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Life Cycle Assessment Based Analysis of Water Bottle Designs for Defence Application

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ABSTRACT

This paper presents the successful implementation of the Life Cycle Assessment (LCA) approach for the sustainable development of a defence product. Alternative designs of this product are evaluated from the environmental burden perspective. The products considered are water bottles used by the armed forces in places like the Siachen glacier, where environmental factors are of great concern. From the environmental degradation perspective, the suitability of three existing bottle types has been analysed using LCA and Life Cycle Impact Assessment (LCIA) approaches on SimaPro software for each of its components and the bottle as a whole. Using this software, uncertainty analysis has also been carried out by conducting a Monte Carlo simulation for a reasonable confidence level. The latest design was found to have the least environmental burden, being 82.62 % less compared to the first design. To augment the environmental performance further, the best design was again reviewed by carrying out component-level analysis to identify feasible alternative materials that would be functionally equivalent but with lower environmental impact. It suggested switching to lower impact material for the cap and cap cover for the proposed design. With the adoption of the changed material, the environmental performance improved by 10.61 per cent as compared to the best design and 84.46 per cent compared to the earliest design.

Keywords: Life cycle assessment; Product design; Design for environment; Product improvement; SimaPro; Environmental conscious design

1. INTRODUCTION

Life Cycle Assessment (LCA) is a technique for quantitative evaluation of the environmental impact of any product or service throughout its life cycle, i.e. raw material extraction, production, use and final disposal. This is done by compiling inventories of relevant inputs and outputs and evaluating the potential environmental impacts associated with those inputs and outputs. Subsequently, the results of the inventory and impact analysis phases are interpreted in relation to the objectives of the study[1-2]. This is depicted in the Input-Processor-Output model shown in Fig.1. For developing a product, natural as well as artificial inputs are fed to some processing unit, which in turn results in outputs in form of product, by-product and also some emissions to the nature.

Life cycle assessment-based product design focuses on optimizing inputs by minimizing the use of depleting natural resources and on optimizing outputs to minimize their impact on the environment. According to Horvath[3] *et al.*, the main goals of LCA-based design are minimizing the toxic releases to the environment, using renewable resources, and effectively managing non-renewable resources. Fiskel and Wapman[4], and Boothroyd and Alting[5] mention five strategies for Design for Environment (DfE), viz., design for (i) energy saving (ii) re-usability (iii) dis-assembly (iv)re-manufacturability, and (v) recyclability. The refurbishment concept, applied to used missiles at DRDO, is a good example of this strategy. Howarth and Hadfield[6] came up with a model for sustainable product development where they talked about the role of all stakeholders, especially designers.

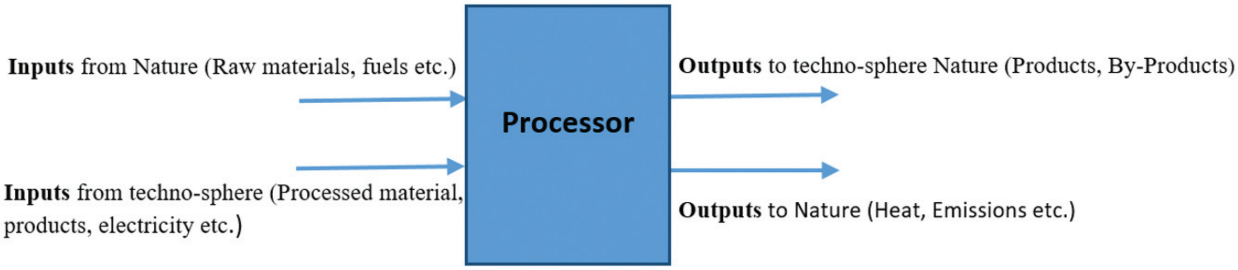

Figure 1. Input-processor-output model.

Due to increasing concern about environmental sustainability, engineering designers are now prompted to adopt a product design methodology, such as DfE, to reduce

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the negative impact on the environment[7-9]. Researchers have attempted to use LCA in conjunction with other tools and techniques to have a better deal. Devanathan[10], *et al.* used LCA with quality function deployment (QFD), functional component matrix and function-impact matrix. Alemam and Li[11] integrate the matrix approach of functional analysis and QFD to support the generation of eco-designs. Roos[12], *et al.* highlighted the importance of a holistic perspective for the Environmental Impact Assessment (EIA) study of textile products.

The sustainable product development approach of Zhang[13], *et al.* integrates life cycle system assessment methodology with some heuristics and knowledge bases. Wang[14], *et al.* proposed a sustainable product development and service approach to address the entire product life cycle in two phases viz. product development and service or use phases.

The Ministry of Defence (MoD) of the UK released version 7.0 of "Sustainability Analysis Guidance: Integrating Sustainability into Acquisition Using Life Cycle Assessment" in June 2020, emphasizing a sustainable supply chain and implementing sustainable procurement principles in all MoD contracts[15-17]. Laboratory for Manufacturing and Sustainability of the Mechanical Engineering Department at the University of California, Berkeley, USA, is developing tools for LCA incorporated-design for manufacturing using greener materials and processes[18]. Horowitz[19], *et al.* conducted an LCA for bottled water and concluded that biodegradable ENSO bottles and recycled PET bottles are good options for decreasing environmental impact[19].

Drawing the motivation from the current trend of caring for the environment, the present work analyses three existing versions (Design-I, Design-II and Design-III) of a water bottle from the perspective of their impact on the environment. Because of their usage in high volume (in several lakhs per year), there is a huge potential for reduction in the related environmental impact. Internal LCA and LCIA of all three versions have been carried out on "cradle to gate" philosophy, with the help of SimaPro software using the ecoinvent database, starting from the components to the bottle as a whole. This gives the environmental performance of the three product versions. The component-wise analysis provided insight for identifying a new design for the bottle with components made of lower environmental impacting materials.

Therefore, the main purpose of the present study is not only to come up with an environmentally conscious design of the water bottle but also to show the way for designing other defence products with similar environmental concerns.

2. LCA METHODOLOGY

Design engineers can contribute to environmental sustainability by designing products and processes that satisfy functional needs while minimizing the associated environmental consequences. Decisions made at the initial product design phase affect future decisions[20]. Figure 2 presents an LCA-based design methodology concept and interlinks between inputs/outputs of the product life cycle, design and environment. LCIA/EIA provides feedback to have the most environmentally conscious design alternative.

2.1 LCA/LCIA Concepts and Terms

Some necessary concepts and terms used in LCA/LCIA study are described below.

2.1.1 LCA Phases

Phases are parts or portions of the LCA procedure. LCA study comprises the main four parts known as

- Goal and scope,
- Life cycle inventory analysis,
- Life cycle impact assessment, and
- Interpretation of results (ISO 14040)[1-2].

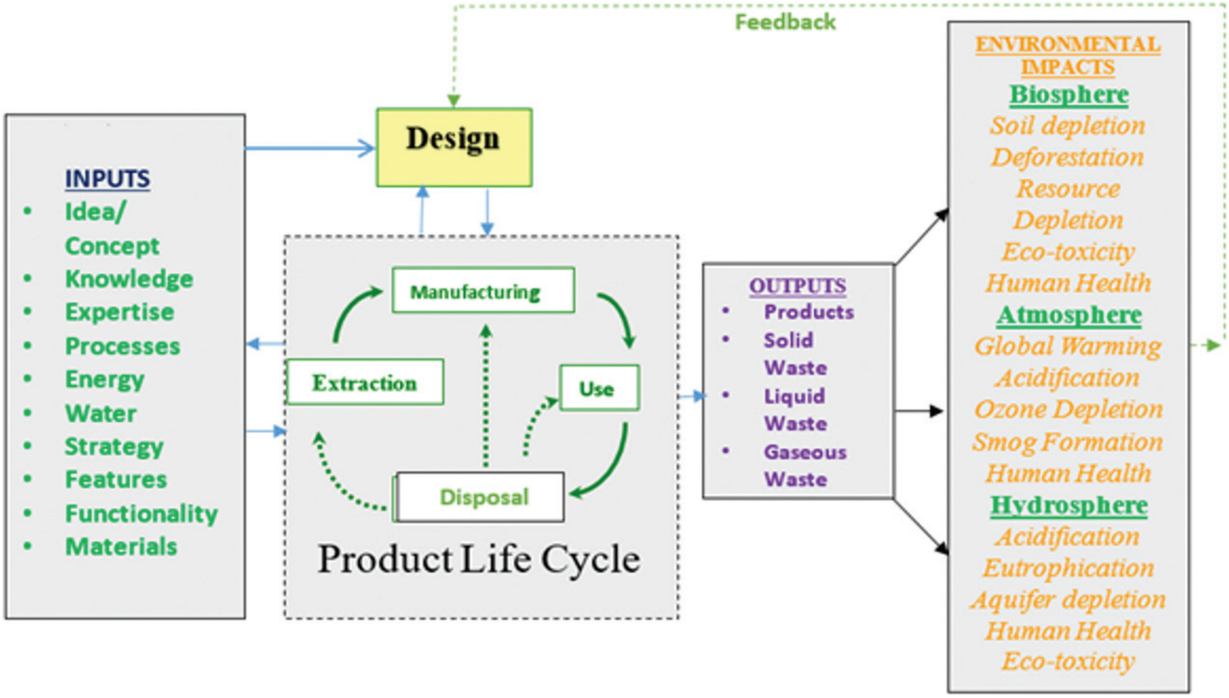


Figure 2. An LCA-based product design approach.

All LCA studies are carried out by going through these phases.

2.1.2 Product Stages

Stages are the sections of the product life cycle. According to ISO 14040, product stages are raw material extraction, production, use, disposal, transport, etc.

2.1.3 Life Cycle

The total life of the product taken under the study is defined which encompasses the production, use and disposal/ waste scenarios of the product.

2.2 LCIA Process of Computing Environmental Impact (EI)

EIs after compilation of inventories are computed through the following steps.

Step I: Impact Category Selection

Impact categories are types of environmental issues caused by inventories (of inputs/outputs). Selected impact categories of concern are Global Warming Potential (GWP), Acidification Potential (AP), Ozone Depletion Potential (ODP), etc.

Step II: Category indicator selection

For a selected category, a common indicator directly correlated with the final impact is picked up, for example, kg CO_2-eq for GWP, kg SO_2-eq for AP, kg CFC-11-eq for ODP, etc.

Step III: Characterisation model selection

For the selection of the impact categories and also for computation, various standard models are available in SimaPro. TRACI 2.1, Eco-indicator 99, CML 2001, and ReCiPe Endpoint (H) are commonly used models.

Step IV: Classification

Here, the inventory's impact on all possible categories is reviewed. For example, the impact of inventory as NH_3 will be reviewed on acidification, human health, air criteria and eutrophication categories.

Step V: Characterisation

For obtaining results in the same category indicator, one impact result may be converted into the other by multiplying it with the characterisation factor[21].For example, we have to convert all the emissions into $\mathrm{kg\,CO_2}-eq$, for GWP. The equivalent of x kg of CH_4 is $34x$ kg of CO_2

$$(xkg\ \mathrm{CH_4\ released})\left(\frac{34kg\ \mathrm{CO_2}-eq}{kg\ \mathrm{CH_4}}\right)=34xkg\ \mathrm{CO_2}-eq$$

Here, 34 is the characterisation factor for CH4 to CO_2 equivalence conversion. Environmental impact category results are calculated from the inventory results and finally shown in bar graph form. This step is called characterisation in LCA, it is an obligatory step in impact assessment.

Step VI: Normalisation

In a characterisation result, each column of an impact category represents the impacts arising from an assembly. The score on each impact category is relatively positioned, with the highest impact value being assigned a value of 100 per cent. It may be noted that the impact categories may have different units, and the highest value on them can be different. Therefore, it will not be easy to visualise the parts of the assembly having the highest overall environmental impact because a bar in the graph represents 100 per cent of a very large impact and also of a smaller one. For a better picture, a more useful scale of measurement as 'Normalisation' is needed.

It is done by dividing the characterisation value by a reference value (e.g. *kg* CO_2 *equivalent* per person per year for Global Warming -Human Health). This procedure is called Normalisation[21]. Normalisation factors are given in the method library. Characterisation factor (CF) and Normalisation concept can be understood by the following example in Table 1.

Step VII: Weighting

Normalisation only reveals large or small effects in relative terms and nothing about their relative importance. Weighting factors are applied to each of the normalisation results to obtain a single score.

Table 1. Characterization and Normalisation

	Impact category indicator					
Inventory and Quantity	Global warming potential		Ozone layer depletion		Eutrophication	
	CF	Result	CF	Result	CF	Result
1 kg CO_2 (carbon dioxide)	1	1				
10 gram CH_4 (methane)	25	0.25				
1 gram CFC-142b	2310	2.31	.07	7.00E-5		
5 gram NO_2					0.56	2.80E-3
Impact Category Indicator or Characterisation results		3.56		7.00E-5		2.80E-3
Unit of result	kg CO_2 equivalent		kg CFC11 equivalent		kg P equivalent	
Normalization reference value in a year	1.12E+4 kg CO_2		2.20E-2 kg CFC11		4.15E-1 kg P	
Normalised result	3.17E-4		3.18E-3		6.75E-3	

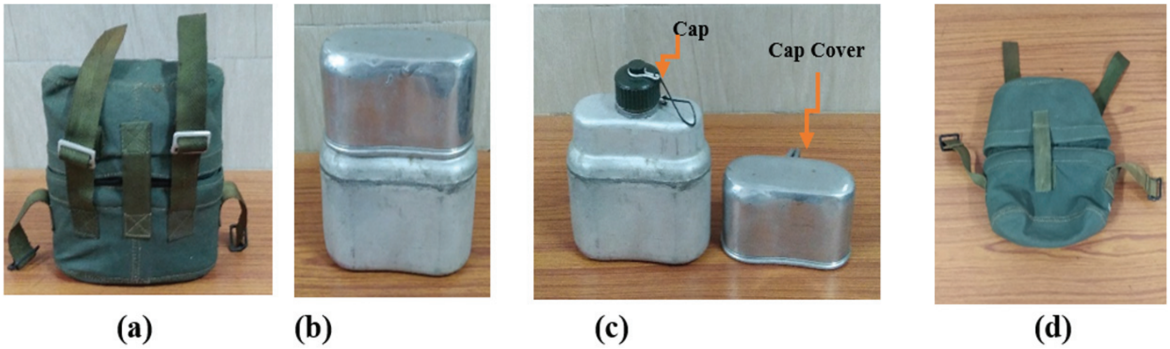


Figure 3. Defence water bottle design D-I (a) All parts assembled (b) Bottle body with cap cover (c) Bottle body, cap and cap cover disassembled (d) Cotton cover.

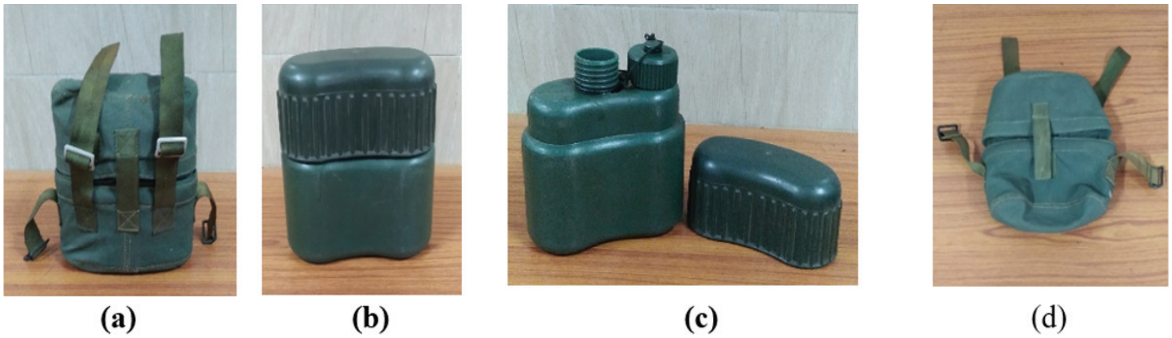


Figure 4. Defence water bottle design D-II (a)All parts assembled (b) Bottle body with cap cover (c) Bottle body, cap and cap cover disassembled (d) Cotton cover.

2.3 ReCiPe Endpoint Method

ReCiPe 2016 Endpoint (H) V1.05 method has been used in the present study for impact category selection, characterisation and LCIA. This method integrates and implements both midpoint indicators and endpoint impact category indicators. The midpoint impact category shows the impact or direct effect on a single environmental issue (eighteen different indicators), e.g. ozone layer depletion, global warming etc. The endpoint shows aggregated effect of midpoint indicators on three more interpretable categories, i.e., damage to human health, ecosystem and resource depletion. The EIs are expressed as mPt (millipoints) unit, where the Pt (point) is the total environmental load expressed as a single score. 1 mPt is the yearly environmental load caused by one average global (e.g. European) inhabitant.

3. DEFENCE WATER BOTTLE UNDER STUDY

A water bottle is a necessary article in a combat kit of a soldier of almost all the armed forces for carrying sufficient water during the execution of their operations. Indian armed forces need a robust and rugged water bottle with the lightest possible weight and long service life in extreme service/ climatic conditions.

3.1 User Requirements and Design Constraints

The specific user qualitative requirements which are linked with design constraints are listed below.

- Stored water should not develop any kind of odour/ synthetic smell. Therefore, bottle material should be food grade & non-reactive to water.
- It must withstand temperatures in the range from -40 ^{0}C to + 50 ^{0}C, meaning the material exhibits stability in its properties within this temperature range.
- Space constraints are due to the soldier's combat kit pouch size of 250 mm in height, 135 mm in width, and 120 mm in thickness.
- It should not develop any crack during operation/normal drops. So material should have high impact strength and low-temperature ductility.
- The water bottle should have a capacity of 1 Litre.
- The bottle design should be flexible and ergonomic.
- There must be provision of good insulation to keep the water close to the original temperature for 4-6 hours of operations.

3.2 Product Improvement (PI) and Three Versions of Defence Water Bottle Design

The PI task is carried out to improve the product's functionality while working on users' feedback (collected after the long-term usage of the product). For LCA, the following three versions of water bottle design, which evolved through these PI exercises, have been considered.

3.2.1 Design D-I

The first version (Fig. 3) of the water bottle was a metallic one. Its bottle body and cap cover was made of food-grade Aluminium Alloy and manufactured by cold working press and welding. An insulating cover, made by stitching knitted cotton fabric, was also provided.

3.2.2 Design D-II

Since the first version was heavier due to being metallic, the bottle body and cap cover material in the second version (Fig. 4) was switched to lightweight plastic material, i.e., food-grade HDPE. Other parts of the bottle were the same as under D-I.

3.2.3 Design D-III

The users reported three problems with the D-II version of the water bottle: (i) unpleasant synthetic odour in stored water, (ii) cracks in plastic parts and (iii) rigid construction causing pain to soldiers during combat operations. Defence Materials and Stores Research & Development Establishment (DMSRDE) obviated these problems by coming up with a new design (Fig. 5), named Flex Water Bottle (D-III). Its body is made of special food-grade polycarbonate (PC) which has higher flexural and impact resistance and low temperature-ductility. It could store the water for a prolonged duration quite close to its original condition and without odour.

The bill of materials and processing details of the three versions of the water bottle are summarised in Table 2.

4 LIFE CYCLE ASSESSMENT STUDY

4.1 Goal and Scope of the Study

Since all logistic and supply chain conditions are common to all the three variations of the bottle, therefore the product analysis and comparison are carried out on the basis of the "Cradle to Gate" philosophy. Internal LCA is carried out to help the decision-maker find how the material selection can change the product's environmental performance and finally lead to the evolution of the optimised design using alternative materials. The following assumptions will help in further understanding the scope of the study.

- In the supply chain of all the three versions of the considered defence water bottle, post-production, transport, and use and disposal scenarios are the same
- The study is carried out for internal LCA

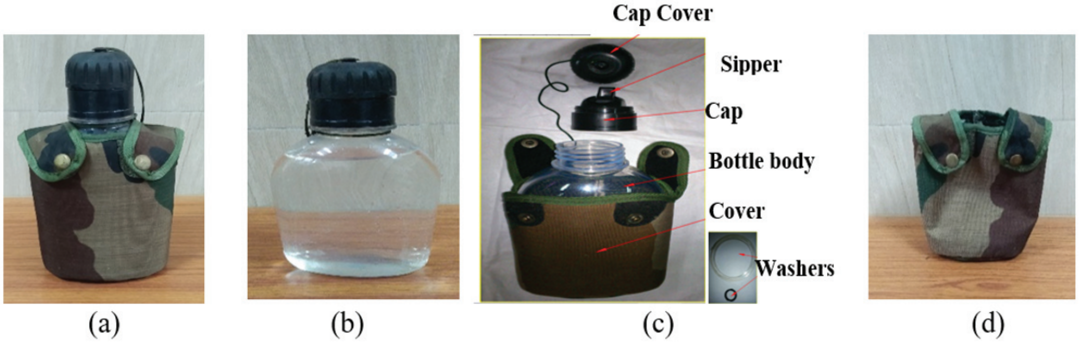


Figure 5. Defence water bottle design D-III (a) All parts assembled, (b) Bottle body with cap cover, (c) Bottle body, cap, cap cover and washer disassembled, and (d) Nylon-66 cover.

Table 2. Materials, processing and weight data of defence water bottle designs

		Defence water bottle		
Sub-assemblies/ components	**Particulars**	**D-I**	**D-II**	**D-III**
Bottle Body	Material	Aluminium Alloy	HDPE	Polycarbonate EXL
	Weight	246 g	229 g	100 g
	Processing	Deep Drawing and TIG Welding	Blow Moulding	Injection Stretch Blow Moulding
Cap Cover	Material	Al Alloy	HDPE	HDPE
	Weight	142 g	140 g	15 g
	Processing	Deep Drawing	Injection Moulding	Injection Moulding
Cap	Material	HDPE	HDPE	PC
	Weight	19 g	20 g	35 g
	Processing	Injection Moulding	Injection Moulding	Injection Moulding
Insulating Cover	Material	Knitted Cotton fabric +Nylon Strap	Knitted Cotton fabric +Nylon Strap	Nylon-66 outer cover + Polyester Pile Fabric
	Weight	80 g+20 g= 100 g	80 g+20 g= 100 g	55 g + 30 g = 85 g
	Processing	Stitching	Stitching	Stitching
Other Small Parts	Material	Al Alloy	Al Alloy	Silicon and SS
	Weight	11 g	11 g	15 g
	Processing	Metal Working	Metal Working	Injection Moulding
Total Weight		518 g	500 g	250 g

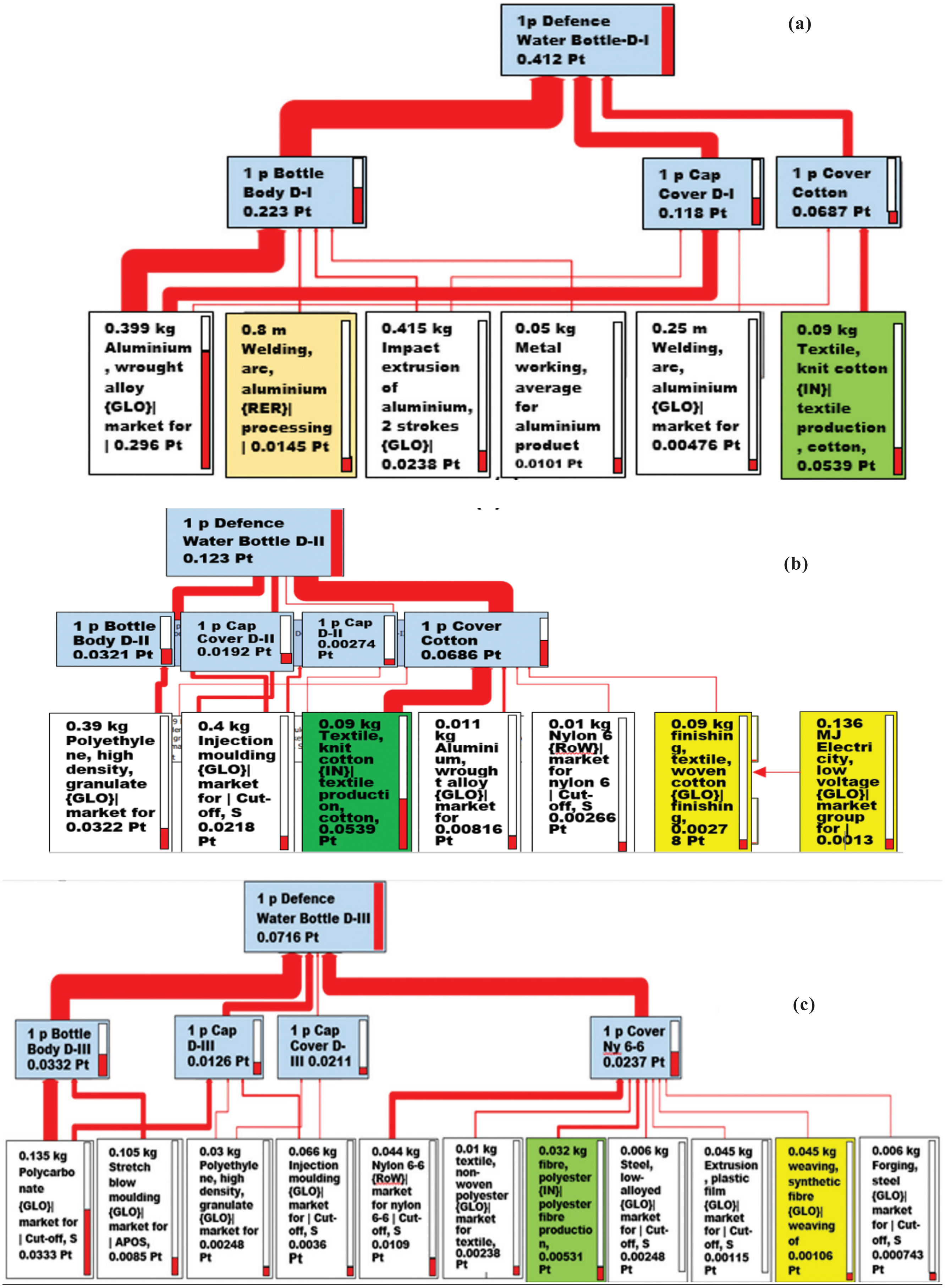


Figure 6. LCA model of design (a) D-I (b) D-II and (c) D-III.

Figure 7. LCIA results of D-I, D-II and D-III design: (a) Characterization, (b) Damage assessment, (c) Normalization, and (d) Single Score.

- For modelling and network simplification, the processes/ components which contribute less than 1 per cent of total impact are not considered, i.e., the cut-off value taken is 1 per cent.

The life cycle analysis of the parts of the bottle was carried out using SimaPro software to determine the best environmental conscious design.

4.2 Life Cycle Model of the Product

Based on the assumptions mentioned in Section 4.1 and the designs as described in Sections 3.2.1, 3.2.2 and 3.2.3, the LCA model of the three different designs is carried out on SimaPro. Material, processing and weight data pertaining to the three designs viz. D-I, D-II and D-III of water bottles is given in Table 2. The data is fed as input to SimaPro and life cycle models of D-I, D-II and D-III designs (screen-shots as produced from SimaPro Software) are shown in respective in Fig. 6 (a), (b) and (c). In an LCA model, the arrow direction in the tree/network like diagrams depicts the product/process flow. The contributions of inventories either in process or as materials are aggregated (rectangular box) by summing up all the upstream impacts. This contribution in relative terms is represented in percentage by a red-coloured thermometer appearing on the right side of the boxes (Fig. 6 (a)-(c)).

4.3 Life Cycle Impact Assessment (LCIA) of the Three Designs

After the life cycle modelling of all the three design versions , LCIA and their comparisons are carried out on the basis of their respective Environmental Impact (EI), using the methodology presented in Section 2.2. and ReCiPe 2016 Endpoint (H) V1.05 method explained in Section 2.3.

4.3.1 Comparison of D-I, D-II and D-III Designs

The water bottle design D-I, D-II and D-III comparisons are done in SimaPro and the results of characterisation, damage assessment, normalisation, and a single score are respectively shown in Fig.7 (a)- 7(d).

Characterisation gives EI results in 18 (22 more detailed) Nos. of midpoint impact indicator categories, shown in bar graph form in Fig. 7(a). For this computation, each inventory quantity (picked up from the ecoinvent database) is multiplied with its linked **m**idpoint characterisation factors[21] (*CFm*). Further for converting midpoint results into endpoint, the *CFm* is multiplied with a constant mid-to-endpoint conversion factors ($\text{FM}_{M\rightarrow E,a}$) per impact category to get endpoint characterisation factors ($CFe_{x,a}$)

$$CFe_{x,a} = CFm_x \text{ X } \text{FM}_{M\rightarrow E,a}$$

Where, ‘a’ denotes the area of protection, i.e. human health (Unit is DALY (Disability Adjusted Life Years)), (terrestrial, freshwater and marine), ecosystems (Unit is species.year) and resource scarcity (Unit is dollar($)), x denotes the stressor of concern[21]. CFm_x and $\text{FM}_{M\rightarrow E,a}$ are picked up from ReCiPe method library inbuilt in the software. Results from each sub-assembly are added to give the final results of the assembly. For comparison, the highest score in each category is scaled as 100 % and other are shown in relation to this value.

Damage Assessment (Fig. 7 (b)) step gives the EI on three end-point categories Human health (in DALYs), Ecosystems (in species.yr) and Resources (in USD($)). This can be computed by summing up the endpoint impact indicators of the same categories (or more simply results which are in the same Unit) for example the addition of mineral resource scarcity and fossil resource scarcity indicators obtained in previous step, shall give total damage assessment of Recourses.

Normalisation as shown in Fig 7 (c) is done by dividing the damage assessment values by a reference normalisation value**,** which gives normalised value of EI in three damage categories. For weighting and single score (Fig. 7(d)), the Weighting Factor (WF) assigned to each category of Human Health (WF=400 Pt)), Ecosystem (WF=400 Pt)) and Resources (WF=200 Pt)[22] is multiplied with normalised result values to get the single score in each category. The category single scores are added to get the overall single score EI (in mPt.).

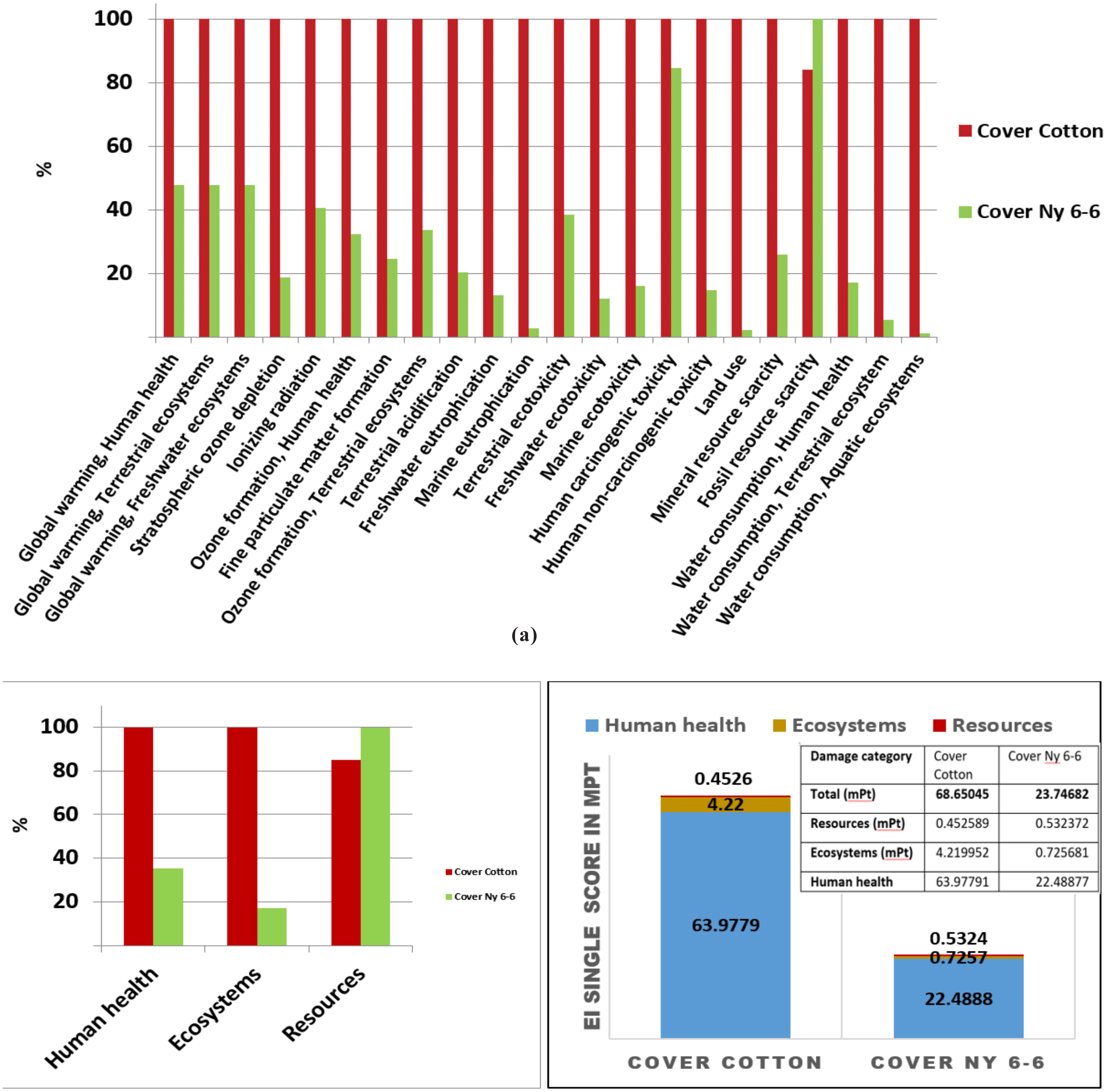
From Fig. 7 (a), it is obvious that the impact of the bottle of the oldest version, D-I, on the environment is substantially higher on all other parameters except for fossil fuel consumption. Fig.7 (b) shows that the performance of D-III is the best and that of D-I is the worst except on resources where D-II performs the worst. It may be noted that the factors such as human health, ecosystems and resources do not have the same level of concern or importance. On normalisation, the emerged picture is shown in Fig. 7 (c). Human health is found to have the maximum impact and the resources to have the least. After assigning the due weights, the scores on these factors are combined and are shown in Fig. 7 (d) as a single score. The journey from D-I to D-III can be seen to be favourable and in the right direction from an overall EI point of view.

For deeper understanding and hotspot identification, component-level analysis is performed. The water bottle can be viewed as a mix of two major sub-assemblies i.e., the bottle body and the insulating cover. Hence the comparison is made in terms of these two subassemblies. In this analysis, only D-II and D-III are considered, and D-I is left out as it substantially differs from the other two, with its EI being very high (Fig. 7 (d)).

4.3.2 Cover Sub-assembly Comparison

There is a variation in the material used in making the cover; the cotton-based fabric is used in D-II and Ny 6-6 in D-III. The characterisation, damage assessment, and single score results are shown in Fig. 8 (a)- 8(c) respectively.

Figure 8 (a) shows that cotton cover is not a good choice based on all the factors except for ‘fossil resource’. Similar results are found in Fig. 8 (b), which shows cotton cover to be an inferior choice except for ‘resources’. From Fig. 8 (c), it can be observed that the use of synthetic Ny 6-6 and polyester-based insulating cover in D-III (EI = 23.7 mPt.) reduced the cover’s negative environmental impacts by 65.5 per cent compared to what it was in D-I and D-II (EI = 68.7 mPt.). Thus the analysis finds the cotton cover’s EI to be much higher in comparison to the Ny 6-6 Cover. Naturally, Ny 6-6 is a better choice over cotton for the cover based on the ‘single score’.



Damage category	Cover Cotton	Cover Ny 6-6
Total (mPt)	68.65045	23.74682
Resources (mPt)	0.452589	0.532372
Ecosystems (mPt)	4.219952	0.725681
Human health	63.97791	22.48877

(a)

(b)

(c)

Figure 8. LCIA results for cover cotton and Ny 6-6: (a) Characterization, (b) Damage assessment, and (c) Single score.

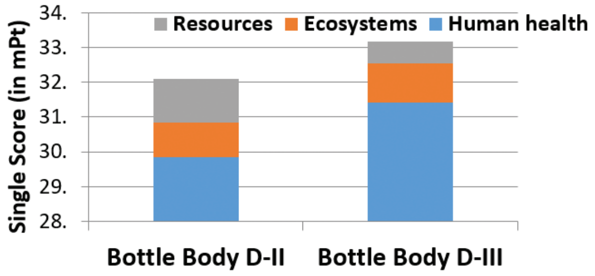


Figure 9. LCIA single score results for the bottle body under D-II and D-III designs.

4.3.3 Sub-assembly Comparison: Bottle Body

Based on the single score (Fig.9), it can be noted that the bottle body under D-II and D-III designs have almost equal net impact on the environment. Thus, the bottle body is not a differentiating factor.

Since this analysis is based on aggregation and does not account for variability, uncertainty analysis has been carried out, and the same is presented in the next subsection.

4.3.4 Uncertainty Analysis of D-II and D-III Designs

The data to be used in life cycle models have some level

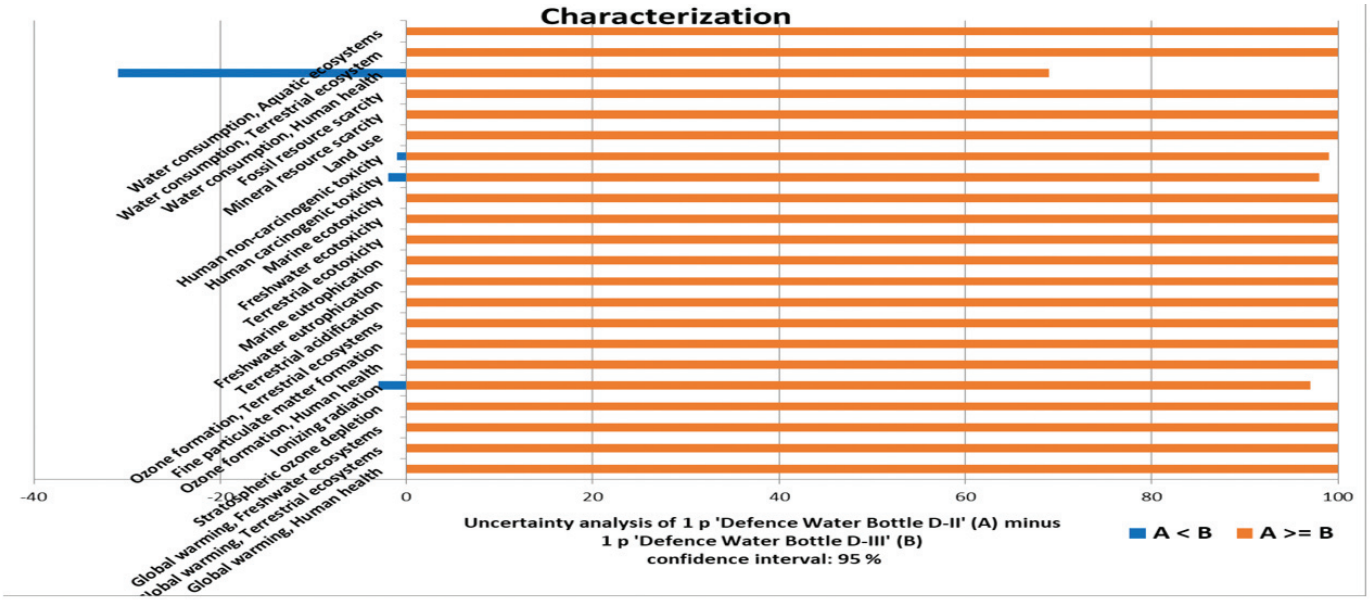


Figure 10. LCIA uncertainty analysis results of D-II and D-III.

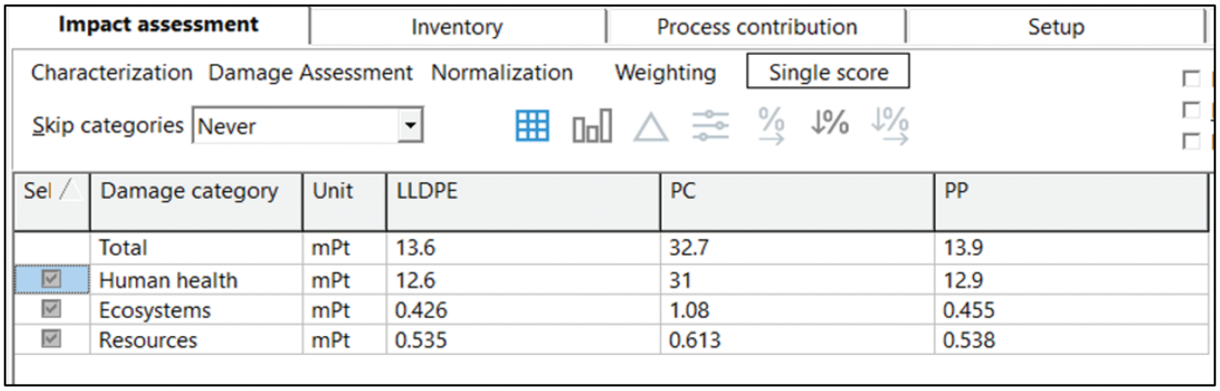
of uncertainty. In the ecoinvent, almost all data points come with a specification of uncertainty. Using the same, uncertainty analysis has been performed on SimaPro, for a fair comparison of D-II and D-III bottles. The EI score of bottle designs D-II and D-III on various characterisation factors are represented by ‘A’ and ‘B’, respectively. For uncertainty analysis, Monte-Carlo simulation runs are performed on (A-B). The results of the analysis are shown in Fig. 10 with 95 % confidence. This analysis finds the D-III design to be superior compared to the D-II design.

4.4 LCIA of Proposed Improved Version of Defence Water Bottle

From the analysis carried out so far, the D-III design has evolved as the best in terms of environmental performance. The main reason behind this was the use of the synthetic nylon-based cover instead of the cotton-based cover. Due to transparency, high impact strength, low-temperature ductility and good functional performance, there is no need to bring any change to the polycarbonate material used for the bottle body. However, the cap (made of PC) and cap cover (made of HDPE) materials used in the D-III bottle can be reviewed for replacement with more environmentally friendly materials. From the mechanical property and functional viewpoints, the two other good material choices are Polypropylene (PP) and Linear Low-Density Polyethylene (LLDPE). These materials are compared with currently used material PC for their suitability in causing lower EIs. LCIA is carried out in SimaPro and the results obtained are presented in Fig. 11.

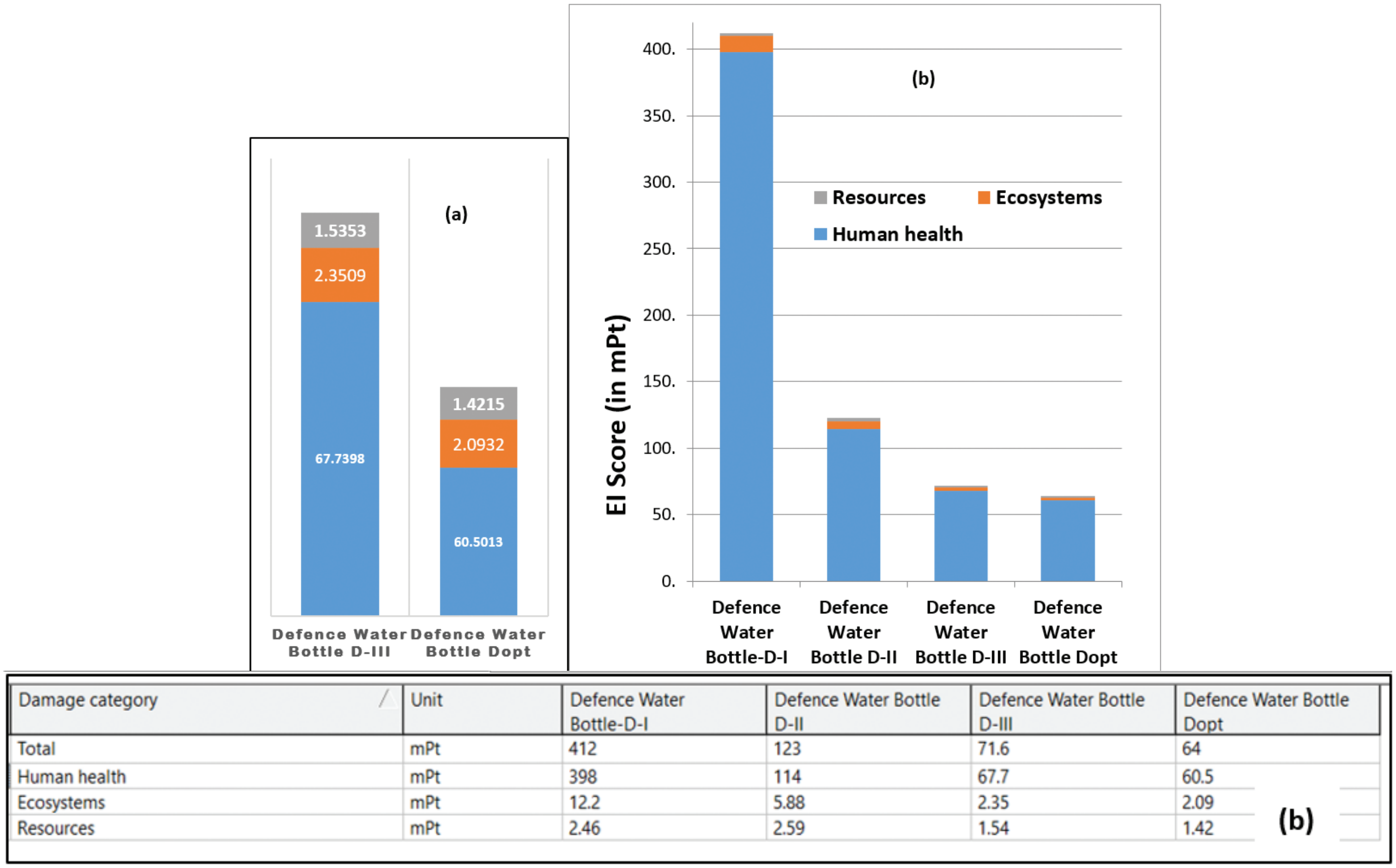
From Fig. 11, it can be noticed that amongst these three materials, LLDPE is going to cause the least EI on every impact category. Therefore, it is recommended to use LLDPE material for the cap and cap cover in the proposed bottle design. This design is referred to as D_{opt} in further discussion and elaboration. D_{opt} is to have a bottle body and cover made of respective materials PC and Ny 6-6, and the cap and cap-cover made of LLDPE. SimaPro is once again used to determine the comparative advantages of D-III and D_{opt} designs. The results obtained are shown in Fig. 12 (a). From Fig. 12 (a) shows that D_{opt} is better on the human health factor (blue portion) by 10.62 per cent (60.5013 against 67.7398), on the ecosystem (amber portion) by 11.06 per cent (2.0932 against 2.3509), and on resources (grey portion) by 7.79 per cent (1.4215 against 1.5353). Figure. 12 (a) clearly shows improvement in all the factors, by going for D_{opt} instead of D-III design.

Figure 12 (b) shows the improvement on an overall basis using a single score of all the variations in the water bottle design. Fig. 12 (b) shows the single EI score (in mPt) of D-I,



Sel	Damage category	Unit	LLDPE	PC	PP
	Total	mPt	13.6	32.7	13.9
☑	Human health	mPt	12.6	31	12.9
☑	Ecosystems	mPt	0.426	1.08	0.455
☑	Resources	mPt	0.535	0.613	0.538

Figure 11. LCIA results regarding LLDPE, PC and PP material.



Damage category	Unit	Defence Water Bottle-D-I	Defence Water Bottle D-II	Defence Water Bottle D-III	Defence Water Bottle Dopt
Total	mPt	412	123	71.6	64
Human health	mPt	398	114	67.7	60.5
Ecosystems	mPt	12.2	5.88	2.35	2.09
Resources	mPt	2.46	2.59	1.54	1.42

Figure 12. LCIA Product comparison on single score between (a) D-III and D_{opt} and (b) D-I, D-II, D-III and D_{opt}.

D-II and D-III designs as 412, 123 and 71.6, respectively. Of these three designs, the latest design (D-III) is the best environmentally conscious one. It has more than 41.79 % reduced environmental burden compared to what was in its immediately earlier version (D-II), and more than 82.62 per cent reduced burden compared to the earliest design (D-I). This figure finds the single total score on EI for D_{opt} design as 64 mPt against 71.6 mPt of D-III design, and thus less by 10.61 %. Thus, D_{opt} design is even better than the D-III design.

5. CONCLUSION

The present paper shows how the alternative engineering designs of a product can be evaluated for their effectiveness in causing the least burden to the environment. Generally, the product improvement (PI) tasks are initiated for improving the functionality and features of the products without caring for environmental sustainability. PI tasks must be reviewed from the perspective of sustainable development. For this purpose, an LCA study should be carried out during the conventional engineering design stage itself.

With the above, in perspective, the three designs of water bottles (being referred to here as D-I, D-II and D-III) used by Indian soldiers have been compared using SimaPro software. LCIA results of water bottle designs D-I, II and III clearly evidence improvement brought in, by switching from the use of metallic (Al alloy) material to rigid HDPE plastic and then to flexible polycarbonate. It improved the product features, functionality (users reported) and environmental performance. The analysis finds the single EI score (in mPt) of D-I, D-II and D-III as 412, 123 and 71.6, respectively. It clearly depicts the latest design (D-III) to be the best environmentally conscious design. It has 41.79 % reduced environmental burden compared to what was in its immediately earlier version (D-II), and 82.62 % reduced burden compared to the earliest design (D-I). The choice for the cover material, even being a small component of the water bottle, impacts EI. The visible significant mitigation in environmental burden is mainly due to change in the cover material from cotton-based fabric to synthetic nylon and polyester-based fabric. The use of synthetic Ny 6-6 and polyester-based insulating cover in D-III (EI = 23.7 mPt) reduced the cover's negative environmental impacts by 65.5 per cent compared to what it was in D-I and D-II (EI = 68.7 mPt.). The results clearly show that there was a substantial reduction in environmental burden by these PI tasks even though it was never in the scope of the envisaged improvements.

Life Cycle Analysis carried out helped to identify the scope for further reducing the environmental burden. The best design (D-III) was reviewed using component-level LCIA to look into feasible functionally-equivalent material alternatives with lower environmental impact. The study establishes that the environmental burden can be further reduced by adopting a new design $D_{opt,}$ by replacing the cap and cap cover material from HDPE/PC in D-III to LLDPE. This proposed design D_{opt} can reduce the EI by 10.61 per cent compared to the currently used best design D-III.

LCA and LCIA-based environmentally conscious design of defence products is the need of the hour. These approaches are important and useful for defence products, particularly for those which have large size consumption. Taking up the LCA-based design of defence products can significantly reduce the environmental burden, resulting in the sustainable development of every country.

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His contribution the current study include: He has extended supervision to the principal author for the analysis, outline of the research work, analysis of the results, literature survey and final scrutiny of the paper.