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Techno-Eco-Efficiency Assessment of Using Recycled Steel Fibre in Concrete

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Abstract: The steel industry is one the three biggest producers of carbon dioxide and it is experiencing technical challenges due to the gradual decrease in the quality of iron ore. Steel is extensively used in the construction industry for structural applications like steel components, while steel fibres are intensively used as additives to concrete in order to improve its performance. It is thus important to consider the use of recycled steel as a replacement for virgin steel in order to address the aforementioned environmental consequences. This paper applies the eco-efficiency framework to determine the economic and environmental implications of the use of recycled fibre in concrete as a replacement for virgin steel. A number of concrete mixes were considered that used virgin, recycled, and treated recycled rebar in concrete. The eco-efficiency framework, which uses a life-cycle assessment approach to calculate the environmental and economic values of concrete mixes in order to determine the portfolio positions of these concrete mixes, was used for comparison purposes and to establish the eco-efficient option(s). Whilst the recovery and recycling process is energy-intensive, the use of recycled steel fibre in reinforced concrete has been found to be eco-efficient and deliver the same level of mechanical performance compared to that obtained using virgin steel fibre. Treating steel fibre could improve its technical performance, but it was found to increase both costs and environmental impacts and was therefore identified as not being eco-efficient.

Keywords: recycled steel fibre; fibre-reinforced concrete; recycling; eco-efficiency

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1. Introduction

The infrastructure industries consume a large amount of energy and materials during the construction process, resulting in a high demand for finite natural resources and disrupting the relationship between ecosystems and human wellbeing. This sector alone consumes 50% of steel, 60–70% of cement, and 40–50% of the total energy consumption and uses 50% of land [1]. The exploitation of these nonrenewable resources is causing an increased ecological footprint, deforestation, loss of biodiversity, waste generation, and resource scarcity. In addition, buildings contribute around 26% of the total gases causing global warming, resulting in increased drought, bushfires, sea level rises, and heatwaves, and ultimately affecting our economy, livelihoods, and daily life adversely [2].

The iron and steel sector emits 7% of global emissions (i.e., 2.6 Gt CO_2e per year), which is mainly due to the use of fossil fuels, and 7–9% of global anthropogenic CO_2 emissions—the highest level among heavy industries [3].

As essential raw materials for forging steel are mined on a large scale, their supply is gradually decreasing, and it is not always possible to meet the demands of the infrastructure sector. Steel prices tend to rise with the increase in demand and continue to increase with growing resource scarcity [4]. This research thus endeavors to use rebar recovered from waste materials in concrete mixes to reduce the dependence on virgin steel.

The incorporation recycled fibers into fiber-reinforced concrete (FRC) marks a significant stride towards sustainable construction practices, aligning with global efforts to reduce waste and promote the use of eco-friendly materials [5]. The utilization of recycled fibers, derived from industrial, post-consumer, or agricultural sources, in FRC not only addresses environmental concerns, but also enhances the mechanical and durability properties of concrete. This innovative approach leverages the inherent strength and resilience of recycled fibers to improve crack resistance, tensile strength, and energy absorption capabilities of concrete structures, thereby extending their service life and reducing related maintenance costs [6]. Moreover, the adoption of recycled fibers in FRC represents a circular economy model in the construction industry, offering a path via which to minimize the carbon footprint associated with building materials and fostering the development of green infrastructure [7]. The integration of recycled fibers into FRC poses unique challenges, including variability in material properties and behavior under loading, which necessitates comprehensive studies and advancements in mix design, processing techniques, and performance evaluation.

Whist FRCs produced using recycled fibre and virgin (non-recycled) fibre were found to exhibit outstanding mechanical performances, these mixes had both economic and environmental implications for energy consumption and treatment processes during their manufacture, transportation, and consumption. An eco-efficiency framework was used to assess the economic and environmental performance of alternative options in order to select eco-efficient options for energy, construction materials, and manufacturing [8–12]. Some of these studies involved the use of by-products (e.g., fly ash, slag) and wastes (e.g., waste crushed brick powder, recycled aggregates) in concrete and geopolymer concrete. A techno-economic analysis revealed that coastal protection concrete structures, with decommissioned components accounting for more than 25% of the concrete weight, could be both economically viable and environmentally friendly options [13]. To date, no research has applied the EE Framework to assess the techno-eco-efficiency of the use recycled steel fibre in concrete. This research is timely considering the fact that the steel is carbon-intensive and so the use of recycled rebar to reinforce concrete could reduce the emissions from steel and the concrete industries by the reducing production and consumption of virgin steel. Therefore, an EE framework was used in this study to assess the environmental and economic implications of using this concrete by using environmental life-cycle assessments and establishing life-cycle costs. The environmental impacts and economic values of these concrete mixes were converted into eco-efficiency portfolios for comparative purposes.

2. Materials and Methods

2.1. Life-Cycle Assessment

Life-cycle assessments (LCAs) evaluate the environmental and economic viability of the use of recycled steel fibres to replace commercial virgin steel fibres in the production of fibre-reinforced concrete. In this study, the LCA was performed in accordance with ISO 14040 [14]. This standard provides guidelines for a life-cycle assessment, specifically when defining the four stages of investigation, i.e., the establishment of goal and scope, inventory analysis, impact assessment, and interpretation. The goal of the LCA is to compare the degree of eco-efficiency of each of the fibre-reinforced concretes, which were produced using different types of steel fibres and volumetric ratios. The scope involves the sourcing of raw material, their conversion into construction materials, their transportation, and the manufacturing of concrete specimens at Curtin University (cradle-to-gate). The functional unit that was used in the life-cycle inventory (LCI) to compare each type of fibre-reinforced concrete was an equivalent of concrete with 1 MPa flexural strength. The life-cycle cost (LCC) also considered cost in relation to strength (i.e., AUD/MPa) as a functional unit. The LCI represented the inputs of each type of FRC, using data specific to the concrete as prepared at Curtin University under Australian conditions.

An LCI is a pre-requisite when determining the environmental impacts of the life-cycle stages of concrete mixes, including the extraction of raw materials, transportation, energy consumption, and manufacturing of concrete mixes. The importance of this stage is defined in relation to the exact inputs going into the creation of the concrete mix at a specific time and place. The processes and transport methods used to move similar mixes manufactured in different locations can alter the overall impacts of the products. Table 1 shows the LCIs of six concrete mixes using different compositions of steel fibres.

Table 1. LCIs of six concrete mixes.

	Cement (kg)	Sand (kg)	Aggregate (kg)	Water (L)	Plasticer (L)	Steel Fibre (kg)	Recycled Steel Fibre (kg)	Treated with Acetone (kg)
M1	398	566	1261	175	1.99	0	0	0
M2VSF	396	563	1255	174	1.98	12		
M3RSF	396	563	1255	174	1.98		12	
M4TRSF	396	563	1255	174	1.98		12	94
M5RSF	394.02	560.34	1248.39	173.25	1.9701	24		
M6RSVS	394.02	560.34	1248.39	173.25	1.9701	12	12	

The LCI data were entered into the Simapro 9.4 LCA software to calculate the total environmental impacts resulting from the production of one functional unit (MPa) of fiber-reinforced concrete (FRC). These environmental impacts resulted from the release of gases, effluents, or their equivalents into the environment. Different pollutants cause different impacts.

Table 2 shows the environmental impacts that are specific to Australian conditions. Each of these environmental impacts is associated with the emission of gases specific to environmental impacts. A total of 14 environmental impacts were calculated using the method of Bengtsson and Howard [15] and Renouf et al. [16]. The input values in the LCI of each concrete mix were multiplied by the corresponding emission factors to estimate the environmental impacts. Data were normalised and weighted in order to convert the environmental impacts into a common unit (i.e., eco-point). The normalisation of data for Australian conditions involves the comparison of environmental impact values with the gross domestic environmental impacts for the average Australian person. The environmental impacts can then be calculated in terms of equivalency to the annual environmental impacts caused by an Australian inhabitant per year. The process of normalisation is essential to understanding the relative significance specific to a population or a region and provides a local impact. The weightings associated with each environmental impact represent the relative importance of each of these environmental impacts. The weightings are specific to Australian conditions as determined by the local experts, with different impacts having different potential outcomes on humans.

Table 2. Environmental impacts and normalisation factors [15].

Environmental Impacts	Gross Domestic Environmental Impact	Weighting
Global warming potential	28,690 kg CO_2 eq	19.50%
Eutrophication	19 kg $PO_4{}^{3-}$ eq	2.90%
Water depletion	930 m^3 H_2O	6.20%
Land use and ecological diversity	26 Ha a	20.90%
Photochemical smog	75 kg NMVOC	2.80%
Human toxicity	3216 kg 1,4-DB eq	2.70%
Terrestrial ecotoxicity	88 kg 1,4-DB eq	10.30%
Freshwater ecotoxicity	172 kg 1,4-DB eq	6.90%
Marine ecotoxicity	12,117,106 kg 1,4-DB eq	7.70%
Ionising radiation	1306 kg U235 eq	1.90%
Ozone depletion	0.002 kg CFC-11 eq	3.90%
Abiotic depletion	300 kg Sb eq	8.20%
Acidification	123 kg SO_2 eq	3.10%
Respiratory inorganics	45 kg $PM_{2.5}$ eq	3.00%

2.2. Life-Cycle Cost

Costing was calculated based on the inputs required to produce concrete mixes with flexural strength equivalent to 1 MPa. Therefore, the functional unit required to maintain consistency is same for both LCA and life-cycle cost (LCC). The same inputs that are contained in the LCI for LCA are used to calculate cost using an LCC. The labor cost was the only item that was not available in the LCI, but it was included in this economic analysis based on recent documents. The local market prices were obtained to estimate the costs shown in Table 3. The environmental and economic values are given in per m^3, which are converted into the values per MPa equivalent by using the averaged flexural tensile strength of fibre-reinforced concrete (Table 4). Flexural bending tests were carried out in the structural laboratory of Curtin University between 6 April 2023 and 24 April 2023 to measure flexural strength. Our mixing, moulding, curing, handling, and testing procedures adhere to the guidelines specified in AS 1012.8.2 [17]. Like the residual tensile strength, the economic and environmental values of these mixes could vary. Therefore, an eco-efficiency framework was used to identify an economically and environmentally viable concrete mix that could be used to deliver the same tensile strength.

Table 3. Costs of different fibre concrete mixes.

Unit Price A$	Cement per kg	Sand per kg	Aggregate per kg	Water (L)	Plasticiser (L)	Steel Fibre per kg	Recycled Steel Fibre per kg	Treated with Acetone kg	Transport tkm	Construction per m^3	Labour per m^3	Total
Unit price	0.22	0.0	0.0	0.002	3.7	3.5	1.5	15.4	0.09	0.55	31.25	
M1	87.56	20.9	42.0	0.35	7.29	0	0	0	4.61	44.43	31.25	238
M2VSF	87.12	20.8	41.8	0.35	7.25	42	0	0	4.60	44.43	31.25	280
M3RSF	87.12	20.8	41.8	0.35	7.25	0	18	0	4.61	44.43	31.25	256
M4TRSF	87.12	20.8	41.8	0.35	7.25	0	18	1440	4.69	44.43	31.25	1696
M5RSF	86.68	20.7	41.6	0.35	7.22	84	0	0	4.56	44.43	31.25	321
M6RSVS	86.68	20.7	41.6	0.35	7.22	42	18	0	4.59	44.43	31.25	297

Source: [18] and Rubber Gem, Wattleup WA 6166, Australia.

Table 4. Weight peak and residual tensile strengths for LCA analysis.

Groups	f_{cl} (MPa)	f_{R1} (MPa)	f_{R2} (MPa)	f_{R3} (MPa)	f_{R4} (MPa)	Average (MPa)
M1	4.20	0	0	0	0	0.84
M2VSF	5.47	2.91	2.29	1.92	1.59	2.8
M3RSF	5.30	0.99	1.00	0.93	0.83	1.8
M4TRSF	5.51	1.66	1.38	1.38	1.41	2.3
M5RSF	5.48	2.03	1.64	1.68	1.69	2.5
M6RSVS	5.64	4.3	3.89	3.54	3.25	4.1

2.3. Eco-Efficiency Analysis

Both environmental and economic data were normalized to produce the eco-efficiency portfolio. We followed the procedure used in Biswas and Zhang's study [18], and the steps for calculating the eco-efficiency portfolios are discussed below. Firstly, the normalised economic cost (N_c) was determined by dividing the concrete sample cost (CS) by the GDP per inhabitant (Equation (1)).

$$N_c = \frac{CS}{GDP}. \tag{1}$$

The environmental impact value (EI) was divided by the corresponding gross domestic environmental impact (GI) to normalise the environmental impact of each type of fibre-reinforced concrete. Equation (2) was used to calculate the normalised value, N_e.

$$N_e = \frac{EI}{GI}. \tag{2}$$

Since different environmental impacts had different levels of importance, the normalised value for each of 14 environmental impacts was multiplied by the corresponding weight (Table 2). The weights (W_i) were specific to Australian conditions and determined the relevance and importance of the environmental impacts of each inhabitant of a region. The sum of all weighted normalised values (E_e) is expressed in Equation (3).

$$E_e = \sum N_e \times W_i. \tag{3}$$

The initial positions (iPP) used for the eco-efficiency portfolio are the ratio of the weighted normalised environmental impact to the normalised cost for each type of FRC, as compared to the average environmental impact and average normalised cost, where MX represents each type of FRC, and the average weighted normalised environmental impacts and normalised costs are the averages for all six types of fibre-reinforced concrete mixtures (Equations (4) and (5)).

$$iPP_{MX,\,e} = \frac{E_{eMX}}{E_{eAV}}, \tag{4}$$

$$iPP_{MX,\,c} = \frac{N_{cMX}}{N_{cAV}}. \tag{5}$$

The portfolio positions were further adjusted by determining the cost-effectiveness of each sample relative to the others. The cost or environmental impact of any individual component changes the portfolio position of each product relative to the others. Also, the performance of one type of concrete changes the eco-efficiency performance of other options. The environmental impact can be expressed in relation to cost relevance factor R using Equation (6).

$$R = \frac{E_{eAV}}{N_{cAV}}. \tag{6}$$

The normalised costs and weighted, normalised environmental impacts were balanced using Equations (7) and (8) in order to calculate the final portfolio positions (PP). This is an important step in ensuring that each of the portfolio positions of concrete mixes are compared relative to each other. As the parameters of one sample change (e.g., through increased emissions or costs), the eco-efficiency performance of other samples change relative to that sample.

$$PP_{MX,\,e} = \frac{iPP_{AV,\,e} + (iPP_{MX,\,e} - iPP_{AV,\,e}) * \sqrt{R}}{iPP_{AV,\,e}}, \tag{7}$$

$$PP_{MX,\,c} = \frac{iPP_{AV,\,c} + (iPP_{MX,\,c} - iPP_{AV,\,c}) / \sqrt{R}}{iPP_{AV,\,c}}. \tag{8}$$

An eco-efficiency portfolio provided a visual representation of the comparison of the levels of eco-efficiency of different concrete mixes. The square diagram compares the normalised economic costs and weighted normalised environmental impacts, as described in Equations (7) and (8), to determine the portfolio positions (PP) of each of the options being compared. The concrete mixes that are not eco-efficient are positioned under the diagonal line of the eco-efficiency portfolio. Any option over the diagonal line on the eco-efficiency portfolio is considered to be eco-efficient. Figure 1 shows an example of an eco-efficiency portfolio.

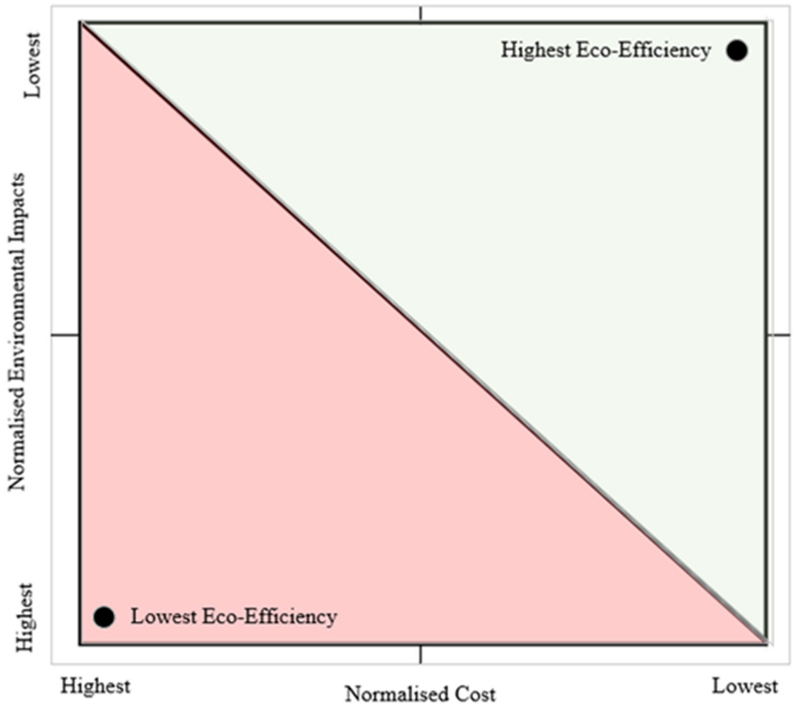


Figure 1. Example of an eco-efficiency portfolio [18].

2.4. Uncertainty Analysis

The LCI data were mainly obtained via consultation with industry partners and using data from the published literature. Uncertainties associated with the use of the data were estimated by applying Monte Carlo Simulation (MCS) to all life-cycle inventory data. The simulation was an iterative process which utilised an input value from a probability function to produce a distribution of all input values for 1000 iterations at a 95% confidence level [19].

3. Results and Discussion

3.1. Life-Cycle Environmental Impacts

The environmental impact values for the six groups of concrete mixtures are presented in Table 5 in terms of flexural strength equivalents of MPa. M4TRSF was found to have the highest environmental impacts compared to other FRC mixes, mainly due to use of acetone to treat recycled rebars. M1, which is a conventional concrete with no rebar, has the highest environmental impacts in terms of MPa, followed by M4TRSF, M3RSF, M5RSF, M2VSF, and M6RSVS, respectively. This is because concrete with no fibre has the lowest strength compared to the FRCs. While the use of recycled fibre as a replacement of virgin commercial steel fibre reduces environmental impacts on a per MPa basis, this is not the case when these values are presented in terms of MPa. This is because the FRCs using recycled fibres have a lower averaged tensile strength than those using commercial fibre, which could be due to the nature of recycled fibre using non-uniform lengths and shapes. Nevertheless, it is worth noting that increasing the amount of recycled fibre from M3RSF to M5RSF significantly increases the averaged concrete tensile strength from 1.81 MPa to 2.5 MPa, as measured at Curtin University's laboratory, and these values are close to those of mixes produced using commercial fibre. It is thus necessary to consider economic aspects when choosing steel fibres.

Table 5. Environmental impacts per unit of MPa.

Impact Category	Unit	M1	M2VSF	M3RSF	M4TRSF	M5RSF	M6RSVS
GWP	kg CO_2	564	171	266	287	197	119
EP	kg PO_4— eq	2.55×10^{-1}	7.59×10^{-2}	1.20×10^{-1}	1.43×10^{-1}	8.66×10^{-2}	5.31×10^{-2}
LU	Ha a	1.33×10^{-3}	3.94×10^{-4}	6.39×10^{-4}	5.97×10^{-4}	4.45×10^{-4}	2.80×10^{-4}
WU	M3 H_2O	2.06×10^{0}	6.23×10^{-1}	9.64×10^{-1}	8.57×10^{-1}	7.21×10^{-1}	4.32×10^{-1}
HTC	DALY	1.18×10^{-6}	3.76×10^{-7}	5.58×10^{-7}	5.43×10^{-7}	4.55×10^{-7}	2.63×10^{-7}
FWAE	DAY	1.08×10^{-10}	3.17×10^{-11}	5.1×10^{-11}	4.89×10^{-11}	3.58×10^{-11}	2.23×10^{-11}
MAE	DAY	5.57×10^{-8}	1.65×10^{-8}	2.71×10^{-8}	2.4×10^{-8}	1.86×10^{-8}	1.19×10^{-8}
TE	DAY	2.24×10^{-11}	6.85×10^{-12}	1.08×10^{-11}	8.95×10^{-12}	8×10^{-12}	4.88×10^{-12}
ODP	kg CFC-11 eq	3.19×10^{-6}	9.4×10^{-7}	1.52×10^{-6}	1.29×10^{-6}	1.06×10^{-6}	6.65×10^{-7}
TAP	kg SO_2 eq	1.92×10^{0}	5.80×10^{-1}	9.13×10^{-1}	1.11×10^{0}	6.69×10^{-1}	4.08×10^{-1}
POF	kg NMVOC	1.94×10^{0}	5.81×10^{-1}	9.16×10^{-1}	1.14×10^{0}	6.65×10^{-1}	4.07×10^{-1}
IR	kBq U235 eq	9.05×10^{-1}	2.67×10^{-1}	5.06×10^{-1}	1.31×10^{0}	3.00×10^{-1}	2.21×10^{-1}
RE	kg PM2.5 eq	1.04×10^{-1}	3.21×10^{-2}	4.95×10^{-2}	5.03×10^{-2}	3.77×10^{-2}	2.25×10^{-2}
ADP	kg Sb eq	0.000176	4.6×10^{-5}	8.47×10^{-5}	6.93×10^{-5}	4.49×10^{-5}	3.28×10^{-5}

GWP = global warming potential; EP = eutrophication potential; LU = land use; WU = water use; HTC = human toxicity—carcinogenic; FWAE = fresh water aquatic ecotoxicity; MAE = marine aquatic ecotoxicity; TE = terrestrial ecotoxicity; ODP = ozone depletion potential; TAP = terrestrial acidification potential; POF = photochemical oxidant formation; IR = ionising radiation; RE = respiratory effects; ADP = abiotic depletion potential.

3.2. Eco-Point Analysis

The environmental impacts of each type of FRC are converted into single score known as 'eco-points'. The eco-point values of M1, M2VSF, M3RSF, M4TRSF, M5RSF and M6RSVS are 2.14×10^{-3}, 1.73×10^{-3}, 2.70×10^{-3}, 3.01×10^{-3}, 1.99×10^{-3} and 1.21×10^{-3}, respectively, in terms of MPa.

The impact of global warming contributed significantly to the overall performance of these mixes, accounting for 67% of the overall environmental impacts of these six mixes. Figure 2a–c show the flow networks of M1, M3RSF, and M4TRSF concrete mixes. It appears that cement alone accounts for between 60% to 82% of the total global warming impact. Whilst steel's carbon footprint is twice as great as cement's, the latter contributes the most due to the use of small amounts of rebar. GWI has also been found to contribute to the significant impact (64–65%) of concrete mixes that use natural and recycled aggregates, OPC, and industrial by-products, mainly due to use of the cement [20]. Future studies, therefore, should consider the partial substitution of Ordinary Portland Cement (OPC) with lesser amounts of energy-intensive materials while maintaining the required level of structural performance and pozzolanic properties. Fly ash, ground granular blast furnace, slag, and nano-silica, which are derived from the combustion of coal, the conversion of iron into steel, and mineral processing, can be considered as partial replacements for cement.

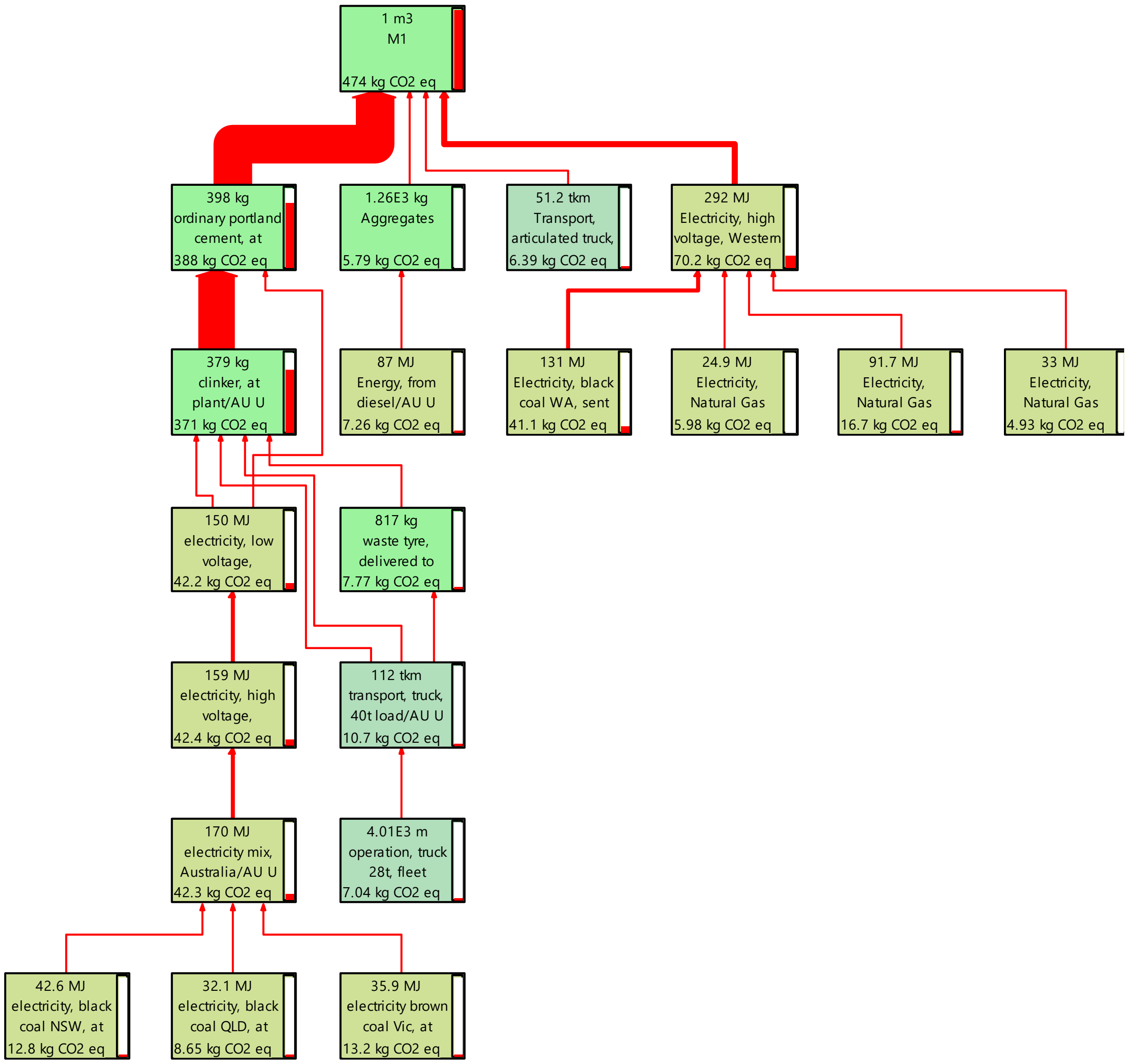
After global warming impact, photochemical smog was the second largest hotspot (12–14%) for all mixes, mainly due to the emissions of NOx and SOx during cement production (Figure 3). This result is similar to those seen in published studies [20].

The implications of recycled fibre treatment were as follows: all FRC mixtures were found to have lower environmental impacts than controlled concrete. The environmental impacts of M2VSF, M3RSF, M4TRSF, M5RSF, and M6RSVS were found to be 70%, 53%, 47%, 65%, and 79% lower than those of the controlled mix. M4TRSF was found to have the lowest potential to reduce environmental impacts. This is because the use of acetone treatment (i.e., 7.8 L per kg of recycled fibre) introduces the additional emission of 171 kg CO_2eq per m^3 of concrete. This alone accounts for 26% of the total carbon footprint, and substantially increases the overall carbon footprint of M4TRSF (Figure 2). On the other hand, the use of acetone to treat recycled fibre was found to increase the averaged flexural strength of FRC by 25%, which increased environmental impacts by 12%.

3.3. Implications of Using Recycled Fibre

The environmental impacts of fibre (e.g., 1.03 kg CO_2/kg of rebar) are slightly higher than those of cement (e.g., 0.97 kg CO_2/kg of OPC), but fibre contributes only 2% of total

CO_2 emissions. This is because fibre accounts for only 0.5% of the total volume of the concrete matrix. The carbon footprint value of recycled fibre is 0.8 kg CO_2 per kg, as opposed to 1.03 kg CO_2 per kg of virgin commercial fibres. This indicates a 22.3% reduction in CO_2 emissions, which is thus beneficial to the environment, especially considering the high levels of global concrete consumption. Similarly, Gan et al. [21] found that the use of steel made of scrap as a replacement for virgin steel when reinforcing the concrete mix could reduce the CO_2 emissions by 18%. However, it is worth noting that because fibre only accounts for 0.5–1.0% of volume in FRC, the replacement of fibres with recycled materials would not make noticeable environmental impacts compared to the replacement of concrete and cement.



(**a**)

Figure 2. *Cont.*

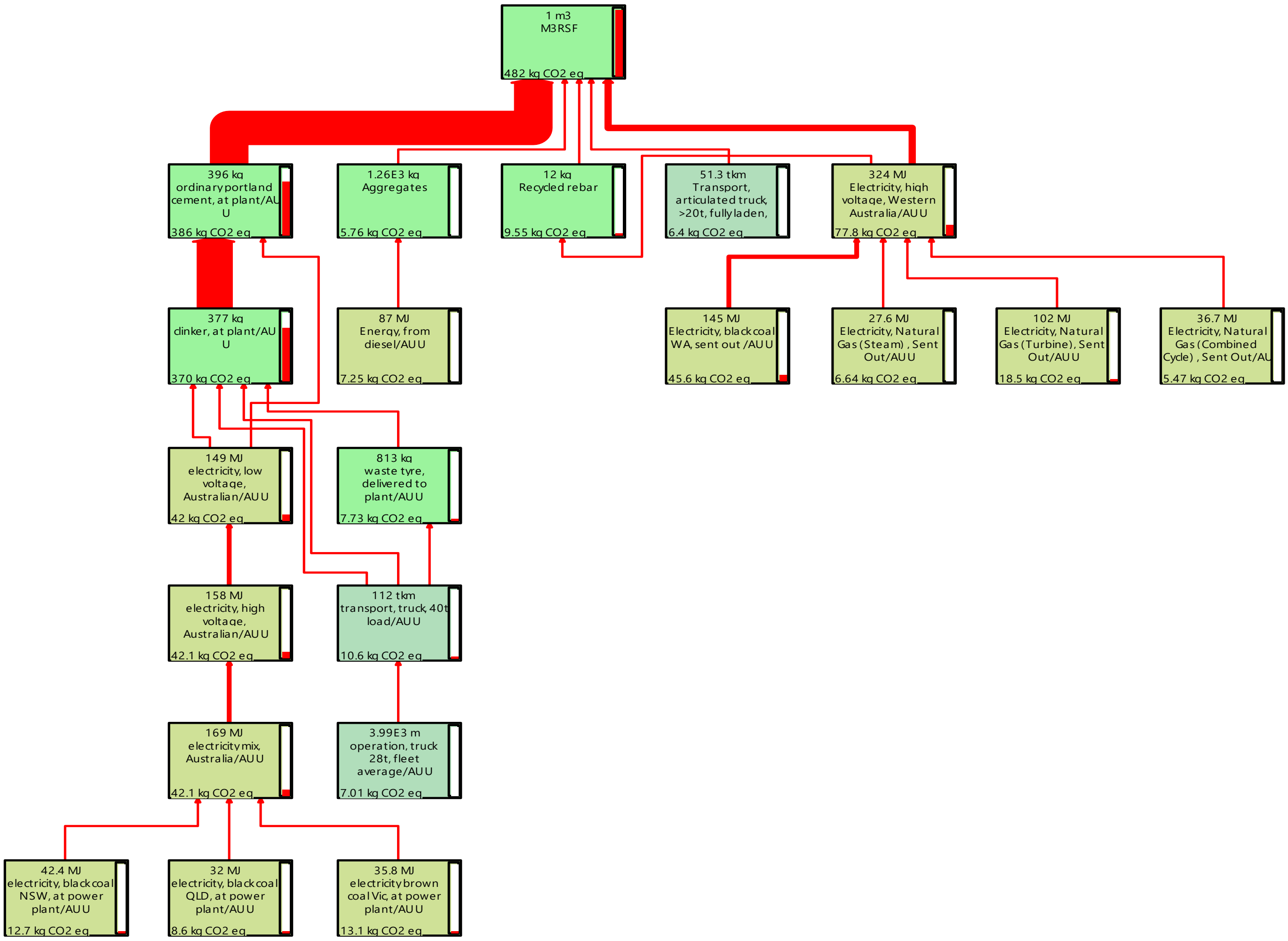


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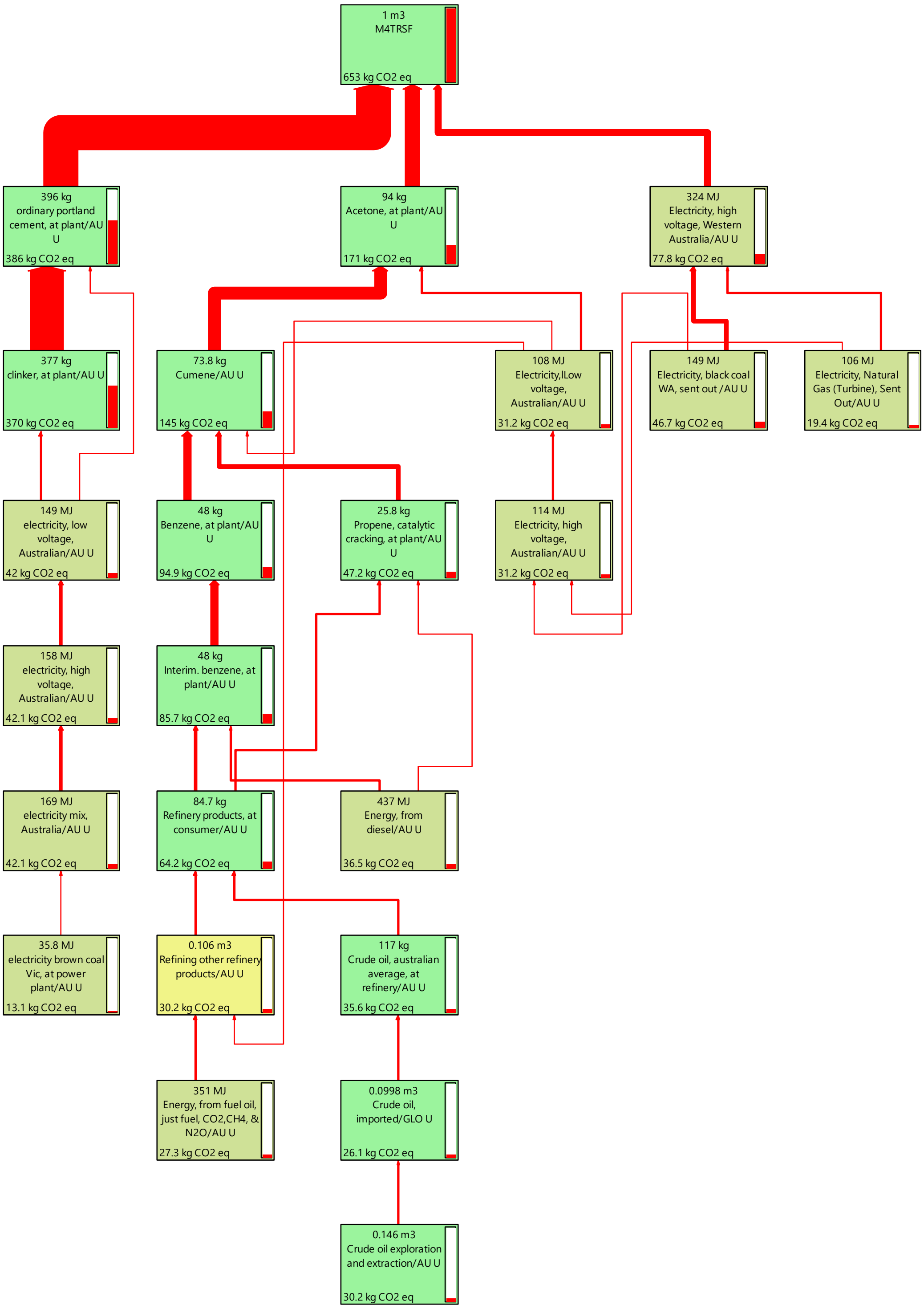
Figure 2. *Cont.*



(c)

Figure 2. Flow networks of concrete mixes: (**a**) M1, (**b**) M3RSF, and (**c**) M4TRSF.

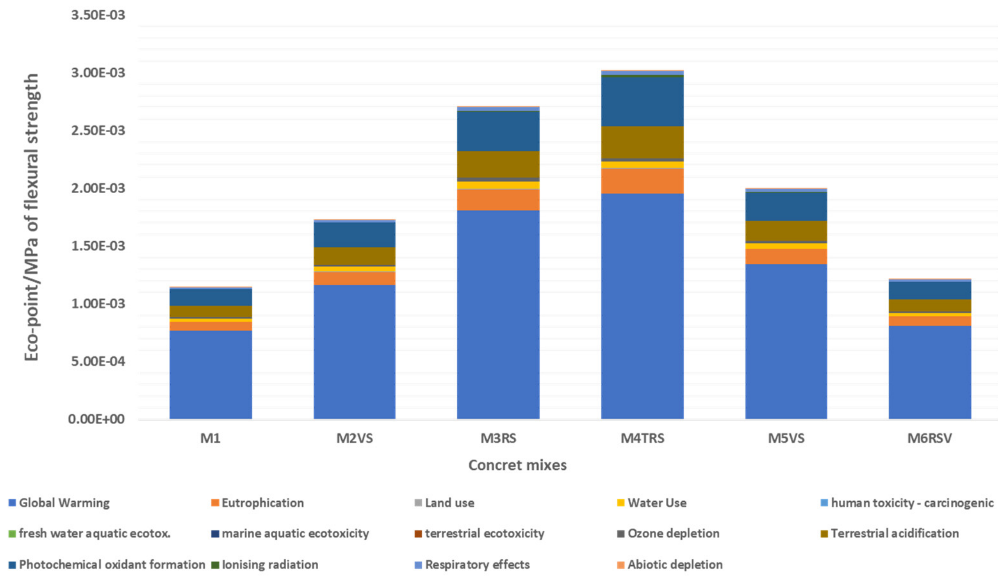


Figure 3. Environmental impacts of six concrete mixes in terms of 'eco-points'.

3.4. Eco-Efficiency Portfolios

The costs of FRC mixes in Table 3 are normalised using Equation (5) and then divided by the corresponding averaged flexural strength to obtain the normalised values per inhabitant. The eco-efficiency portfolios (PP'e and PP'c) of six types of concrete mixes can then be determined using the normalised values for costs and the environmental impact values. As shown in Figure 4, all concrete mixes except for M4TRSF are found eco-efficient (above the diagonal line), confirming that the use of recycled fibre in concrete could improve the economic and environmental performances of the products, delivering a better concrete mechanical performance. The use of expensive and carbon-intensive acetone to treat recycled rebar made concrete not eco-efficient.

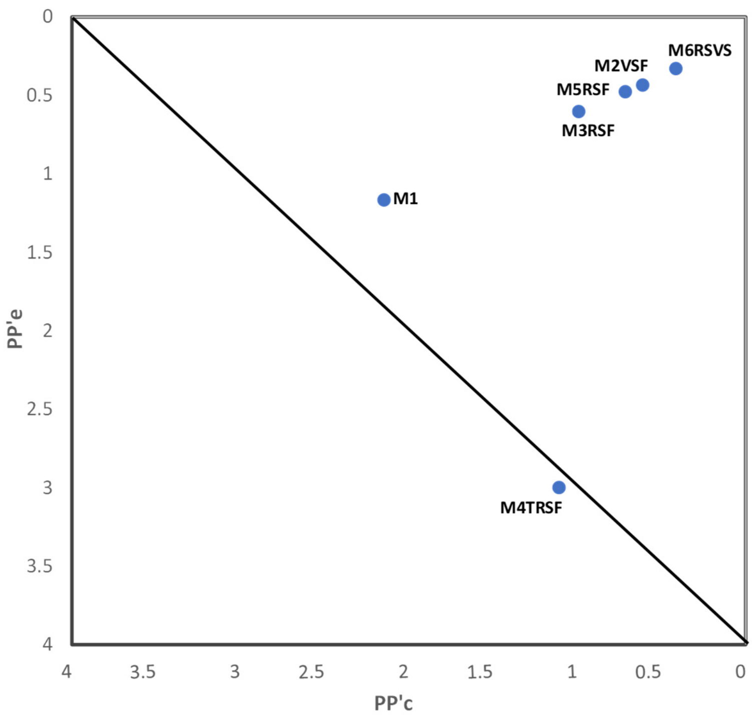
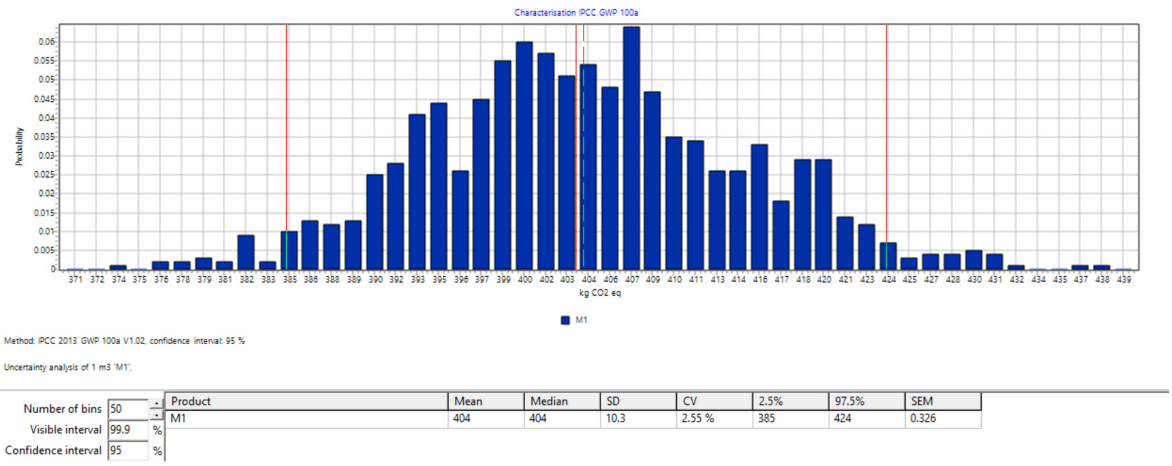


Figure 4. Eco-efficiency portfolios of different concrete/fibre-reinforced concretes.

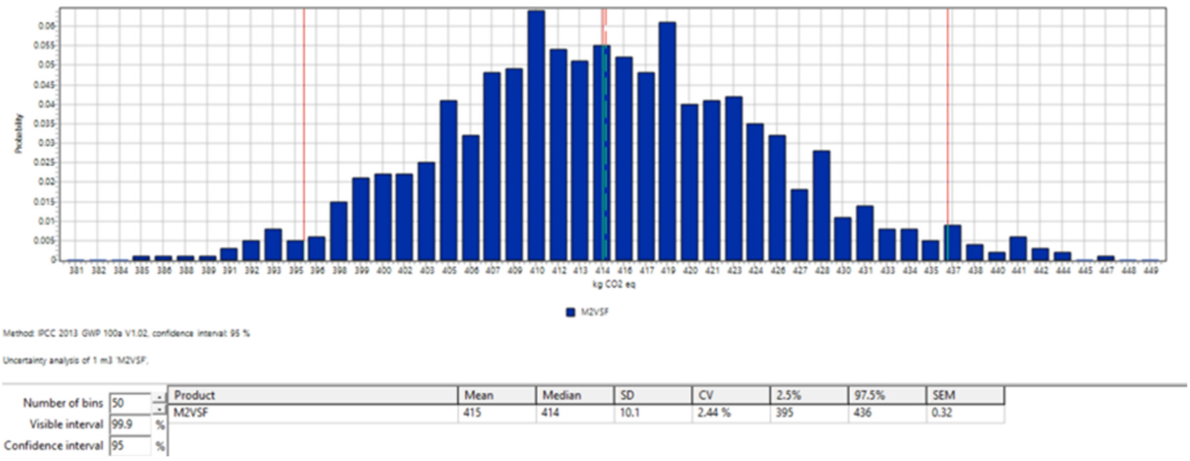
3.5. Uncertainty Analysis

Figure 5 shows the results of the uncertainty analysis of carbon footprints of six concrete mixes (M1, M2VSF, M3RSF, M4TRSF, M5RSF, and M6RSVS). Monte Carlo analysis was performed for 1000 iterations with a confidence interval of 95% to determine the uncertainty of the impacts of the quality of inventory data on the quality of results. Since GWP was found to have the most significant impact, the uncertainty analyses of the results for the global warming potential were assessed to assess the statistical validity of the LCA outputs.

The mean values of these mixes varied from 404 kg CO_2 eq. to 574 kg CO_2 eq (Figure 5). The differences between the calculated impact values and mean were between 1.9% and 2.55%. The values of standard deviation (SD) of the global warming potential or carbon footprint indicate that the degree of uncertainty in the calculated impact is relatively small. The mean values of GWP (i.e., between 404 and 574 kg CO_2 eq.) are of similar magnitudes to the values reported by Crossin (401 kg CO_2 e-) for Australian concrete mix [22] and international studies (361–387 kg CO_2 e-) by Braga et al. [23] and Kurda et al. [24].

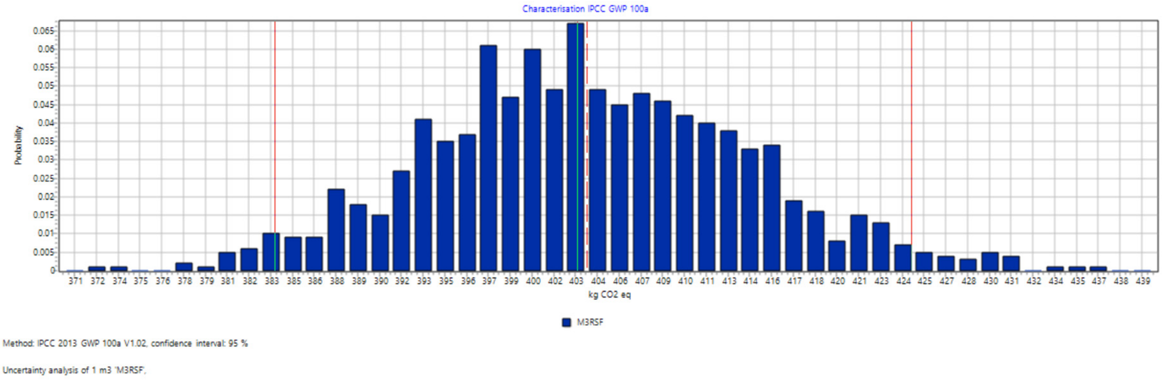


M1



M2VSF

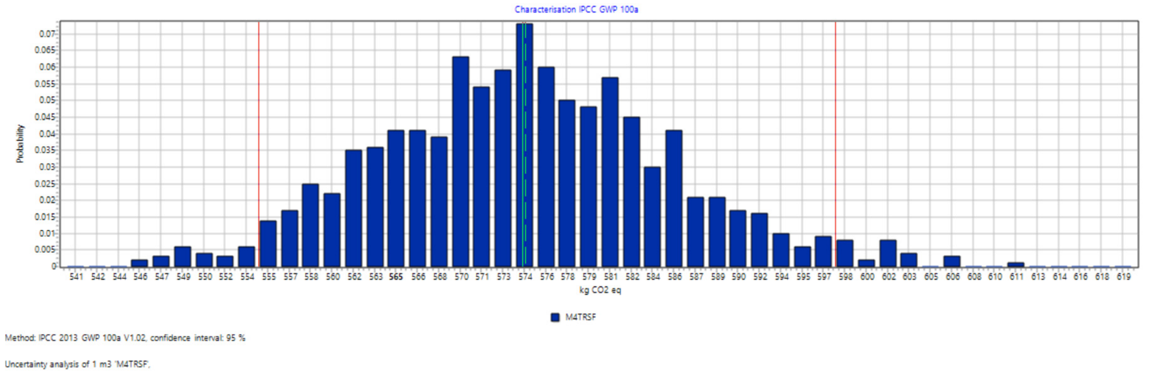
Figure 5. *Cont.*



Number of bins	50
Visible interval	99.9 %
Confidence interval	95 %

Product	Mean	Median	SD	CV	2.5%	97.5%	SEM
M3RSF	404	403	10.2	2.53 %	384	424	0.322

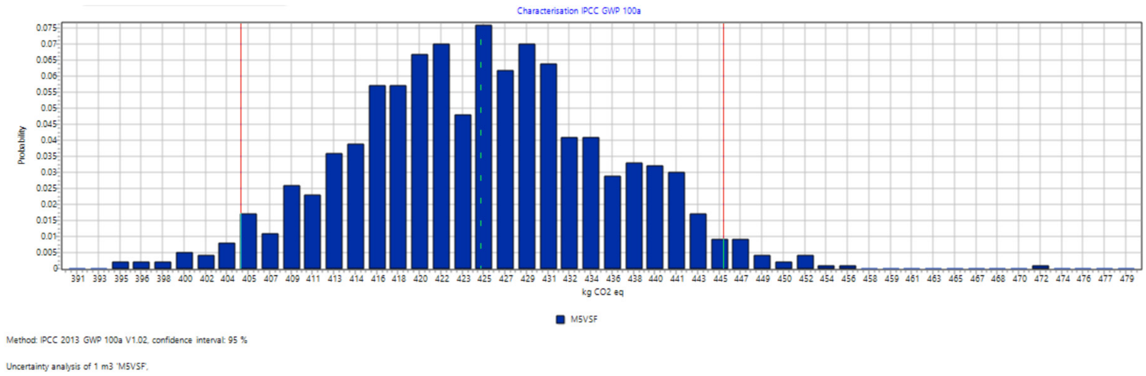
M3RSF



Number of bins	50
Visible interval	99.9 %
Confidence interval	95 %

Product	Mean	Median	SD	CV	2.5%	97.5%	SEM
M4TRSF	574	574	10.9	1.89 %	555	598	0.344

M4TRSF

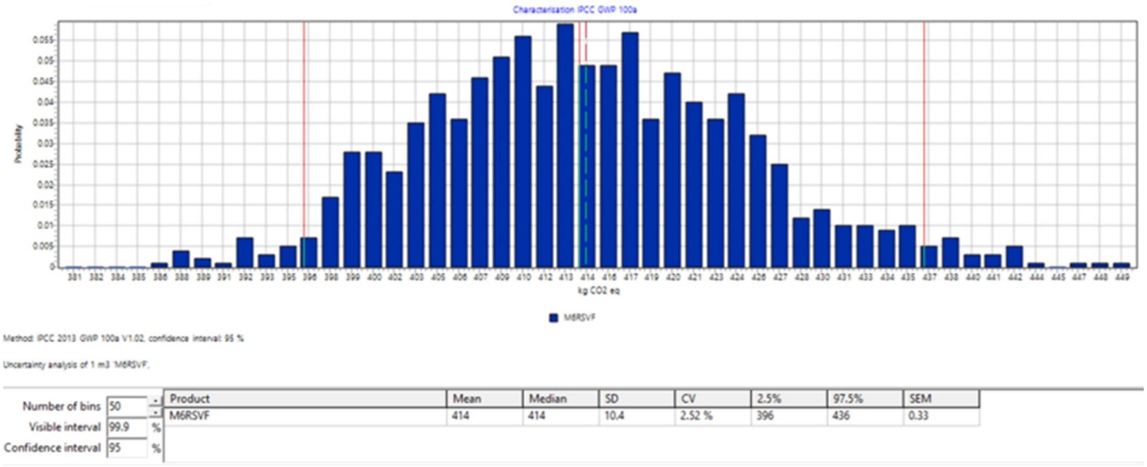


Number of bins	50
Visible interval	99.9 %
Confidence interval	95 %

Product	Mean	Median	SD	CV	2.5%	97.5%	SEM
M5VSF	425	425	10.6	2.49 %	405	445	0.334

M5RSF

Figure 5. *Cont.*



M6RSVS

Figure 5. Monte Carlo Analysis.

4. Conclusions

Global warming was found to be the primary significant impact resulting from the production of cement and steel. The use of recycled steel fibre in concrete as a complete or partial replacement of virgin fibre can reduce its impacts. These impacts are reduced in terms of volume, but not be in terms of flexural strength, as the use of recycled and by-product-based materials reduces the structural strength of concrete mixes. The use of recycled steel fibres to produce FRC was found to be eco-efficient, reducing environmental impacts and reducing costs. The use of treated steel fibre (TSF) was found to increase both costs and environmental impacts and therefore the concrete made using TSF was identified as not being eco-efficient. We therefore suggest performing further studies to discover effective and efficient fibre pretreatment methods.

The important aspect of the use of recycled rebar is that it can decarbonize the steel industry, as the steel industry alone is responsible for 8% of GHG emissions [3]. A gradual change from virgin steel to recycled steel can reduce the production of steel and so lower its overall contribution to global GHG emissions.

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