1	4.24 µm	8.90 µm	-
RPLA I_2	4.15 µm	8.89 µm	-
RPLA I_3	4.24 µm	9.56 µm	-
VPLA I_1	3.24 µm	8.42 µm	-
VPLA I_2	3.15 µm	8.53 µm	-
VPLA I_3	3.87 µm	8.22 µm	-
IMPLA	-	-	2.35 µm

I_x impeller number

3.1.7 Hydraulic performance

The hydraulic performance of the selected pump fitted with different pump impellers was tested in the recirculating pump test rig to measure the flow rates from shutoff to maximum flow. Table 17 presents the results of the pump performance test for RPLA impellers, VPLA impellers, and the OEM impeller. The pressure readings in the pressure gauge were converted from psi to kPa for clarity. The hydraulic performance curves (Fig. 12) were plotted using the results (Table 17).

The results show that RPLA impellers perform slightly worse than the VPLA impellers as it consumes higher power to maintain the same pressure load. However, the RPLA impellers show comparatively higher performance when compared to the stainless steel AISI 304 OEM pump impeller. This could be due to the higher density in Stainless Steel AISI 304 material of the OEM impeller, which is significantly higher than the RPLA material.

3.1.8 Surface morphology

The fracture surface micrographs of the tensile specimens are presented in Fig. 13. The fracture surface of the VPLA tensile specimen has uniform print lines and lower porosity compared to the RPLA specimen. The RPLA and VPLA specimens indicated the presence of significant voids, print lines, and porosity compared to the IPLA specimen, which has led to higher crack nucleation and propagation. The results show many commonalities to fracture surface observations of RPLA presented in other studies [14].

3.1.9 Overall technical feasibility assessment

Table 18 presents the comparison of technical properties for the RPLA, VPLA, and IMPLA specimens.

The overall technical feasibility assessment shows that the RPLA specimens have a slightly lower technical performance

Table 17 Hydraulic performance data of the impellers

Pressure head (kPa)		41.4	48.3	55.2	62.1	69.0	75.8	82.7	89.6
$\dot{Q}$ (m^3/s)	RPLA I_1	0.0021	0.0019	0.0016	0.0015	0.0011	0.0008	0.0004	
	RPLA I_2	0.0022	0.0020	0.0018	0.0016	0.0014	0.0011	0.0007	0.0002
	RPLA I_3	0.0020	0.0018	0.0015	0.0013	0.0009	0.0006	0.0004	
	VPLA I_1	0.0023	0.0021	0.0018	0.0016	0.0012	0.0009	0.0005	
	VPLA I_2	0.0023	0.0021	0.0019	0.0017	0.0015	0.0011	0.0008	
	VPLA I_3	0.0021	0.0019	0.0016	0.0013	0.0010	0.0007	0.0004	
	OEM Impeller	0.0021	0.0018	0.0014	0.0010	0.0006	0.0001		

I_x impeller number

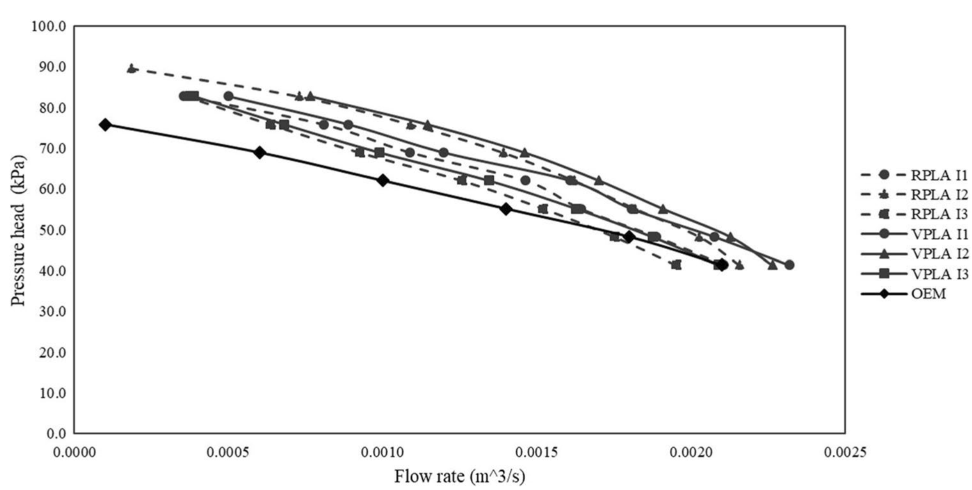


Fig. 12 Hydraulic performance (H vs $\dot{Q}$) curves of the impellers

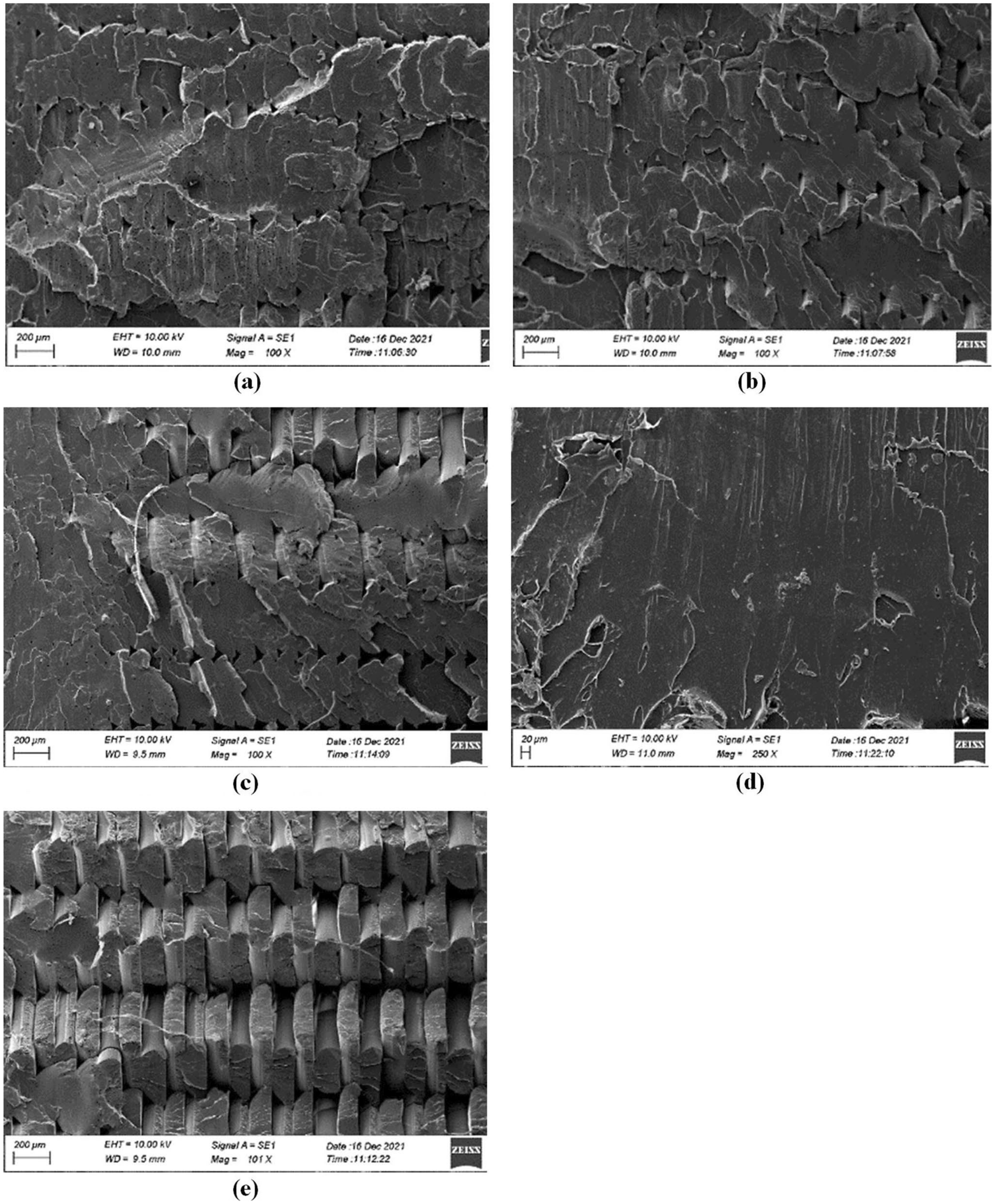


Fig. 13 Fracture surface micrographs of **a** VPLA specimen A, **b** VPLA specimen B, **c** RPLA specimen A, **d** RPLA specimen B, and **e** IMPLA specimen

Table 18 Summary of technical feasibility assessment

Parameter	RPLA	VPLA	IMPLA
Density ($g.cm^{-3}$)	1.09–1.14	1.18	1.24
Ultimate tensile strength (mean) (MPa)	56.70	63.38	70.0
Fatigue strength @ 10^6 cycles (MPa)	14.56	17.20	19.70
Hardness (D scale)	80.4	81.5	84.7
Surface roughness (shroud/vane) (µm)	3.54/8.96	4.22/8.89	3.20/3.20

compared to VPLA and IMPLA specimens. The RPLA specimens indicate a relative density of 87.9–91.9% compared to the IMPLA material. This could be due to the increased presence of defects, porosity, and voids in the recycled material. However, the relative density of RPLA material was only slightly lower than the VPLA specimen (92.3–96.6%). The ultimate tensile strength of the RPLA material was 10.5% lower than the VPLA material and 19% lower than the IMPLA material. This could be due to the voids and high porosity contributing to crack nucleation and propagation in RPLA material. The fatigue strength of RPLA has also slightly reduced to 84.6% of the VPLA value due to the lower UTS values in the RPLA material. However, the hydraulic performance of the RPLA impellers exhibited better values compared to the OEM impeller.

Furthermore, since the material feedstock used in the RPLA specimens has been recycled, it is expected that the impact of reduced service life of these specimens could be offset by lower life cycle costs and environmental impacts. Although it will require an increased number of RPLA impellers due to the reduced service life and mechanical properties, it does not affect the pumping performance. At least the use of recycled PLA material in impeller manufacturing could reduce the PLA waste going to landfill and thereby contribute to conserving virgin resources supporting the circular economy. Therefore, the pump impellers produced by RPLA material have been considered to be technically feasible for the functional application of wastewater pumping with particles up to 10 mm.

3.2 Environmental life cycle assessment (ELCA)

The PLA feedstock material recycled from preconsumer plastic waste was found to be a feasible alternative in manufacturing 3D printed pump impellers, which reduces the virgin material consumption. Therefore, the reduction of environmental impacts from the conservation of resources and avoidance of plastic waste from end-of-life disposal should be assessed using an ELCA. Table 19 shows the total life cycle environmental impacts of RPLA and VPLA impellers for environmental performance comparison under indicators chosen in Sect. 2.3.4.

The results show that the RPLA impellers have indicated lower LCEI values for all environmental impact indicators, compared to the VPLA impellers, except for the abiotic depletion potential (ADP) which determines the level of resources extracted. Even though recycled feedstock material is used in the manufacture of RPLA impellers, multiple RPLA impellers (2.8) are required to match the service life of a single VPLA impeller, which increases the ADP of RPLA impellers by 17.9%. The network chart as presented in Fig. 14 shows that 79% of ADP of RPLA impellers have been attributed to the manufacturing stage, while 19.1% have been attributed to the material extraction stage.

Table 19 Breakdown of LCEI based on indicators

Impact category	Unit	Total LCEI		Variance
		RPLA	VPLA	
GWP[a]	kg CO_2 eq	3.4650	119.9354	−97.1%
Eutrophication[a]	kg PO^{4---} eq	0.0014	0.0472	−97.0%
Land use[a]	Ha. A	0.0000	0.0006	−96.8%
Water use[a]	m^3 H_2O	0.0096	0.1984	−95.1%
Energy consumption[a]	kWh	0.2316	2.5729	−91.0%
Acidification potential[b]	kg SO_2 eq	0.0083	0.2728	−97.0%
Abiotic depletion potential[b]	kg Sb eq	2.68E-06	2.27E-06	+17.9%
Human toxicity[c]	kg 1,4-DB eq	0.3108	8.1443	−96.2%
Freshwater toxicity[c]	kg 1,4-DB eq	0.1002	2.1742	−95.4%
Marine toxicity[c]	kg 1,4-DB eq	330.7713	7170.4679	−95.4%
Terrestrial toxicity[c]	kg 1,4-DB eq	0.0048	0.1566	−97.0%
Photochemical smog[d]	kg NMVOC eq	0.0117	0.3901	−97.0%
Particulate matter[d]	kg PM 2.5 eq	0.0010	0.0346	−97.2%

[a]Australian indicator set with embodied energy V2.01, [b]EPD (2013) V1.02, [c]ILCD 2011 midpoint + V1.08/EU27 2010, equal weighting, [d]CML-IA baseline V3.03/EU25

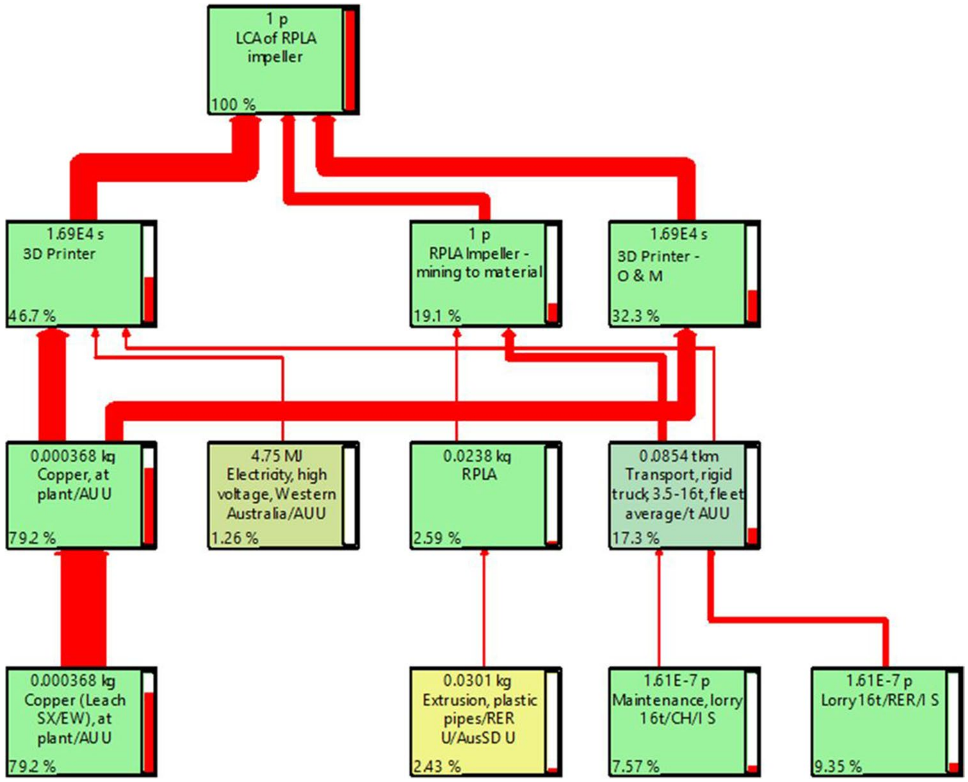


Fig. 14 Network chart for ADP of RPLA impeller

The energy consumption of each RPLA impeller also accounts for a 91% reduction compared to the VPLA impeller. However, the emissions from energy consumption from fossil fuel sources have contributed significantly to other environmental impacts. The global warming potential (GWP) has significantly reduced by 97.1% due to the replacement of the VPLA impeller by RPLA impeller. Figure 15 shows the network chart for GWP, which is significantly attributed to the energy consumption in the design stage and manufacturing stage, where the electricity is predominantly produced from black coal and natural gas. The highest environmental impact reduction was observed in particulate matter (97.2%), while the lowest reduction was observed in water use (95.1%). Even though the RPLA impeller has exhibited lower service life compared to the VPLA impeller, the environmental impacts have been significantly reduced due to the use of recycled materials.

After the evaluation of environmental impacts, economic impacts should be investigated since environmentally friendly technologies are not always economically viable.

3.3 Life cycle costing (LCC)

Table 20 shows the price of the impeller (PI) for the RPLA and VPLA cases. The use of recycled materials has significantly reduced the cost of feedstock material for AM. However, the higher production output (PO) of VPLA impellers due to lower printing time has resulted in a lower PI (7.85%) for VPLA impellers.

The $PV_{total,\ p}$ value of RPLA and VPLA impellers was calculated from the PV of capital cost and the PV of utility costs (Table 21).

The fatigue life estimations of 208.5 h for the RPLA impeller and 584.6 h for the VPLA impeller were converted to SL to conduct the LCC analysis. Accordingly, a pump using a RPLA impeller can operate for 2 months and 12 days, whereas a pump using a VPLA impeller can operate for 7 months and 6 days. It was estimated that 3 RPLA impellers were needed to meet the SL of one VPLA impeller. This was incorporated into the capital cost calculation of the service stage. The VPLA impeller shows a lower energy consumption (5.13%) in the use stage, when compared to the RPLA impeller, due to the lower surface roughness of the VPLA impellers resulting in higher hydraulic efficiency. The lower service life of the RPLA impeller has resulted in higher $PV_{total,\ p}$ due to the higher capital cost (3.24 times). The $LCC_{P,\ SL}$ of the VPLA and RPLA pump impellers are presented in Table 22.

The total life cycle cost of the RPLA impeller is significantly higher than the total life cycle cost of the VPLA impeller, due to higher pumping costs and lower service life of the 100% RPLA impeller. The durability and service life of the RPLA impellers could be further improved by blending RPLA material with virgin material, e.g. 50% wt. RPLA [14]. The addition of fillers and reinforcement fibre material [26] to the blend could also further reduce the life cycle cost of the RPLA impellers and make them cost-competitive with the VPLA impellers.

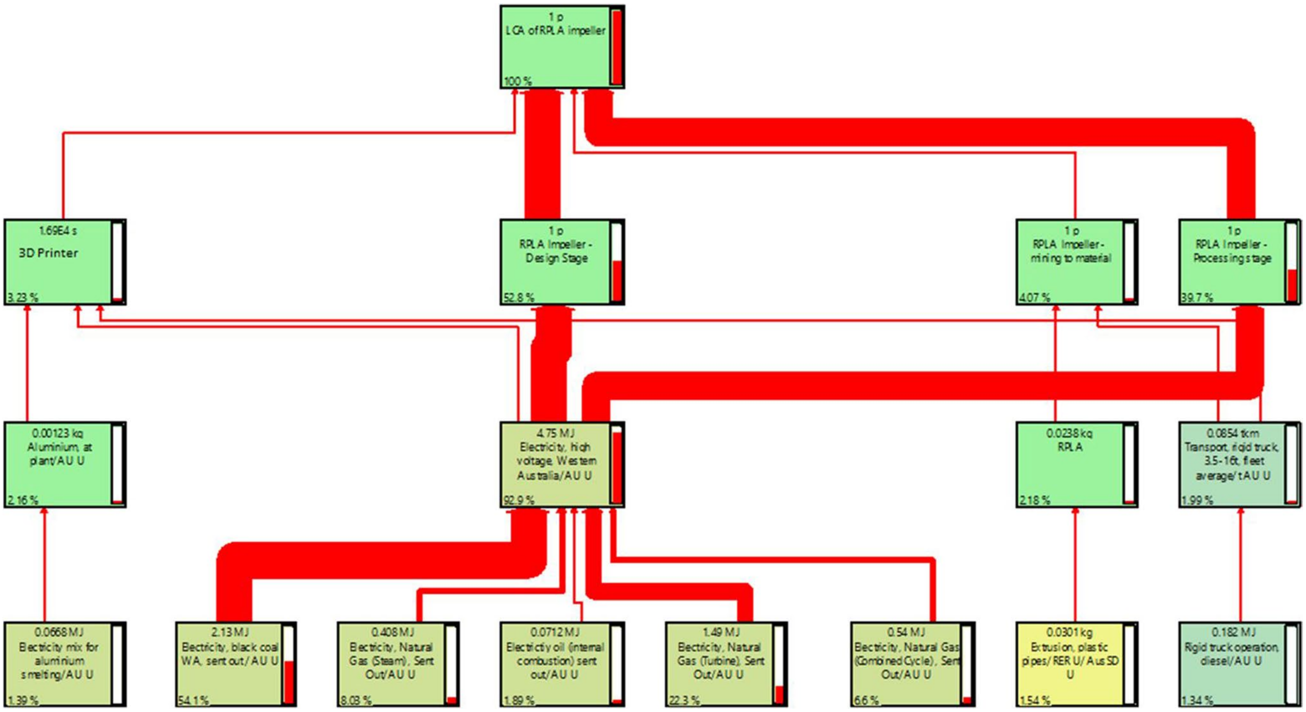


Fig. 15 Network chart for GWP of RPLA impeller

Table 20 Price of the impeller

	$PV_{total, prod.}$ (AUD)	Annuitised cost (AUD)	PO	$LCC_{impeller, prod}$ (AUD)	PI (AUD)
RPLA	12,821.04	3126.93	425	7.35	9.93
VPLA	12,808.17	3123.79	461	6.78	9.15

Table 21 Present values of the pump usage costs

Month	RPLA impeller		VPLA impeller	
	Capital cost (AUD)	Utility cost (AUD)	Capital cost (AUD)	Utility cost (AUD)
0	9.93	-	9.15	-
1		7.58	-	7.19
2	-	7.56	-	7.18
3	9.88	7.55	-	7.16
4	-	7.54	-	7.15
5	-	7.53	-	7.14
6	9.84	7.52	-	7.13
7	-	7.50	-	7.12
8	-	7.49	-	7.11
Total	29.65	60.27	9.15	57.18
$PV_{total, p}$	89.92		66.33	

Table 22 Life cycle cost of pump usage

	$PV_{total, P}$ (AUD)	Annuitised cost (AUD)	$LCC_{P, SL}$ (AUD)
RPLA	89.92	148.51	685.45
VPLA	66.33	109.55	180.09

3.4 Eco-efficiency assessment (EEA)

Whilst RPLA impellers offer significant environmental benefits compared to VPLA impellers, the economic assessment showed that the costs of impellers using recycled material are slightly higher than those made from virgin materials. Further analysis is required to investigate the environmental impacts per dollar invested in each manufacturing strategy in order to ascertain options that balance both economic and environmental objectives. As a result, an eco-efficiency analysis was performed to determine the eco-efficiency of RPLA and VPLA impellers. Table 23 shows the normalised environmental impacts (NEI) of RPLA and VPLA impellers over their service life in terms of inhabitants per functional unit of pump impeller delivering fluid. The RPLA impeller showed 93% lower normalised environmental impact when compared to the VPLA impeller.

Several environmental impacts were found to be the dominant contributors to the NEI. The energy consumption per

Table 23 Normalised environmental impacts in terms of number of inhabitants per FU (FU, a pump impeller delivering fluid over service life)

Indicator	RPLA impeller		% contribution				VPLA impeller		% contribution			
	EI	TC	DC	MPC	MfgC	UC	EI	TC	DC	MPC	MfgC	UC
GWP	1.38E-08	2.74	52.8	4.1	43.0	0.1	4.78E-07	6.37	16.2	23.0	60.7	0.1
Eutrophication	7.19E-09	1.43	49.9	8.5	41.4	0.2	2.36E-07	3.15	9.0	56.5	34.3	0.2
Land use	6.34E-11	0.01	46.9	16.1	37.0	0.1	1.96E-09	0.03	7.4	65.6	26.9	0.1
Water use	1.14E-09	0.23	31.2	25.8	42.7	0.3	2.34E-08	0.31	7.3	46.3	46.1	0.4
Energy consumption	3.83E-07	76.1	42.7	4.4	52.8	0.1	4.27E-06	56.8	15.9	46.3	59.6	0.2
AP	5.62E-09	1.11	50.4	6.6	42.8	0.2	1.86E-07	2.48	14.8	26.8	58.1	0.3
ADP	8.79E-13	0.00	0.7	19.1	79.5	0.7	7.47E-13	0.00	0.1	30.3	68.9	0.7
Human toxicity	9.73E-09	1.93	39.7	22.7	36.9	0.7	2.55E-07	3.40	7.6	59.2	32.5	0.7
Freshwater ET	5.86E-08	11.6	32.4	35.2	31.4	1.0	1.27E-06	16.96	4.0	77.6	17.8	0.6
Marine ET	2.75E-09	0.54	32.5	33.5	33.0	1.0	5.96E-08	0.79	4.6	73.1	21.5	0.7
Terrestrial ET	5.46E-09	1.08	49.7	11.5	38.7	0.2	1.79E-07	2.39	7.6	65.0	27.3	0.1
PS	1.41E-08	2.79	51.0	6.6	42.3	0.1	4.71E-07	6.27	16.0	22.6	61.2	0.3
Particulate matter	2.28E-09	0.45	53.6	3.7	42.6	0.1	8.02E-08	1.07	18.3	14.6	67.0	0.2
Total	5.04E-07						7.51E-06					

EI environmental impact, *TC* total contribution, *Des* design stage contribution, *MPC* material processing stage contribution, *MfgC* manufacturing stage contribution, *UC* use stage contribution, *GWP* global warming potential, *ADP* abiotic depletion potential, *ET* eco-toxicity, *AP* acidification potential, *PS* photochemical smog

pump impeller showed the highest contribution (76.1% for RPLA and 56.8% for VPLA) to the NEI in both scenarios. This could be due to high energy consumption in the manufacturing stage (52.8% RPLA and 59.6% VLPA). In addition, the design stage energy consumption of RPLA impeller (42.7%) also significantly contributed to the total energy consumption. This could be due to the higher process design time when dealing with recycled feedstock material. The material processing stage (46.3%) contributed significantly to the energy consumption of the VPLA impeller. This could be due to high energy consumption in virgin material feedstock production.

The next significant environmental impact was identified as freshwater eco-toxicity, which contributes 11.6% to the NEI of the RPLA impeller and 16.96% to the NEI of VPLA impeller. The material processing stage showed the highest contribution to the freshwater eco-toxicity (35.2% for RPLA and 77.2% for VPLA). The photochemical smog (2.79% for RPLA and 6.27% for VPLA) and GWP (2.74% for RPLA and 6.37% for VPLA) were found to be other significant contributors to the NEI. The manufacturing stage of 3D printing had significantly contributed to the photochemical smog (42.3% for RPLA and 61.2% for VPLA) and GWP (43.0% for RPLA and 60.7% for VPLA).

The abiotic depletion values observed for the RPLA impeller were lower than that of the VPLA impeller, but the contribution of this impact to the NEI was not significant. The level of contribution not only depends on the life cycle inputs but also on the weights assigned by the experts on relevance to manufacturing in Australia. The sum of normalised environmental impacts was used with normalised costs for the eco-efficiency assessment to determine the environmentally friendly option not entailing excessive costs.

Table 24 presents the overall normalised costs and normalised environmental impacts of the RPLA and VPLA impellers in terms of Australian inhabitants. These values were calculated according to Eqs. 7–9.

The results show that the normalised environmental impact of AM decreased from 7.51E-06 to 5.04E-07 inhabitant equivalents, i.e. 93% lower, by replacing virgin material with recycled material. However, the normalised cost of the AM process has increased the GDP produced by 2.56E-03 inhabitants per year to 9.748E-03 inhabitants per year, which is 74% higher than when using virgin material for AM. These values must be integrated by conducting an eco-efficiency assessment, to determine the environmental impact per dollar invested in recycling.

3.4.1 Eco-efficiency portfolio analysis

The initial eco-efficiency portfolio positions were determined using normalised environmental impacts and normalised costs. The calculated RE/C value of 0.001 indicates that costs

Table 24 Normalised costs and normalised environmental impact of impellers

Configuration	EIn (inhabitants)	NCn (inhabitants)
RPLA	5.04E-07	9.74E-03
VPLA	7.51E-06	2.56E-03

outweigh environmental impacts. Table 25 displays the portfolio positions. These portfolio positions are depicted in Fig. 16 as a graph of normalised environmental impact vs normalised cost.

The portfolio analysis showed that the RPLA impeller was placed above the diagonal, whereas the VPLA impeller was placed below the diagonal. This infers that the RPLA impeller is eco-efficient, while the VPLA impeller is not eco-efficient. The lower normalised environmental impact (93%) of the RPLA impeller compared to VPLA impeller has offset the higher normalised costs of the RPLA impeller (74%) compared to the VPLA impeller. It is evident that the recycling of plastic material for AM reduces the environmental impacts of additive manufacturing significantly for each dollar invested in recycling by 93%. Even though recycled material entails significantly higher costs than virgin material (74%), the potential for environmental impact reduction by recycling is significantly higher than for other resource recovery methods.

The normalised costs and cumulative energy demand of the RPLA impeller, which also accounts for a significant portion of normalised environmental impacts, could be further reduced by using renewable energy for operating these AM pump impellers.

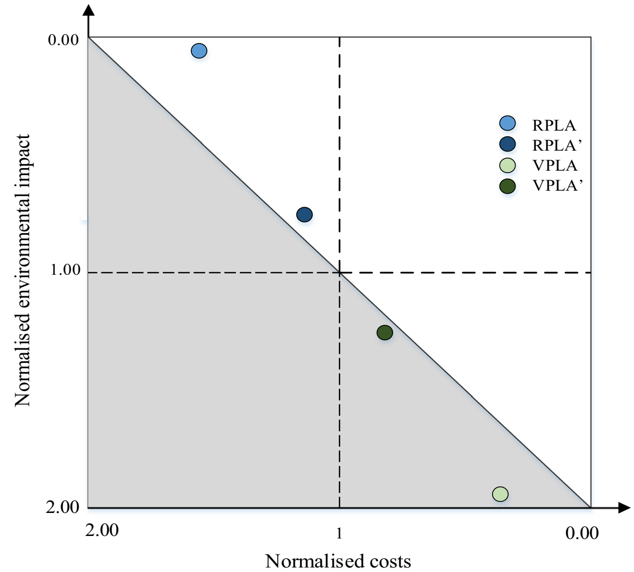


Fig. 16 Eco-efficiency portfolio (RPLA, portfolio position of RPLA impeller; VPLA, portfolio position of VPLA impeller; RPLA', revised portfolio position of RPLA impeller; SM', revised portfolio position of VPLA impeller)

3.5 Social impact assessment

The social impacts affecting the employee stakeholders of a company (mass manufacturing pump impellers using additive manufacturing) have been evaluated as follows using the product-specific primary data in terms of resource use and working hours.

3.5.1 Health and safety

The occupational health and safety of employees are an important consideration in the manufacturing industry. In mass manufacturing scenarios using AM, it was reported that non-fatal accidents, such as minor cuts, occurred when removing parts from the print bed and also for removing support structures in some AM processes [35]. However, AM has eliminated fatal accidents in manufacturing by reducing human–machine interactions and eliminating cutting tools and fixtures in conventional subtractive manufacturing [33]. Table 26 presents the HTP values of the RPLA and VPLA impellers. The results indicated that the RPLA impeller reduces the HTP by reducing the emission of PLA materials into air during the AM process.

The reduction of HTP, and other fatal and non-fatal accidents through AM, could also result in positive economic impacts as they lower the costs of compensation and health, avoid downtime, and improve productivity.

Table 25 Portfolio positions of pump impellers

Impeller	PPe	PPc	PP'e	PP'c
AM	0.0563	1.5839	0.7680	1.1436
SM	1.9437	0.4161	1.2320	0.8564

3.5.2 Employment level

The employment level changes for the same product when using different manufacturing strategies. AM reduces the labour hours in manufacturing time for setup/configuration, repair, and monitoring. Table 27 shows the calculation of changes to the level of employment in mass manufacturing scenarios under different manufacturing strategies. The results show that the level of employment is reduced when AM is replaced by IM and SM. The reduction of jobs in manufacturing VPLA impellers is higher compared to that of RPLA impellers as the latter involves more person-hours to sort out any expected difficulties in setup/configuration, repair, and monitoring of equipment with recycled material feedstock.

There are socio-economic implications of the production of AM impellers in terms of employment, which could

Table 26 HTP calculation

Parameter	RPLA	VPLA
Mass of impeller (kg)	0.0238	0.0252
Filament volume (cm^3)	21.0	21.5
Density ($g.cm^{-3}$)	1.14	1.18
Mass of material used (filament volume × density) (kg)	0.02394	0.02537
Mass emission	0.00014	0.00017
HTP	0.0868	0.1054

Table 27 Employment levels

Parameter	RPLA	VPLA	IMPLA	SM
No. of hours of labour for FU	0.618	0.57	0.84[a]	2.24[a]
Reduction from IM	26.4%	43.0%	-	-
Reduction from SM	72.4%	74.6%	-	-

[a][26]

Table 28 Conservation of natural resources

Parameter	RPLA	VPLA	IMPLA	SM
Primary material for FU (kg)	0.0238	0.0252	0.0273[a]	0.3161[a]
Reduction from IM	12.8%	7.7%	-	-
Reduction from SM	92.5%	92.0%	-	-

[a][26]

potentially be overcome through mass manufacturing that involves a highly skilled workforce.

The social impacts affecting the stakeholders, including the local community and society, have been evaluated as follows in terms of the conservation of natural resources and reduction of landfill. The data specific to each impeller have been used in the calculation of resource use and disposal in mass manufacturing scenario.

3.5.3 Conservation of natural resources

The conservation of natural resources has been investigated with the intensity of primary materials used in different manufacturing strategies in the mass manufacturing scenario.

The results in Table 28 show that the RPLA impeller reduces the material consumption by 12.8% compared to IMPLA impellers and 92.5% compared to SM impellers. The VPLA impeller reduces the material consumption by 7.7% compared to IMPLA and 92.0% compared to SM. This demonstrates that AM and material recycling could significantly reduce virgin PLA production, easing the burden on food production, i.e. sugar cane and corn starch.

Approximately 91% of the energy consumption can be reduced by replacing VPLA impellers with RPLA impellers for production, resulting in the conservation of resources for future generations, and thereby enhancing intragenerational social equity.

3.5.4 Reduction of landfill

The recycled PLA material used in mass manufacturing of RPLA impellers amounts to 101.2 kg per annum. Therefore, 9.25E-04 ha of landfill could be reduced from an industrial manufacturer mass manufacturing pump impellers with one 3D printer. The ELCA of the study also showed a reduction of land use by 96.8% by an RPLA impeller compared to a VPLA impeller. The diversion of waste PLA to 3D printing applications not only reduces toxins and leachate from landfill, but also reduces landfill area.

4 Conclusions and recommendations

The technical feasibility assessment evaluated the durability and service life of the RPLA and VPLA impellers. The estimated service life of the RPLA impeller was significantly reduced due to its lower density, ultimate tensile strength, and fatigue strength compared to the VPLA material. However, the RPLA impeller exhibited higher hydraulic performance compared to the original component in the hydraulic performance test. The RPLA impeller was deemed technically feasible since it exhibits higher pumping performance which was not affected by the reduced service life and mechanical properties.

The ELCA results showed that the RPLA impeller creates significantly lower environmental impacts compared to the VPLA impeller (93%). However, the life cycle costs of the RPLA impeller were significantly higher (74%) due to its lower service life compared to the VPLA impeller and its higher energy consumption in pump usage. The eco-efficiency assessment revealed that recycled materials significantly improve eco-efficiency performance. The social impact assessment revealed positive social impacts from additive manufacturing for employees in terms of health and safety. The employment levels of AM have reduced compared to SM due to high machine automation in AM, while opportunities for high-skilled employment and mass additive manufacturing have increased. The replacement of VPLA with an RPLA impeller could strengthen food security by conserving natural resources, including land and crops. The study found that the use of recycled material in AM is more techno-eco-efficient than the use of virgin materials and increases the waste diversion rate.

The techno-eco-efficiency assessment in this study was limited to the PLA material. The techno-eco-efficiency of recycling other common filament feedstock such as ABS, PET, and nylon could be further explored in future research. However, the results might be expected to vary due to the effects of viscosity and hygroscopic properties of different recycled materials [14]. As recycled PLA has lower technical performance properties when compared to virgin PLA, blends of recycled virgin materials (20% wt., 30% wt., and 50% wt.), fillers, and reinforcement fibres could be further investigated to improve technical performance and the resulting service life of the impellers. Furthermore, the benefits of using renewable energy sources for the production of manufacturing parts using recycled materials could also be investigated. In addition, the SLCA in this study could be further extended in future research using a reference scale approach to assess qualitative indicators, such as fair wages, employment relationships, social responsibility parameters, local employment opportunities, commitment to sustainability management and product performance, and end-of-life waste management responsibilities.

Appendix

Table 29 Factors for normalisation and weighing of the environmental impacts [26]

Environment impacts (EIs)	$GDEI_i$	Unit (per inhabitant/y)	Weight (Wi)
Global warming potential (GWP)	28,690	t CO_2 eq	11.44%
Photochemical smog	75	kg NMVOC	9.06%
Particulate matter	45	kg $PM_{2.5}$ eq	10.42%
Eutrophication	19	kg PO_4^{3-} eq	9.51%
Human	3216	kg 1,4-DB eq	10.08%
Terrestrial	88	kg 1,4-DB eq	10.08%
Freshwater	172	kg 1,4-DB eq	10.08%
Marine	12,117,106	kg 1,4-DB eq	10.08%
Land use	26	Ha a	8.83%
Acidification potential	123	kg SO_2 eq	8.38%
Abiotic depletion potential (ADP)	300	kg Sb eq	9.85%
Water use	930	m^3 H_2O	10.99%
Cumulative energy demand (CED)	246,900	MJ	11.44%

CO_2 carbon dioxide, *NMVOC* non-methane volatile organic compound, *$PM_{2.5}$* particulate matter, *PO_4^{3-}* phosphate, *DB* dichlorobenzene, *Ha a.* hectare per year, *SO_2* sulphur dioxide, *Sb* antimony, *H_2O* water, *eq.* equivalent, *MJ* megajoule

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The research data and material will be made available at Curtin Research Data Collection.

Declarations

Ethics approval The ethics approval for this research work was obtained from Curtin University under approval number HRE2020-0203.

Conflict of interest The authors declare no competing interests.

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