

# **Life Cycle and Techno-economic Assessments of Porous Radiant Burner and Proposed Organizational Design of the Entity Associated**

*A thesis submitted in partial fulfillment of the requirements for the degree of*

**Doctor of Philosophy**

**by**

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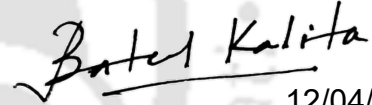


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### THESIS CERTIFICATE

It is certified that the work contained in the thesis entitled **Life Cycle and Techno-economic Assessments of Porous Radiant Burner and Proposed Organizational Design of the Entity Associated by Shaik Sofia Rani**, a student in the Department of Design and Department of Mechanical Engineering, Indian Institute of Technology Guwahati, India, for the award of the degree of the **Doctor of Philosophy** has been carried out under my supervision and that this work has not been submitted elsewhere for the degree.



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*Dedicated to*

# *All my teachers and my son, Sutej*

*Bright and hot, flames flicker and dance  
On the burners, pots and pans perch in stance  
Cooking up a storm, the heat rises high  
Aroma of food, fills up the sky*

*Boiling water, sizzling oil,  
With the burners, cooking's not a toil  
A simmering stew or a frying fry  
The burners make cooking a delight*

*A cup of tea or a cup of coffee  
A bowl of soup or a plate of toffee  
The burners have a magic spell  
Turning raw ingredients, into meals that are swell*

*Oh, burners! You make life so easy  
Cooking food, can be done so breezy  
With your help, kitchens come alive  
And the joy of cooking, thrives and thrives*

*So, let us all, give thanks today  
For the burners, that come our way  
Making our meals, wholesome and hot  
And filling our hearts, with foodie thoughts.*

*- Sofia Rani Shaik*

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## Abstract

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In 2005, the United Nations proposed sustainable development goals (SDG) with 17 objectives as a replacement for millennium development goals (MDGs), as MDGs could not be achieved to their fullest capacity. The third SDG which focuses on ‘ensuring healthy lives and promoting well-being for all at all ages, is a broader goal when compared to the MDG, which concentrates only on maternity and child health. A lot is yet to be done to achieve the complete objective of the third SDG before 2030. Sustainable Development Goal (SDG) 7 is to ensure the usage of clean cooking fuel to 100% of households by 2030. An effort of developing a Porous Radiant Burner (PRB) at the Indian Institute of Technology Guwahati, Guwahati, India has been made considering these goals. In the present research work, different applications of PRB have been tested for sustainability.

The environmental sustainability of PRB has been tested by conducting a Life Cycle Assessment (LCA) of PRB when used for cooking and industrial applications. For cooking applications, LCA has been conducted to test the environmental sustainability of PRB when integrated with cook-stoves that are operated with Biogas and LPG fuels. As a part of the research to test the environmental sustainability of PRB when integrated with cook-stove and operated with biogas, the environmental impact of biogas operated Porous Radiant Burner (BGS<sub>PRB</sub>) based domestic cook-stove is compared with that of a Conventional Burner (BGS<sub>CB</sub>) based domestic cook-stove available in the Indian market. Also, the environmental impact of constructing a 3 m<sup>3</sup> biogas plant which can generate up to 1 m<sup>3</sup> biogas each day is analyzed. The comparison of the cook-stoves is done by conducting a “cradle-to-grave” LCA of eighteen midpoints and three endpoint levels under the ReCiPe method, with the help of the SimaPro database. The functional unit considered for the present study comprises a production unit and a consumption unit. The production unit is of 1 m<sup>3</sup> biogas generation per day with a life span of 25 years. The consumption unit is the utilization of the generated biogas by the cook-stoves which have a life span of 10 years. The environmental impact of the plant and the cook-stoves is assessed from the extraction of the raw material the construction and fabrication to its usage and discard. It is observed from the LCA of cook-stove that all the midpoint and endpoint impact categories are considerably driven by the operation phase of cook-stoves rather than the making. Some critical results reveal that the BGS<sub>PRB</sub> technology is potentially viable compared to the BGS<sub>CB</sub> technology in terms of all the endpoint impact categories. The BGS<sub>PRB</sub>

technology has the potential of reducing the impacts on human health, ecosystem damage, and resource depletion in the ranges of  $7.69\text{E-}09$  DALY (Disability-Adjusted Life Year),  $2.79\text{E-}11$  species.yr and  $2.67\text{E-}04$  \$, respectively. The impact of  $\text{BGS}_{\text{PRB}}$  is lesser than  $\text{BGS}_{\text{CB}}$  due to the efficient burning of the fuel. This thesis could serve as a source of scientific information for decision-making on environmental sustainability in biogas projects in India.

To test the environmental sustainability of PRB when integrated with cook-stove and operated with LPG, the environmental impact of a 1-3 kW LPG operated Porous Radiant Burner ( $\text{PRB}_{\text{LPG}}$ ) based domestic cook-stove is compared with that of a Conventional Burner ( $\text{CB}_{\text{LPG}}$ ) based domestic cook-stove of the same capacity. This study is also a “cradle-to-grave” LCA which includes eighteen midpoint and three endpoint levels of the ReCiPe method in the SimaPro database. The functional unit considered includes the fabrication and the operation phases of LPG cook-stoves ( $\text{PRB}_{\text{LPG}}$  and  $\text{CB}_{\text{LPG}}$ ) with a life span of 10 years. Life Cycle Inventory (LCI) is considered for the quantitative representation of the embodied energy of the material required. Life Cycle Impact Assessment (LCIA) is performed for 1 kW and 3 kW power output. It is observed that all the midpoint and endpoint impact categories are considerably driven by the operation phases of cook-stoves than fabrication. Also,  $\text{PRB}_{\text{LPG}}$  when compared to  $\text{CB}_{\text{LPG}}$  cook-stove has the potential of reducing the impacts on human health (DALY), ecosystem damage (species.yr), and resource depletion (\$) by 15%, each for 1 kW output. Whereas, the respective values for 3 kW power output are also reduced by 15% each for  $\text{PRB}_{\text{LPG}}$  when compared to  $\text{CB}_{\text{LPG}}$  cook-stove. This study could serve as a source of scientific information for decision-making on the environmental sustainability of cook-stoves.

In the present research, the environmental assessment of PRB is also conducted when it is used in industrial applications. PRB is integrated with a Small-scale Medical Waste Incinerator (SMWI), for the disposal of medical waste. For the LCA, the design of an SMWI equipped with an LPG-operated Porous Radiant Burner ( $\text{PRB}_{\text{LPG}}$ ) is presented as a solution for disposing of medical waste generated in remote areas. Based on simple mass and heat balance analysis, SMWI is designed to have primary and secondary chambers of volumes of  $1 \text{ m}^3$  and  $0.754 \text{ m}^3$ , respectively. The proposed SMWI is evaluated for its environmental impact by performing an LCA and compared with an SMWI equipped with an Electric heater (SMWI-EH). The total primary energy required for the construction of SMWI is 48285.56 MJ. It is found that the damage caused by the operation of  $\text{PRB}_{\text{LPG}}$  in SMWI is lesser when compared to that of an Electric heater. In SMWI-PRB, LPG consumption contributed to about 17488.27 kg  $\text{CO}_2\text{-eq}$  in the global warming category, whereas in the case of SMWI-EH, electricity consumption

contributed to about 243766.11 kg CO<sub>2</sub>-eq. The operation of SMWI-PRB showed a reduction of about 54% in the resource utilization category in comparison with SMWI-EH. The results obtained from the LCA study indicated that PRB<sub>LPG</sub> is a better option as an auxiliary heating device in SMWI than Electric heaters due to its environmental superiority.

The economic sustainability of PRB has been tested by conducting a Techno-economic Assessment (TEA) of PRB when used for domestic and commercial cooking applications. In this area of research, a Techno-economic Assessment of 1-3 kW and 5-7 kW PRB-based LPG cook-stoves operating in domestic households, and eateries and restaurants are conducted. Process flow study has been performed primarily to understand the technological process involved in the PRB and also to estimate the cost of manufacturing. The cost estimation has been done considering direct costs such as material costs and labor costs, and indirect costs such as factory costs, works costs and administration costs. Sensitivity analysis has been performed considering the production capacity of 50, 250, and 500 cook-stoves each day. An economic feasibility study of PRB cook-stoves has been done by estimating the Pay Back Period, Net Present Value, and Internal Rate of Return. For a manufacturing capacity of 250 cook-stoves per day, PRB yields a 52.1% return on investment with a payback period of 1.1 years for 1-3 kW domestic cook-stove and a 51.4% return on the investment with a payback period of 0.25 years for small-scale eateries, 0.2 years for medium-scale eateries and 0.07 years for large-scale eateries with commercial cook-stoves. These results indicate high savings with PRB-based cook-stoves both for domestic usage and commercial usage making PRB highly viable economically.

Once the environmental and economic sustainability of PRB has been tested, study has been conducted to see the viability of PRB for its mass production and bringing it to public usage. For this, an Organizational Design has been proposed and a business model has been developed. An organizational design plays a major role in the effective and efficient functioning and management of all resources. To obtain an effective design, a proper analysis of the business model and the value chain has to be made and competencies have to be framed for various functional units and job roles. The present research proposes a business model for an entity to start with PRB cook-stoves manufacturing to portray the value these products propose to the end user. The business model in the present study is developed by taking the business canvas model into reference. The business model canvas majorly comprises of three sections viz., the value the entity provides to its customers, the procurement of the necessities to provide those values, and the customer base and how to reach it. In the present study, along

with these three sections, two more sections have been added. One represents the environmental and societal benefits a product provides and the other represents the economic benefits provided to the consumers and manufacturers. Assessing the business model, an organogram is proposed with more of a mechanistic structure as well as a slight tinge of organic structure; thereby work-flow has been analyzed. Each organization will have a unique design of its own depending on its type, the services it provides, its culture, communication, and the way it interacts with the external environment. In the present study, organizational design is proposed taking various aspects of the business model into consideration to provide the best output in the due course of the manufacturing of PRB cook-stoves. In the organogram, both the line and staff functions have been analyzed thoroughly and represented. A user study has been conducted for the production department based on the workflow analysis for various job roles and job positions and based on this, competency indicators have been proposed for job positions of the production department. The present study can be used for the recruitment, performance appraisal, and training modules for an entity in the PRB cook-stoves manufacturing business. This study can also be used as a reference to conduct user studies for other departments to propose respective competency indicators.

## Nomenclature

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<i>Symbols</i>	<i>Comments</i>
<b>Al<sub>2</sub>O<sub>3</sub></b>	Alumina
<b>Ba</b>	Barium
<b>Cd</b>	Cadmium
<b>CFC</b>	Chlorofluorocarbons
<b>CH<sub>4</sub></b>	Methane
<b>(C<sub>2</sub>H<sub>3</sub>Cl)<sub>x</sub></b>	Vinyl chloride complexes
<b>(C<sub>2</sub>H<sub>4</sub>)<sub>x</sub></b>	Ethylene
<b>C<sub>3</sub>H<sub>8</sub></b>	Propane
<b>C<sub>4</sub>H<sub>10</sub></b>	Butane
<b>C<sub>5</sub>H<sub>10</sub>O<sub>3</sub></b>	3-Hydroxypentanoic acid
<b>C<sub>6</sub>H<sub>10</sub>O<sub>5</sub></b>	Diethyl pyrocarbonate
<b>CO</b>	Carbon monoxide
<b>CO<sub>2</sub></b>	Carbon dioxide
<b>DALY</b>	disability-adjusted life year
<b>DB</b>	dichlorobenzene
<b>EN-30</b>	Series of steel
<b>Fe</b>	Iron
<b>HC</b>	hydrocarbon
<b>H<sub>2</sub>O</b>	Water
<b>kJ</b>	kilo Joules
<b>kW</b>	kilo Watts
<b>MAH</b>	MonoAromatic Hydrocarbons
<b>Mn</b>	Manganese
<b>N</b>	Nitrogen
<b>Ni</b>	Nickel
<b>NMVOC</b>	Non-methane volatile organic compounds
<b>NO<sub>x</sub></b>	Nitrogen Oxides
<b>P</b>	Phosphorus
<b>PAH</b>	Polycyclic Aromatic Hydrocarbons

<b>Pb</b>	Lead
<b>PCDD</b>	Polychlorinated dibenzodioxins
<b>PCDF</b>	Polychlorinated dibenzofurans
<b>Pt</b>	Platinum
<b>ReCiPe</b>	An impact assessment method in Life Cycle Assessment
<b>Sb</b>	Antimony
<b>SiC</b>	Silicon Carbide
<b>SiSiC</b>	Silicon infiltrated Silicon Carbide
<b>SO<sub>2</sub></b>	Sulfur dioxide
<b>THC</b>	Tetrahydrocannabinol
<b>U-235</b>	Uranium-235
<b>VOC</b>	Volatile Organic Compound
<b>Zn</b>	Zinc



## Abbreviations

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<b>AC<sub>PRB</sub></b>	Administrative costs of PRB
<b>APCD</b>	Air Pollution Control Devices
<b>aLCA</b>	attributional Life Cycle Assessment
<b>BGS<sub>CB</sub></b>	CB-embedded domestic biogas stove
<b>BGS<sub>PRB</sub></b>	PRB-embedded domestic biogas stove
<b>BLI</b>	Bioenergy Livestock Integrated
<b>BMWM</b>	Bio-Medical Waste Management
<b>BPGTP</b>	Biogas Power Generation (Off-Grid) and Thermal energy application Programme
<b>CAMARTEC</b>	Centre for Agricultural Mechanism and Rural TEChnology
<b>CB</b>	Conventional Burner
<b>CB<sub>LPG</sub></b>	LPG-operated Conventional Burner
<b>CCR</b>	Charnes-Cooper-Rhodes
<b>CEEIC</b>	Chengdu Energy Environment International Cooperation
<b>COVID-19</b>	Coronavirus Disease 2019
<b>CPRB</b>	Cluster Porous Radiant Burner
<b>CZ</b>	Combustion Zone
<b>DCF<sub>PRB</sub></b>	discounting the cash flows of PRB
<b>DCS</b>	Distributed Control System
<b>DEA</b>	Data Envelopment Analysis
<b>DRES</b>	Department of Renewable Energy Sources
<b>EH</b>	Electric Heater
<b>FC<sub>PRB</sub></b>	Factory costs of PRB
<b>FF</b>	Free Flame
<b>FFC</b>	Free Flame Combustion
<b>FS</b>	Flame Stabilizer
<b>GI</b>	Galvanized Iron
<b>HCF</b>	Health Care Facilities
<b>HRT</b>	Hydraulic Retention Time
<b>IPCC</b>	International Panel on Climate Change lists the climate change

<b>IPEN</b>	INCLEN Program Evaluation Network
<b>IRR</b>	Internal Rate of Return
<b>IRR<sub>PRB</sub></b>	Internal Rate of Return of the PRB cook-stoves
<b>ISO</b>	International Organization for Standardization
<b>IWA</b>	International Workshop Agreement
<b>KVIC</b>	Khadi Village Industries Commission
<b>LCA</b>	Life Cycle Assessment
<b>LCI</b>	Life Cycle Inventory
<b>LCIA</b>	Life Cycle Impact Assessment
<b>LPG</b>	Liquified Petroleum Gas
<b>MC<sub>PRB</sub></b>	Manufacturing costs of PRB
<b>MERS</b>	Middle East Respiratory Syndrome
<b>MNRE</b>	Ministry of New and Renewable Energy
<b>MP<sub>PRB</sub></b>	Manpower costs of PRB
<b>MSB</b>	Matrix Stabilized Burner
<b>MW</b>	Medical Waste
<b>MWI</b>	Medical Waste Incinerators
<b>MWM</b>	Medical Waste Management
<b>MZ</b>	Mixing Zone
<b>NCF<sub>PRB</sub></b>	Net cashflows of PRB
<b>NCL</b>	National Chemical Laboratory
<b>NITI</b>	National Institution for Transforming India
<b>NNBOMP</b>	New National Biogas and Organic Manure Programme
<b>NPV</b>	Net Present Value
<b>NPV<sub>PRB</sub></b>	Net Present Value of PRB
<b>OD</b>	Organizational Design
<b>PA</b>	Primary air Adjuster
<b>PBP</b>	Pay Back Period
<b>PBP<sub>PRB</sub></b>	Pay Back Period of PRB cook-stoves
<b>PCC</b>	Primary Combustion Chamber
<b>PC<sub>PRB</sub></b>	Production cost of PRB
<b>PFD</b>	Process Flow Diagram
<b>PM</b>	Porous Matrix

<b>PMC</b>	Porous Media Combustion
<b>ppcm</b>	Pores per centimetre
<b>PRB</b>	Porous Radiant Burner
<b>PRB<sub>LPG</sub></b>	LPG-operated Porous Radiant Burner
<b>PrC<sub>PRB</sub></b>	Prime costs of PRB
<b>PRRB</b>	Porous Radiant Recirculated Burner
<b>PV</b>	Photo Voltaic
<b>PVC</b>	Polyvinylchloride
<b>PZ</b>	Preheating Zone
<b>PV</b>	Photo Voltaic
<b>PVC</b>	Polyvinylchloride
<b>SARS</b>	Severe Acute Respiratory Syndrome
<b>SB</b>	Swirl Burner
<b>SCC</b>	Secondary Combustion Chamber
<b>SP<sub>PRB</sub></b>	Sales Price of PRB
<b>SDG</b>	Sustainable Development Goals
<b>SMWI</b>	Small-scale Medical Waste Incinerator
<b>SNCR</b>	Selective Non-Catalytic Reduction
<b>SS</b>	Stainless Steel
<b>SSB</b>	Surface Stabilized Burner
<b>TEA</b>	Techno-economic Assessment
<b>TREMAP</b>	Technology Refinement and Marketing Programme
<b>UN</b>	United Nations
<b>US\$</b>	United States Dollar
<b>WBT</b>	Water Boiling Test
<b>WHO</b>	World Health Organization

# Contents

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<b>1</b>	<b>Introduction</b>	1
1.1	Porous Radiant Burner	2
1.2	Applications of Porous Radiant Burner	4
1.3	Possibilities of further studies on Porous Radiant Burner	5
1.4	Structure of the Thesis	7
<b>2</b>	<b>State-of-the-art</b>	10
2.1	Literature on Porous Radiant Burner based cook-stoves	10
2.1.1	Cook-stoves based on their design with respect to the fuels	10
2.1.2	Cook-stoves based on their performance with respect to the fuels	18
2.2	Literature on Medical Waste Incinerators	24
2.2.1	Medical Waste Management and its treatment across the globe	25
2.2.2	Medical Waste Management and Disposal using Medical Waste Incinerators	27
2.2.3	Types of Medical Waste Incinerators	27
2.3	Literature Closure	35
2.3.1	Cook-stoves	35
2.3.2	Medical Waste Incinerators	36
2.4	Research Questions and Objectives	39
<b>3</b>	<b>Methodology</b>	41
3.1	Methodology for LCA	41
3.1.1	Goal and Scope	42
3.1.2	Inventory Analysis	42
3.1.3	Impact Assessment	43
3.1.4	Interpretation of Results	44
3.2	Methodology for TEA	44
3.2.1	Conceptual design	45
3.2.2	Cost estimation and calculation	45
3.2.3	Economic Analysis	46
3.3	Methodology for Organizational Design	47
3.3.1	Business Model	47
3.3.2	Organogram / Organizational Design	48
3.3.3	Value chain analysis and Competency Mapping	48
3.4	Summary	49
<b>4</b>	<b>Life Cycle Assessment of Porous Radiant Burner-based applications</b>	50
4.1	Need for conducting LCA on biogas-operated Porous Radiant Burner	51
4.1.1	Goal, Scope and Functional unit for LCA of Biogas operated PRB	52

4.1.2	Description of Deenbandhu type Biogas dome plant	53
4.1.3	System Boundary for biogas operated cook-stoves	55
4.1.4	Inventory Analysis for LCA of Biogas operated PRB	57
4.1.5	Impact Assessment for Biogas operated PRB	59
4.1.6	Sensitivity Analyses	60
4.1.7	Results Interpretation	60
4.1.8	Interpretation of Sensitivity Analyses Results	70
4.2	Need for conducting LCA on LPG-operated Porous Radiant Burner	78
4.2.1	Goal, Scope, and Functional unit for LCA of LPG-operated cook-stoves	79
4.2.2	System Boundary	80
4.2.3	Life Cycle Inventory Analysis of LPG-based cook-stoves	81
4.2.4	Life Cycle Impact Assessment of LPG-based cook-stoves	82
4.2.5	Results of Assessment of LPG-based cook-stoves	84
4.2.6	ReCiPe at midpoint characterization	87
4.2.7	ReCiPe at endpoint characterization	90
4.3	Need for conducting LCA on Small Scale Medical Waste Incinerator	93
4.3.1	Design specifications of Small-scale Medical Waste Incinerator	94
4.3.2	Life Cycle Assessment of Small-scale Medical Waste Incinerator	96
4.3.3	Energy requirement for the fabrication of SMWI	98
4.3.4	Comparison of environmental impacts of SMWI equipped with different heaters	98
4.4	Summary	101
<b>5</b>	<b>Techno-economic Assessment of Porous Radiant Burner-based cook-stoves</b>	<b>104</b>
5.1	Need for conducting TEA on PRB-based cook-stoves	104
5.2	Process flow of the cook-stoves	105
5.3	Cost estimation and calculation of PRB-based cook-stoves	106
5.3.1	Direct Costs	106
5.3.2	Factory Costs	107
5.3.3	Administrative Costs	107
5.3.4	Production Costs	107
5.3.5	Sales Cost	107
5.4	Economic Analysis of PRB-based cook-stoves	107
5.4.1	Net Present Value (NPV)	108
5.4.2	Internal Rate of Return (IRR)	108
5.5	Benefit to the consumer	109
5.6	Results of the Assessment	109
5.6.1	Consumption by PRB-based cook-stoves	109
5.6.2	Cost savings on LPG by PRB-based cook-stoves	111

5.6.3	Returns at the end of life of PRB-based cook-stove	112
5.7	Sensitivity Analyses	113
5.7.1	Profit margin of the manufacturing unit	113
5.7.2	Cost of the cook-stoves	115
5.7.3	Effect of manufacturing capacity on the $PBP_{PRB}$ of the consumers	116
5.8	Summary	118
<b>6</b>	<b>Proposed Organizational Design to mass produce Porous Radiant Burner-based Cook-stoves</b>	<b>119</b>
6.1	Need for the business model for PRB-based cook-stoves manufacturing	119
6.2	Business Model for value proposition	120
6.3	Organogram / Organizational Design	120
6.4	Value chain analysis and Competency Mapping	120
6.5	Results of Proposition	115
6.5.1	Proposed Business Model	121
6.5.2	Proposed Organizational Design	123
6.5.3	Value chain and Competency Indicators	124
6.6	Summary	130
<b>7</b>	<b>Conclusion and Future Scope</b>	<b>132</b>
7.1	Life Cycle Assessment of PRB	132
7.1.1	PRB based cook-stoves used with biogas	132
7.1.2	PRB based cook-stoves used with LPG	133
7.1.3	PRB when integrated with Medical Waste Incinerator	134
7.2	Techno-economic Assessment of PRB-based cook-stoves	134
7.3	Proposed Organizational Design for mass production of PRB-based cook-stoves	134
7.4	Future Scope	135
7.4.1	PRB based cook-stoves used with biogas	135
7.4.2	PRB based cook-stoves used with LPG	135
7.4.3	Medical Waste Incinerator integrated with PRB	136
7.4.4	Techno-economic Assessment of PRB-based cook-stoves	136
7.4.5	Proposed Organizational Design for mass production of PRB-based cook-stoves	136
	<b>References</b>	<b>137</b>
	<b>List of Publications</b>	<b>153</b>

## List of Figures

Fig. No.	Figure name	Page No.
1.1	Pillars of sustainability	1
1.2	Photographic view of Porous Radiant Burner (Deb and Muthukumar, 2021)	3
1.3	Schematic of Porous Radiant Burner (Deb and Muthukumar, 2021)	3
2.1	Porous Radiant Burner developed by Makmool et al. (2013)	12
2.2	Domestic Porous Radiant Burner developed by Mishra and Muthukumar (2018)	12
2.3	Various designs of biogas cook-stoves	16
	a) Biogas cook-stove developed by CAMARTEC (Sasse et al., 1991)	15
	b) Biogas stove-KVIC model (Kandpal et al., 1995)	15
	c) DCS burner used in Nepal (Fulford, 1996)	15
	d) Biogas stove designed by Itodo et al. (2007)	15
	e) Biogas stove for baking developed by Kurchania et al. (2010)	15
	f) Domestic biogas stove developed by Kurchania et al. (2011)	15
	g) 1) Regular-shaped burner, 2) Cyclone 1-shaped burner, 3) Cyclone 2-shaped burner (Syamsuri et al., 2015)	16
	h) Biogas Injera baking burner (Mulugeta et al., 2017)	16
	i) Biogas burner (Stove) developed by Awulu et al. (2020)	16
	j) Biogas burner developed by Petro et al. (2020)	16
	k) Biogas-operated porous radiant burner developed by Kaushik et al. (2021)	16
2.4	Environmental scattering and carcinogenicity of harmful emissions of MWIs (Ansari et al., 2019)	26
2.5	Multiple-chamber pathological-waste incinerator (Shaaban, 2007)	30
	a) Front-view of the incinerator	30
	b) Top-view of the incinerator	30
2.6	Flue gas treatment configuration (Shaaban, 2007)	31
2.7	Schematic of the mobile MWI (Wajs et al., 2019)	32
2.8	Graphical representation of energy flow in the mobile medical waste incinerator (Wajs et al., 2019)	32
2.9	Pictorial and schematic view of the step grate package incinerator (Olisa et al., 2016)	33
2.10	Operational flow chart rotary grate incinerator (Xie et al., 2009)	35
3.1	Methodology of LCA	42
3.2	Techno-Economic Assessment methodology	44
3.3	Approach towards competency indicators	47

<b>4.1</b>	Top-view of constructional plan of Deenbandhu-type biogas plant (Sangha, 2013)	53
<b>4.2</b>	Sectional representation of Deenbandhu-type biogas plant (Sangha, 2013)	54
<b>4.3</b>	Scope of the study and system boundary of biogas operated cook-stoves	56
<b>4.4</b>	Cradle-to-grave endpoint characterization and damage assessment categories of the plant	67
<b>4.5</b>	Impact of the endpoint characterization factors on damage assessment categories	68
<b>4.6</b>	Damage assessment factors due to the operation of BGS <sub>PRB</sub> and BGS <sub>CB</sub>	70
<b>4.7</b>	Damage assessment due to the operation of BGS <sub>PRB</sub> and BGS <sub>CB</sub> at 7.5% biogas leakage and 3.5% digestate leakage	73
<b>4.8</b>	Damage assessment due to the operation of BGS <sub>PRB</sub> and BGS <sub>CB</sub> at 5% biogas leakage and 2% digestate leakage	76
<b>4.9</b>	Performance of BGS <sub>PRB</sub> at different biogas and digestate leakages	78
<b>4.10</b>	System boundary and scope of the study of LPG based cook-stoves	81
<b>4.11</b>	Midpoint and endpoint assessment categories	83
<b>4.12</b>	Damage assessment categories - fabrication and recycling of PRB <sub>LPG</sub> and CB <sub>LPG</sub> cook-stoves	87
<b>4.13</b>	Damage assessment categories – operation of PRB <sub>LPG</sub> and CB <sub>LPG</sub> cook-stoves at 1 kW LPG power output	92
<b>4.14</b>	Damage assessment categories – operation of PRB <sub>LPG</sub> and CB <sub>LPG</sub> cook-stoves at 3 kW LPG power output	93
<b>4.15</b>	System boundary (within the dashed lines) considered for LCA of SMWI	96
<b>4.16</b>	Scheme of IMPACT 2002+ method (Wilson, 1907)	97
<b>4.17</b>	Characterized data on SMWI-PRB (Impact category)	99
<b>4.18</b>	Characterized data on SMWI-EH (Impact category)	99
<b>4.19</b>	Impact of SMWI-PRB and SMWI-EH on Human health	101
<b>4.20</b>	Impact of SMWI-PRB and SMWI-EH on Ecosystem quality	101
<b>4.21</b>	Impact of SMWI-PRB and SMWI-EH on Climate change	101
<b>4.22</b>	Primary energy required for SMWI-PRB and SMWI-EH	101
<b>5.1</b>	Process Flow Diagram of PRB-based cook-stove	106
<b>5.2</b>	Annual cost spent on LPG by 1-3 kW cook-stoves and savings of PRB	111
<b>5.3</b>	Annual cost spent on LPG by 5-7 kW cook-stoves and savings of PRB	111
<b>5.4</b>	Returns on the investment of 5-7 kW cook-stoves by small, medium and large-scale eateries	113
<b>5.5</b>	PBP <sub>PRB</sub> of 1-3 kW PRB-based cook-stoves at different profit margins of manufacturing unit	114
<b>5.6</b>	PBP <sub>PRB</sub> of 5-7 kW PRB-based cook-stoves at different profit margins of manufacturing unit	114
<b>5.7</b>	PBP <sub>PRB</sub> of 1-3 kW PRB-based cook-stoves at different SP <sub>PRB</sub>	115
<b>5.8</b>	PBP <sub>PRB</sub> of 5-7 kW PRB-based cook-stoves at different SP <sub>PRB</sub>	116
<b>5.9</b>	PBP <sub>PRB</sub> and SP <sub>PRB</sub> of 1-3 kW PRB-based cook-stoves for different plant capacities	117

<b>6.1</b>	Proposed business model for an entity to mass produce PRB cook-stoves	122
<b>6.2</b>	Proposed organogram for the mass production of PRB cook-stoves	123
<b>6.3</b>	Value Chain of PRB cook-stoves	125



## List of Tables

Table No.	Table name	Page No.
2.1	Design features of improved LPG cook-stoves	12
2.2	Design features of biogas cook-stoves	16
2.3	MW generated in different continents (Minoglou et al., 2017)	24
2.4	Types of MW disposal methods in developing countries	25
2.5	Merits and Demerits of incinerators	28
2.6	Various studies reported on incineration	36
4.1	Dimensions of constructional plan of biogas plant	54
4.2	Material used for the biogas plant construction	61
4.3	Impact of constructional phase and recycling phase on the midpoint categories	62
4.4	Comparison of the impacts of construction and recycling of PRB and CB on midpoint categories	63
4.5	Impact of the operation of BGS <sub>PRB</sub> and BGS <sub>CB</sub> on midpoint characterization environmental factors	65
4.6	Impact of the construction and recycling of PRB and CB on midpoint characterization environmental factors	68
4.7	Impact of the operation of BGS <sub>PRB</sub> and BGS <sub>CB</sub> on endpoint characterization environmental factors	69
4.8	Impact of the operation of BGS <sub>PRB</sub> and BGS <sub>CB</sub> on midpoint characterization environmental factors for 7.5% biogas leakage and 3.5% digestate leakage	71
4.9	Impact of the operation of BGS <sub>PRB</sub> and BGS <sub>CB</sub> on endpoint characterization environmental factors for 7.5% biogas leakage and 3.5% digestate leakage	72
4.10	Impact of the operation of BGS <sub>PRB</sub> and BGS <sub>CB</sub> on midpoint characterization environmental factors for 5% biogas leakage and 2% digestate leakage	74
4.11	Impact of the operation of BGS <sub>PRB</sub> and BGS <sub>CB</sub> on endpoint characterization environmental factors for 5% biogas leakage and 2% digestate leakage	75
4.12	Impact of BGS <sub>PRB</sub> for different biogas and digestate leakages	77
4.13	Fuel consumption and emissions of PRB <sub>LPG</sub> and CB <sub>LPG</sub> for 10 years	80
4.14	Midpoint characterization values of fabrication and recycling of PRB <sub>LPG</sub> and CB <sub>LPG</sub> cook-stoves	85
4.15	Endpoint characterization values of fabrication and recycling of PRB <sub>LPG</sub> and CB <sub>LPG</sub> cook-stoves	86
4.16	Endpoint damage assessment categories - fabrication and recycling of PRB <sub>LPG</sub> and CB <sub>LPG</sub> cook-stoves	87

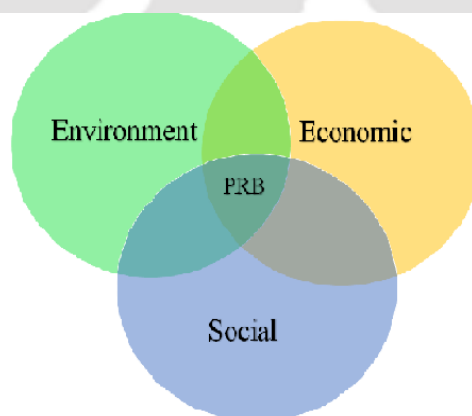
<b>4.17</b>	Midpoint characterization values of operating PRB <sub>LPG</sub> and CB <sub>LPG</sub> cook-stoves at 1 kW LPG power output	88
<b>4.18</b>	Midpoint characterization values of operating PRB <sub>LPG</sub> and CB <sub>LPG</sub> cook-stoves at 3 kW LPG power output	89
<b>4.19</b>	Endpoint characterization values of operating PRB <sub>LPG</sub> and CB <sub>LPG</sub> cook-stoves at 1 kW	90
<b>4.20</b>	Endpoint characterization values of operating PRB <sub>LPG</sub> and CB <sub>LPG</sub> cook-stoves at 3 kW LPG power output	91
<b>4.21</b>	Endpoint damage assessment of operating PRB <sub>LPG</sub> and CB <sub>LPG</sub> cook-stoves at 1 kW LPG power output	92
<b>4.22</b>	Endpoint damage assessment of operating PRB <sub>LPG</sub> and CB <sub>LPG</sub> cook-stoves at 3 kW LPG power output	92
<b>4.23</b>	Classification of Medical Waste (Easo and Swamy, 2011)	95
<b>4.24</b>	Composition of the medical waste considered and its heat content (Easo and Swamy, 2011)	95
<b>4.25</b>	Total energy required for fabrication of SMWI	98
<b>5.1</b>	LPG consumption for PRB-based and CB-based domestic cook-stoves	109
<b>5.2</b>	LPG consumption for PRB-based and CB-based commercial cook-stoves	110
<b>5.3</b>	PBP <sub>PRB</sub> and SP <sub>PRB</sub> of 5-7 kW PRB-based cook-stoves for different plant capacities	117
<b>6.1</b>	Competency indicators for Product Manager	119
<b>6.2</b>	Competency indicators for Team Lead	127
<b>6.3</b>	Competency indicators for Senior Engineer Level	128
<b>6.4</b>	Competency indicators for Junior Engineer Level	129
<b>6.5</b>	Competency indicators for Assembly Level Workers	130

# Chapter 1

## Introduction

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Sustainability is gaining the utmost importance in recent times as non-renewable resources are depleting day by day. The world is focusing on SDGs (Sustainable Development Goals) since the UN proposed 17 SDGs in 2005. Though the seventh SDG is proposed on ensuring access to affordable, reliable, sustainable, and modern energy for all, one-third of the world population still lacks facilities for safe and efficient cooking systems. Bringing in energy-efficient cooking technologies can address this issue to a reasonable extent. As the population is growing day by day in India, there is also growth in energy requirements. The consumption of LPG alone has increased by a 7% Compound Annual Growth Rate in the last ten years. Considering the Geospatial Energy Map of India released by the National Institution for Transforming India (NITI) Ayog, it is evident that the reserves of fossil fuels in our country are limited. In order to meet the energy requirement, India imports 50% of its Liquefied Petroleum Gas (LPG) fuel. Research is being conducted across the world to come up with technologies to address the energy crisis. Since most technologies are in the infant stage of their development, opening them up for public usage without performing proper feasibility tests will do more harm to society than benefit it does. Thus, any new technology has to be checked for its sustainability.



**Fig. 1.1** Pillars of sustainability

One such energy-efficient product is the Porous Radiant Burner (PRB) which has been developed at the Indian Institute of Technology Guwahati. For any product, to test its sustainability and feasibility, the three pillars of sustainability viz., environment, economic and social sustainability have to be considered. **Fig. 1.1** represents the relation of the efficiency of

the new technology of PRB with respect to the three pillars of sustainability. Also, the benefit it provides to society and all the stakeholders is to be estimated so that when PRB is put into real use, it will contribute to the betterment of society at large.

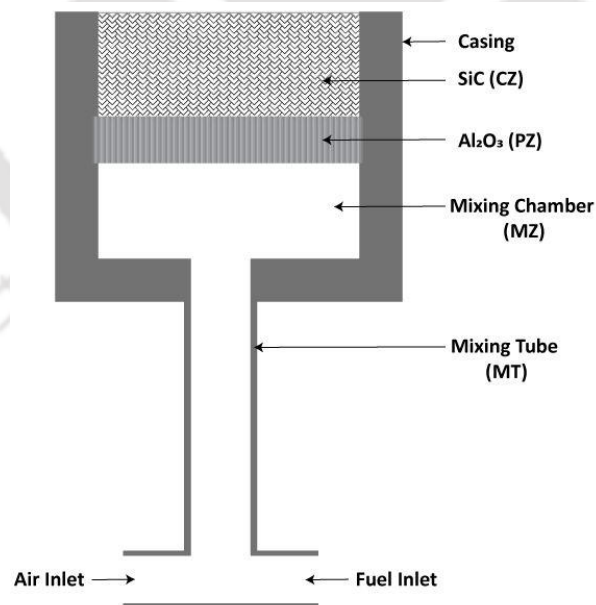
### **1.1 Porous Radiant Burner**

Porous Radiant Burners (PRBs), also known as excess enthalpy burners, burn the premixed air-fuel mixture within the three-dimensional volumetric porous matrix known as the porous reactor. PRBs are called excess enthalpy burners as some part of the combustion heat is recirculated to preheat the incoming air-fuel mixture, resulting in a higher combustion temperature compared to the adiabatic temperature of the mixture. The main mode of heat transfer is radiation. The efficiency of the PRB is high when compared to the conventional free-flame burner, and the CO and NO<sub>x</sub> emissions are very low in these burners. The main advantage of PRB is that fuels with low calorific value can be efficiently combusted in the porous matrix with low emissions. The recirculation of heat inside promotes preheating by the incoming air-fuel mixture, thereby increasing the combustion efficiency. A porous material is used in PRBs to evenly distribute the fuel and air mixture, creating a uniform flame that radiates heat in all directions. The porous material is typically made of ceramic or metal and is designed to have a high surface area, which allows for efficient heat transfer. When the fuel and air mixture enters the porous material, it is dispersed evenly across the surface of the burner. As the mixture moves through the pores of the material, it ignites and burns, creating a flame that radiates heat outwards. The heat is then absorbed by the surrounding objects, creating a warm and even temperature throughout the space. PRBs are of two types, single-layer, and double-layer. In a single-layered Porous Radiant Burner (PRB), an air-fuel mixture is fired up on the top surface and the flame front travels in the upstream direction and envelops the entire region of the porous structure. A two-layer PRB is composed of a Preheating Zone (PZ) and a Combustion Zone (CZ). The low porosity of PZ averts the probability of self-ignition and hence prevents flame propagation towards upstream, which prohibits flashback. The fuel-air mixture gets preheated in this particular region which aids in extending the lower flammability limit and enhancing the combustion efficiency. Thus, preheating increases the stable region of the combustion regime. Because of the high porosity in the CZ, combustion sustains, flame propagates, and a wide reaction zone (RZ) exists. Another positive outcome is the reduction of NO<sub>x</sub> formation due to the homogenization of temperature. The interface of PZ and CZ serves as an RZ where the combustion stabilizes. The PRB considered in the study is a double-layered

PRB (Deb & Muthukumar, 2021). It has a tube called a mixing tube, a Mixing Zone (MZ), and two porous matrices, of which one is called a Preheating Zone (PZ), and the other is a Combustion Zone (CZ). The material used for Combustion Zone is a reticulated foam of SiC, whereas the Preheating Zone is made of Alumina porous matrix. These matrices are enclosed in a refractory cement casing to withstand high temperatures and also to prevent heat loss from the burner to the surroundings. The photographic views of PRBs of 5-7 kW and 12.6 kW are shown in **Fig. 1.2** and the schematic view of PRB is shown in **Fig. 1.3**.



**Fig. 1.2** Photographic views of Porous Radiant Burner



**Fig. 1.3** Schematic of Porous Radiant Burner (Deb and Muthukumar, 2021)

It may be noted that PRB technology can be effectively applied to cook-stoves, incinerators, ceramic industry, and cremation units among others.

## **1.2 Application of Porous Radiant Burner**

There is a wide scope for the application and integration of PRB in the below mentioned products or fields.

### ***Cook-stoves***

Across the globe, the design and appearance of cook-stoves change drastically. But the purpose of these cook-stoves is to become a platform for burning the in the course of cooking. These are not limited to cooking and are used for space heating also in some cases. A good quality cook-stove should cook food in less time and the emissions should be less. It has to be safe in handling and should consume less fuel. Also, it has to be affordable and easy to maintain besides being ergonomically and aesthetically pleasing.

### ***Incinerators***

An incinerator is a device used to decompose the solid waste thermally in an enclosed chamber under controlled conditions. Generally, an incinerator has two chambers, primary and secondary. In the primary chamber, waste is treated thermally to produce ash and volatile gases. The combustion process in this chamber is oxygen deficit and the temperature requirement is 800–900°C. The primary chamber requires a heating device to start the process. The volatile gases from the primary chamber reach the secondary chamber and will be combusted under excess air condition at the constant temperature of 1000–1100°C, maintained by a heating device. The exhaust from here is treated and released into the atmosphere.

### ***Ceramic products***

Ceramics are materials made up of non-metallic compounds with most of their composition made up of inorganic material. They are made permanent by the firing process. Ceramics can be clay-based or non-clay-based and can be glazed or unglazed, porous or vitrified. They should have high strength, wear resistance, inertness, long service life, non-toxicity and resistance to heat and fire.

### ***Cremation units***

Cremation is the procedure in which a body is reduced to its basic elements. This procedure is done in a specially designed furnace called as cremation chamber or retort or cremation unit. The body is prepared and placed properly in the container. Here, it is exposed to intense heat and evaporation. It has two chambers viz., combustion chamber and environmental chamber.

Generally, the time is 60 to 90 min and the average heat is 1000-1100°C in the combustion chamber and 1100-1300°C in the environmental chamber.

### **1.3 Possibilities of further studies on Porous Radiant Burner**

Several studies were conducted on PRB to test its emissions, thermal efficiency and fuel consumption. Only one study was conducted on the environmental viability of PRB and the study was done focusing on the energy efficiency of the product (Kaushik and Muthukumar, 2018). However, no studies were reported about the environmental sustainability in terms of fabrication and recycling, and the operation of PRB. The environmental feasibility study can be conducted through Life Cycle Assessment (LCA). The definition of LCA as given by ISO is “the compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle” (ISO\_354 2003). LCA assesses environmental traits and the impacts of a service, process or product throughout its life (Adamczyk and Dzikuć 2014; Ehtiwesh et al., 2016). Besides determining the environmental impacts, it will also categorize the environmental hotspots which affect the environmental impacts, hence giving an opportunity to choose better environmentally sustainable processes or products or services (Evangelisti et al., 2014; Abdelsalam et al., 2019). LCA can be performed by adopting different methods, depending on the requirement and the nature of the study. Methods of LCA include cradle-to-gate, gate-to-gate, gate-to-grave and cradle-to-grave. In the “cradle-to-gate” method, the environmental impacts of a product or a process are assessed partially, from the raw material extraction to their transportation to the factory gate. The “gate-to-gate” method also includes a partial environmental impact assessment since LCA is conducted only at one value-added process in the entire production chain. Whereas in the “gate-to-grave” method, LCA is done for the functional unit of the product or process or service, till the discard. These three methods of LCA are adopted for projects having a longer duration. The “Cradle-to-grave” method of LCA is the method in which the impact assessment of a product or service or process is done from the raw material extraction, its transportation, manufacturing, usage, and till its discard.

After testing the product for its environmental sustainability, it has to be tested for economic sustainability which is done through Techno-economic Assessment. TEA is significant especially when the viability of a new product or a technology has to be estimated and when there is no ready information available on the industries of the similar technology or product. A techno-economic study on the hydrogen storage grid was performed, to analyze the

operational flexibility and capability of hydrogen production, storage, compression, and utilization (Wu et al., 2022). The authors suggested that as the value streams from bundling grid services sum up to 76% of the total profit, they play a major role in making the hydrogen energy storage project economically feasible. A different assessment was conducted from a land management perspective in Brazil, to assess the financial viability of Bioenergy Livestock Integrated (BLI) systems (de Souza et al., 2022). It was found that BLI reduces the payback period (PBP) to half the time besides increasing the Net Present Value (NPV) five times the initial investment. In a different study, TEA of building energy-efficient systems was conducted by Himeur et al. (2022), the economic assessment was performed for the data collection, analysis and detection of an anomaly, and data visualization of energy-efficient systems. The system proved to be economically viable as the TEA showed up to 28%-68% savings in the consumption of energy. TEA study coupled with LCA was another study performed by Nugroho et al. (2022) to assess the environmental and economic viability of methane supply chains. After the analysis, the team recommended to use an agent-based simulation optimization as this pathway of the technology leads to a higher Internal Rate of Return (IRR), lower PBP, and also lower carbon emissions. However, there is no study performed on the TEA of PRB except for the studies conducted on the PRB-based stove operated with waste cooking oil and LCA and TEA of LPG operated PRB cook-stove for 5-10 kW (Kaushik and Muthukumar, 2018, 2020). The results indicated that PRB is economically feasible when operated with waste cooking oil; and also environmentally and economically feasible even with 5-10 kW LPG. These economic assessments performed for the technology of PRB were focused on the performance of the PRB when used with different fuels. But, no TEA of PRB was performed to assess the economic feasibility of PRB-based cook-stoves working with 1-3 kW and 5-7 kW; when the industry has to be set up for the mass production of PRB-based cook-stoves. Studies are to be conducted to verify PRB's financial viability, and the returns, the consumers are going to get on their investment in PRB-based 1-3 kW and 5-7 kW cook-stoves. Therefore, a need has been identified to conduct an economic assessment before commercializing the present technology to minimize the cost wherever possible and reduce the financial risks (Abdelhady, 2021).

Environment and economic sustainability tests act as decision making tools as they indicate if a product has to be manufactured or not in purview of the effect on the environment and society. Once these tests prove a product to be a feasible one, a business model can be developed to bring in the strategies to the mass production and circulation of the product for the public use.

## **1.4 Structure of the Thesis**

The present thesis work is organized into seven chapters and the details are as mentioned below:

### ***Chapter 1: Introduction***

This chapter describes the importance of sustainable technologies and the need of the technological innovations in the era of depleting non-renewable energy resources. Importance of energy-efficient cooking technologies besides them being environmentally, economically and socially sustainable is highlighted. The need of such technologies to be brought into public usage for providing healthy cooking atmosphere along with cost, energy and time saving is presented. As PRB is one such sustainable product, its importance, applications and possibilities of future research on PRB have been presented in this chapter.

### ***Chapter 2: State-of-the-art***

This section mainly focuses on the literature survey on the emergence of cook-stoves that are being used with LPG and biogas. Thereafter the literature of PRB-based cook-stoves and their performance when used with biogas and LPG as fuels is highlighted. This chapter also includes the literature on Medical Waste Incineration and the design aspects of Medical Waste Incinerators (MWI). Summarizing the findings, the literature has been closed and research questions have been framed. Based on the research questions, objectives are framed to carry forward with the research on PRB-based applications, to test the sustainability of PRB.

### ***Chapter 3: Methodology***

In the third chapter, methodology associated with the testing of sustainability of PRB has been presented. To analyze PRB's environmental sustainability, Life Cycle Assessment (LCA) methodology has been adapted. Whereas to test the economic sustainability of PRB, Techno-economic Assessment (TEA) methodology associated is described in the chapter.

The importance of initialization of such breakthrough technology to be brought into public usage through the designing business model is presented through the methodology adopted for Organizational Design (OD). This methodology of OD is applied to an entity which would start mass production of PRB-based cook-stoves.

#### ***Chapter 4: Life Cycle Assessment of PRB based applications***

In this section, LCA of PRB based applications for cooking and medical waste incineration has been presented. In the first section, the environmental impacts of the construction of a 3 m<sup>3</sup> Deenbandhu type biogas plant are presented. Also, the environmental impacts of the cook-stoves with PRB and conventional burner (CB) that use the same capacity of biogas from this plant for cooking are analyzed and presented. ReCiPe method has been used for the impact assessment of the construction of the plant as well as for the production of the gas and the consumption of the biogas by both the burners. All the results are summarized and presented to take a decision on the environmentally sustainable burner.

Also, the analysis conducted on 1-3 kW cook-stoves that are operated with LPG fuel is summarized in the second section of the chapter. The comparison of environmental impacts of 1-3 kW PRB-based cook-stove with that of 1-3 kW CB-based cook-stove are presented. Eighteen midpoint categories and 3 endpoint categories are assessed and the results of all the categories are summarized and compared between the cook-stoves of both the burners.

In the final section of the chapter, the methodology of LCA and the analysis conducted on small-scale Medical Waste Incinerator (MWI) with different heating devices to analyze the environmental impact of each are presented. The scope of the study has been explained and MWI equipped with PRB is compared with incinerators equipped with electric heater. The results have been compiled which indicated that PRB has a lesser environmental impact than the other heating devices.

#### ***Chapter 5: Techno-economic Assessment of PRB***

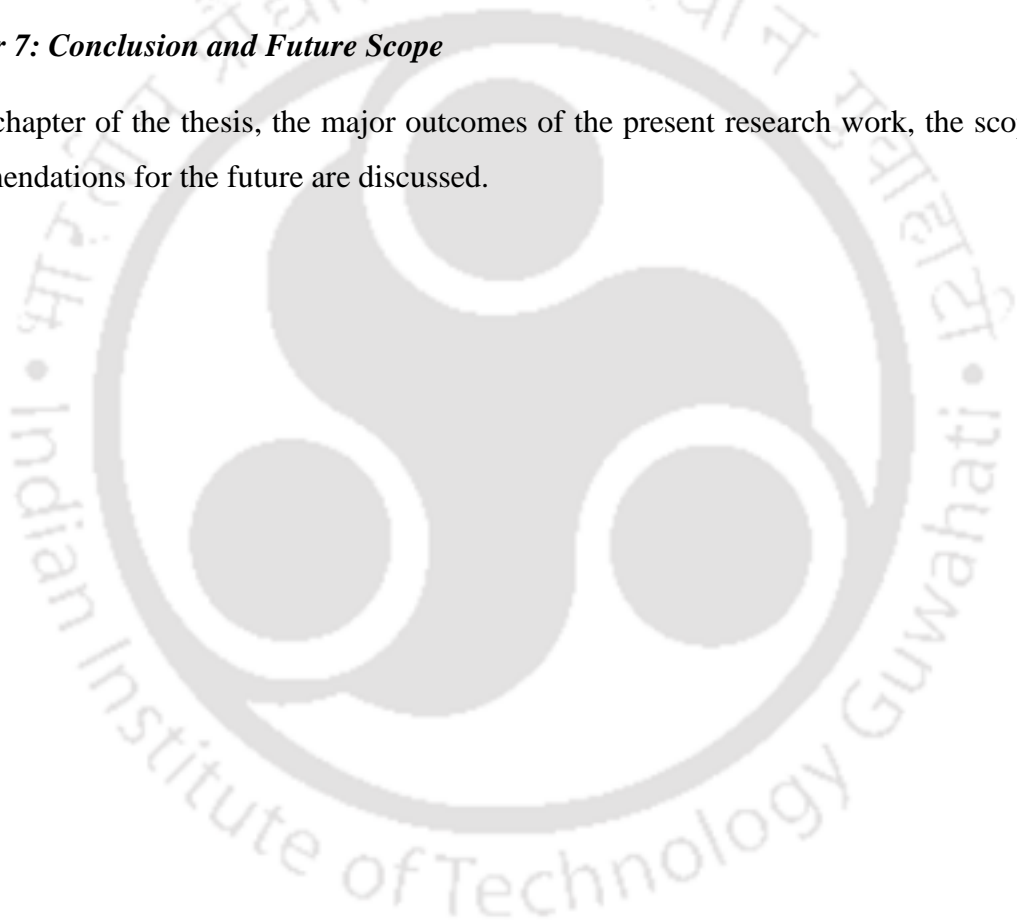
In this chapter, the conceptual design for the functioning of the LPG based cook-stoves for domestic cooking application and commercial cooking application has been discussed. The cost estimation has been made by gathering the material required to match the conceptual design and the direct and indirect costs have been calculated. The Prime Cost has been calculated taking the direct labor, direct material and other direct expenses involved with the product. And also, the factory and the work costs have been calculated taking other fixed costs and variable costs into consideration. The cost benefit analysis has been done through Net Present Value, and Internal Rate of Return for the manufacturing unit with the capacity of 250 units per day. The Pay Back Period (PBP) for both the consumers and manufacturing unit has been estimated and the results are summarized.

### ***Chapter 6: Proposed Organizational design for an entity of PRB***

In this chapter, the required business model has been proposed to an entity to start with the manufacturing of PRB-based cook-stove. The business model includes the values the entity is going to provide to the consumers/customers and the requirements for providing those values. Based on the Business Model, an organogram is presented with competency indicators for various roles to make the manufacturing and sales of the PRB successful and in line with the business values. Both line and staff departments have been considered for the organogram and competency indicators have been developed for the production department.

### ***Chapter 7: Conclusion and Future Scope***

In this chapter of the thesis, the major outcomes of the present research work, the scope and recommendations for the future are discussed.



## Chapter 2

### State-of-the-art

---

The present chapter is mainly divided into three sections. In the first section, literature has been reviewed on the emergence of Porous Radiant Burner (PRB) technology integrated with cook-stoves, and its usage with different types of fuels. In the second section, literature has been gathered about medical waste incineration to check the possibility of integrating PRB as a heating device. Based on the gathered literature, the research questions are framed in the last section. Based on the research questions objectives have also been framed in the last section.

#### **2.1 Literature on Porous Radiant Burner based cook-stoves**

In recent years, improvements in cook-stove designs with gaseous and liquid fuels have been studied according to the vast variety of literature available. Malico and Mujeebu (2011) focused on cook-stoves with heat recirculating burners and the influence of burner size and materials on their performance. Ismail et al. (2018) highlighted the scope of further research in the development of a numerical model on cook-stoves with heat recirculating burners. Khan (2020) described the performances of some of the LPG operated cook-stoves and their variation with design modifications. Datta et al. (2021) provided a detailed review of natural gas and LPG based domestic cook-stoves operating on flame impingement heat transfer.

##### ***2.1.1 Cook-stoves based on their design with respect to the fuels***

From the time cook-stoves came into application use, numerous improvements have been reported to their design. These works on their design improvements were mostly done on their operating factors. As the present study is limited to the application of the LPG and biogas fuels, the literature has been gathered about the cook-stoves operating on these fuels and the possibility of integrating PRB with these cook-stoves has been explored.

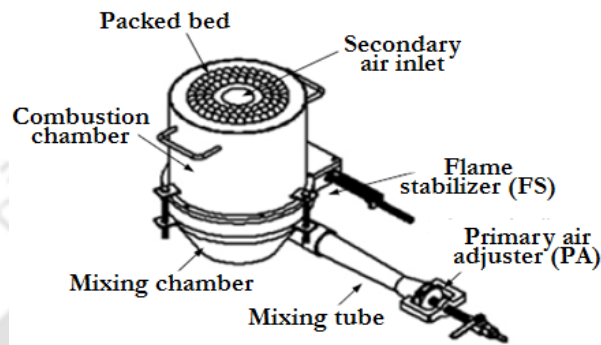
##### ***Liquefied Petroleum Gas (LPG)***

These stoves are designed essentially based on partially-aerated type burner design, described by Berry et al. (1921). The traditional free-flame cook-stoves are generally based on the Bunsen burner design. In these designs (P. Agarwal et al., 2015; Aroonjarattham, 2016; Das et al., 2021; Fakinle et al., 2019; Shen et al., 2018), there are several holes located on the burner head

where the flame jets are anchored. Most of the burner heads are made of metal like cast iron or brass. The details of the various improved cook-stove designs are presented in **Table 2.1**. Zhen et al. (2014) redesigned the traditional domestic cook-stove by modifying the burner cap. The design modifications facilitated induced swirl flows. With the insertion of an extended spill-tray and an annular metal insert, Das et al. (2021) improved the performance of traditional domestic cook-stoves. These improvements increased the heat transfer to the load by guiding the combustion products and air more toward the load.

Later, utilization of Porous Matrix (PM) for improving the performance of traditional cook-stoves was demonstrated by Jugjai and Sanitjai, (1996) in their Porous Radiant Recirculated Burner (PRRB). Unlike PRB, PRRB is not characterized by a submerged flame inside PM. Instead, it has an FF, and the PM only fosters the recirculation of heat from the exhaust gas to the unburnt air-fuel mixture. Further Jugjai and Rungsimuntuchart, (2002) developed a semi-confined PRRB by using the same ring burner as in the Conventional Burner (CB), i.e., PRRB(CB). Further improvement in thermal efficiency of the burner was realized by combining the PRRB with the swirling central flame ring burner (SB), i.e., the PRRB(SB). Compared to their previous design (Jugjai and Sanitjai, 1996), they scaled up the capacity of the burner from 5 kW to 30 kW, making it suitable for various applications, especially in small-scale food processing industries. Mujeebu et al. (2011) added another feather in the field of PRB cook-stoves by exploring the operation of double-layered PRBs on the surface and submerged combustion modes. These modes of PMC operation at the same power input were obtained by using different PMs. For a power input of 0.62 kW, PRB with PZ and CZ of Alumina foams of different porosities was used to obtain surface stabilized flame, while PRB was formed by porcelain foam and alumina spheres were-used to obtain a matrix stabilized flame. Another improved domestic PRB cook-stove based on the flat-flame operation was reported by Wu et al. (2014). The PRB was of diameter 50.8 mm and thickness 3 mm, and the PM was formed with bronze pellets of diameter 0.5 mm with a porosity of 0.237. Mishra (2015), presented an improved cook-stove with double-layer PRB for commercial cooking (5-10 kW). The PRB was 120 mm in diameter, and SiC and Alumina formed the CZ and PZ of PRB, respectively. Similarly, for domestic applications, Herrera et al. (2015), developed 160 mm diameter PRB, where the preheater material was uniquely chosen from Alumina grinding wastes and the CZ comprised of SiC ceramic foam. Another milestone of PRB for domestic cooking was obtained by Makmool et al. (2013), who developed a self-aspirating annular PRB with an adjustable flame stabilizer. A flame stabilizer was used to control flame location in the

annular packed bed by varying an opening area allowing the incoming of the air-fuel mixture, which is represented in **Fig. 2.1**. In a first of its kind, a self-aspirated double-layered PRB cook-stove in the range of 1-3 kW was developed by Mishra and Muthukumar (2018), which is represented in **Fig. 2.2**. The CZ and the PZ comprised SiC reticulated foam and an Alumina filter. These were enclosed in a housing made of a refractory cement casing. This design was based on submerged PMC.



**Fig. 2.1** Porous Radiant Burner developed by Makmool et al. (2013)



**Fig. 2.2** Domestic Porous Radiant Burner developed by Mishra and Muthukumar (2018)

**Table 2.1** Design features of improved LPG cook-stoves

S. No.	Design details	Ref.
1.	<p><b>Swirl Burner I:</b></p> <ul style="list-style-type: none"> <li>Ten guided vanes; the air/fuel mixture flowing through the curvy channels is guided to form ten separate swirling flame jets.</li> <li>The curvy channel has an inclination angle of 60° and a radius of 3 mm.</li> <li><b>Non-dimensional burner port spacing: 0.8.</b></li> </ul> <p><b>Swirl Burner II:</b></p>	Zhen et al. (2014)

	<ul style="list-style-type: none"> <li>The concave surface of the burner cap has an inclined angle of 30° towards the horizontal plane, and the slots are fabricated with an angle of 10° off the normal direction of the surface, such that a skewed channel, similar to that of the guided vane, is formed inside each slot.</li> <li><b>Non-dimensional burner port spacing:</b> 0.8.</li> </ul>	
2.	<ul style="list-style-type: none"> <li>High pressure gas burner for street food, restaurants, hotels (size KB-5)</li> <li><b>Cross-sectional area of injector:</b> 0.64 mm<sup>2</sup></li> <li><b>Cross-sectional area of burner port:</b> 254.44 mm<sup>2</sup></li> <li><b>Heat capacity:</b> ~52,752 kJ</li> <li><b>Type of LPG:</b> Propane</li> <li><b>Material:</b> Cast iron</li> </ul>	Aroonjaratham, (2016)
3.	<ul style="list-style-type: none"> <li><b>LPG composition:</b> 60% butane and 40% propane</li> <li><b>LPG supply pressure:</b> 0.14 bar</li> <li><b>Combustion rate:</b> 1-4 kW</li> <li><b>Porous medium:</b> SS wire mesh (40 meshes/Inch)</li> <li><b>Body Materials:</b> SS sheet</li> </ul>	Jugjai and Sanitjai, (1996)
4.	<ul style="list-style-type: none"> <li><b>Power input:</b> 0.62 kW</li> <li><b>LPG composition:</b> 70% (C<sub>4</sub>H<sub>10</sub>) and 30% (C<sub>3</sub>H<sub>8</sub>)</li> <li><b>Surface Stabilized Burner (SSB):</b> PH: Alumina (Al<sub>2</sub>O<sub>3</sub>) foams (26 ppcm, 12.7 mm thick, porosity 86%); CZ: Alumina (Al<sub>2</sub>O<sub>3</sub>) foams (8 ppcm, 12.7 mm thick, porosity 84%)</li> <li><b>Matrix Stabilized Burner (MSB):</b> PH: porcelain form (18 ppcm and 15 mm thickness); CZ: Alumina spheres of 30 mm size</li> <li><b>Body material:</b> Stainless steel body (thickness 3mm)</li> </ul>	Mujeebu et al. (2011)
5.	<ul style="list-style-type: none"> <li><b>Combustion rate:</b> 1 kW,</li> <li><b>Porous medium:</b> Plug (diameter 50.8 mm; thickness of 3 mm) average diameter of the bronze pellet was 0.5 mm and had a porosity of 0.237</li> </ul>	Wu et al. (2014)
6.	<ul style="list-style-type: none"> <li><b>LPG composition:</b> 60% butane and 40% propane</li> <li><b>LPG supply pressure:</b> 1.5 bar</li> <li><b>Combustion rate:</b> 5-15 kW</li> <li><b>Porous medium:</b> PZ (Al<sub>2</sub>O<sub>3</sub> matrix) - 120 mm diameter thickness 10 mm with through holes (1.5 mm diameter 463 holes); CZ (SiC reticulated foam) - diameter 120 mm and thickness 25 mm and porosity 90%.</li> <li><b>Port:</b> 4 ports with 21 mm diameter</li> <li><b>Slot's length and width:</b> 30 mm and 10 mm</li> <li><b>Orifice diameter:</b> 0.25 mm</li> <li><b>Body Materials:</b> Casing: castable cement</li> </ul>	Mishra, (2015)
7.	<ul style="list-style-type: none"> <li><b>LPG composition:</b> 60% propane and 40% butane</li> <li><b>LPG supply pressure:</b> 0.023 bar</li> <li><b>Air pressure:</b> Dry air at 0.7 bar</li> <li><b>Combustion rate:</b> 98.5 – 244 kW/m<sup>2</sup></li> <li><b>Porous medium:</b> PZ: Average equivalent diameter of 11 mm. 85 mm in height amorphous Al<sub>2</sub>O<sub>3</sub> particles resulting from grinding wastes. CZ: SiSiC ceramic foam disks, 20 ppi Height 15 mm and diameter 16 cm</li> <li><b>Body Materials:</b> Steel housing</li> </ul>	Herrera et al. (2015)
8.	<ul style="list-style-type: none"> <li><b>Porous material:</b> Annular packed bed of alumina spheres with diameter of 15 mm</li> <li><b>Material used for combustion chamber:</b> Cylindrical steel chamber of 3 mm wall thickness enclosed by high temperature cement.</li> <li><b>Fuel injector:</b> 1.5-mm-diameter nozzle.</li> </ul>	Makmool et al. (2013)

9.	<ul style="list-style-type: none"> <li>• <b>LPG composition:</b> 60% butane and 40% propane</li> <li>• <b>LPG supply pressure:</b> 1.2 bar</li> <li>• <b>Combustion rate:</b> 1-3 kW</li> <li>• <b>Porous medium:</b> PZ: (Al<sub>2</sub>O<sub>3</sub> matrix) - 80 mm diameter thickness 10 mm with through holes (1.5 mm diameter 204 holes); CZ: (SiC reticulated foam) diameter 80 mm and thickness 20 mm and porosity 90%.</li> <li>• <b>Port diameter:</b> 21 mm</li> <li>• <b>Slot's length and width:</b> 30 mm and 10 mm</li> <li>• <b>Orifice diameter:</b> 0.35 mm</li> <li>• <b>Body Materials:</b> Casing: castable cement</li> </ul>	Mishra and Muthukumar, (2018)
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## Biogas

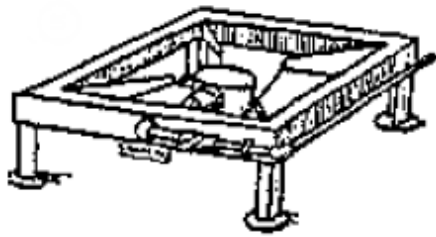
Biogas-based cook-stove technology has been widely implemented in several countries such as India (Ministry of New & Renewable Energy - Government of India., 1992), China (Giwa et al., 2020), Bangladesh (Bangladesh National Biogas Program Monitoring Services), and Pakistan (Yasmin and Grundmann, 2019) with subsidization of biogas plants. These cook-stoves are similar to the traditional LPG-based cook-stoves working on FFC (Petro et al., 2020) or PMC (Kaushik et al., 2021).

A biogas cook-stove usually has a single or double-layer burner with varying gas consumption rates viz., Domestic burners: 1.2 to 5.5 kW, and Commercial burners: 5.5 to 17 kW (Fulford, 1996). The burner itself has several parts viz., Jet (Injector orifice), air intake holes, mixing tube (diffuser), flame port, baffle, burner manifold, frame, and brackets welded on the top of it. There are two types of FFC-based biogas cook-stove designs: one is a modified design of the existing LPG cook-stoves and the other is an original design based on the properties of biogas (Sasse et al., 1991). In the early 90s, Chandra et al. (1991), presented hydrodynamical modeling of a biogas cook-stove with analytical expressions for the design parameters of a burner.

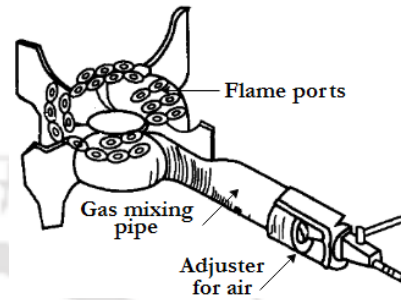
With the help of the analytical expressions, for a given biogas pressure and pressure drop across the nozzle orifice, the design parameters of a biogas burner such as orifice, the interspace between orifice and the mixing tube for aspiration of primary air, burner head area, and port number could easily be selected.

In 1996, Fulford presented a detailed design equation for biogas cook-stove consistent with the scientific and technical criteria for low-pressure burners. They also presented a typical design calculation for a DCS cook-stove to supply about 1.5 kW for cooking. Using similar design

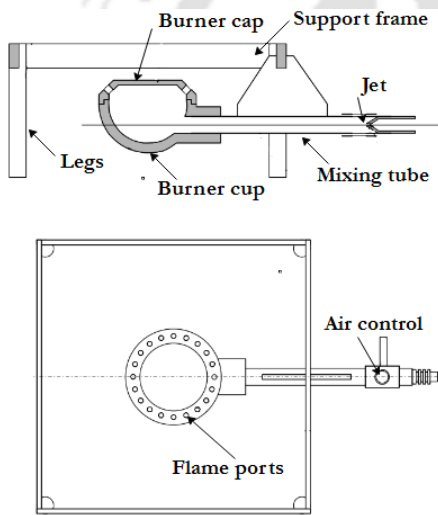
principles, Kurchania et al. (2010, 2011), developed biogas cook-stoves for cooking and baking corresponding to biogas consumption of 1 m<sup>3</sup>/h and 0.375 m<sup>3</sup>/h, respectively. Analogous designs of domestic cook-stoves can be found in the literature (Awulu et al., 2020; Decker et al., 2018; Itodo et al., 2007; Kandpal et al., 1995; Mulugeta et al., 2017; Petro et al., 2020; Syamsuri et al., 2015).



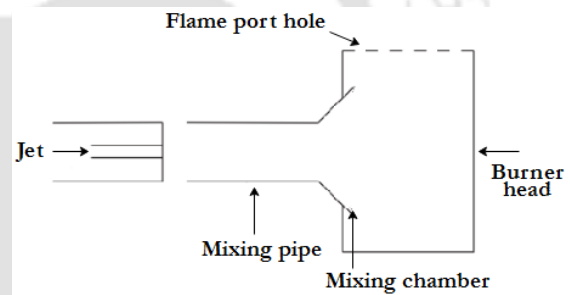
a) Biogas cook-stove developed by CAMARTEC (Sasse et al., 1991)



b) Biogas stove-KVIC model (Kandpal et al., 1995)



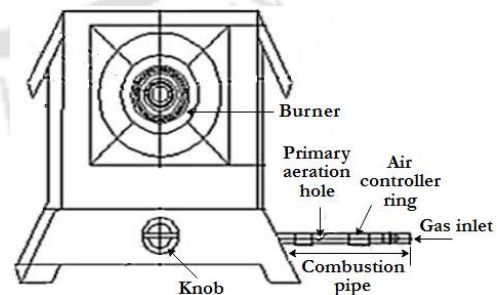
c) DCS burner used in Nepal (Fulford, 1996)



d) Biogas stove designed by Itodo et al. (2007)



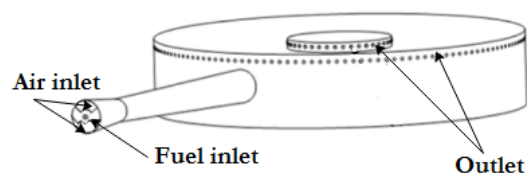
e) Biogas stove for baking developed by Kurchania et al. (2010)



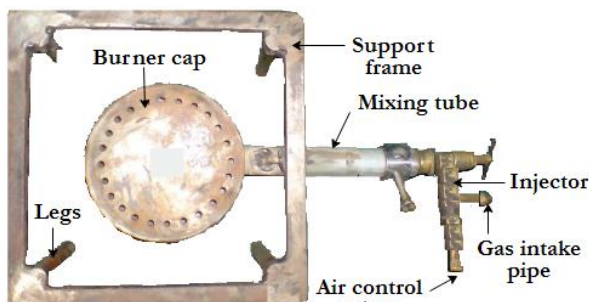
f) Domestic biogas stove developed by Kurchania et al. (2011)



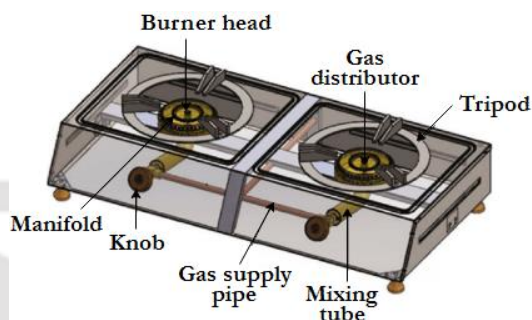
g) 1.) Regular-shaped burner, 2.) Cyclone 1-shaped burner, 3.) Cyclone 2-shaped burner (Syamsuri et al., 2015)



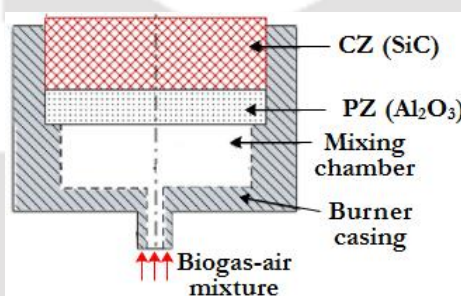
h) Biogas Injera baking burner (Mulugeta et al., 2017)



i) Biogas burner (Stove) developed by Awulu et al. (2020)



j) Biogas burner developed by Petro et al. (2020)



k) Biogas operated porous radiant burner developed by Kaushik et al. (2021)

**Fig. 2.3** Various designs of biogas cook-stoves

Recently, by using PMC, Kaushik et al. (2021) developed a domestic double-layer PRB cook-stove for biogas following the design of Mishra (2015), meant for LPG.

The various biogas cook-stove designs are illustrated in **Fig. 2.3**, and their basic design specifications are listed in **Table 2.2**.

**Table 2.2:** Design features of biogas cook-stoves

S. no.	Design details	Fig.	Ref.
1.	<ul style="list-style-type: none"> <li><b>Materials:</b> High-quality steel or cast iron</li> <li><b>Air-intake holes of the mixing pipe:</b> Two drillings of 8 mm diameter</li> </ul>	10 a)	Sasse et al. (1991)

2.	<ul style="list-style-type: none"> <li>• <b>KVIC model</b></li> </ul>	10 b)	Kandpal et al. (1995)
3.	<ul style="list-style-type: none"> <li>• <b>Biogas supply pressure:</b> 0.01bar</li> <li>• <b>Biogas flow rate:</b> 0.471 m<sup>3</sup>/h</li> <li>• <b>Injector size:</b> 2.1 mm</li> <li>• <b>Port hole:</b> 20 holes of 5 mm diameter (total burner port area = 390 mm<sup>2</sup>)</li> <li>• <b>Materials:</b> cast iron, aluminium, mild steel, ceramics</li> </ul>	10 c)	Fulford, (1996)
4.	<ul style="list-style-type: none"> <li>• <b>Jet diameter:</b> (d<sub>o</sub>) 16 mm</li> <li>• <b>Diameter of mixing pipe:</b> (d) 97 mm</li> <li>• <b>Length of air intake hole (Max., Min.):</b> (L<sub>max</sub>, L<sub>min</sub>) 679, 131 mm</li> <li>• <b>Diameter of mixing chamber:</b> (D) 126 mm</li> <li>• <b>Length of mixing chamber:</b> (L) 146 mm</li> <li>• <b>Number of ports:</b> (n) 35</li> <li>• <b>Diameter of flame port:</b> (d<sub>H</sub>) 2.5 mm</li> </ul>	10 d)	Ito do et al. (2007)
5.	<ul style="list-style-type: none"> <li>• <b>Length of gas and air mixing tube:</b> 960 mm</li> <li>• <b>Inner diameter of tube:</b> 19 mm</li> <li>• <b>Number of air holes for primary aeration:</b> 16</li> <li>• <b>Diameter of air holes for primary aeration:</b> 18 mm</li> <li>• <b>Number of perforated tubes for burner:</b> 2</li> <li>• <b>Number of ports:</b> 56</li> <li>• <b>Diameter of each port:</b> 2.5 mm</li> <li>• <b>Distance between pan and burner:</b> 35 mm</li> <li>• <b>Orifice diameter:</b> 3 mm</li> </ul>	10 e)	Kurchania et al. (2010)
6.	<ul style="list-style-type: none"> <li>• <b>Length of the gas and air mixing tube:</b> 850 mm</li> <li>• <b>Inner diameter of tube:</b> 14 mm</li> <li>• <b>Number of air holes for primary aeration:</b> 4</li> <li>• <b>Diameter of air holes for primary aeration:</b> 4 mm</li> <li>• <b>Number of ports:</b> 49</li> <li>• <b>Diameter of each port:</b> 2 mm</li> <li>• <b>Distance between pan and burner:</b> 35 mm</li> <li>• <b>Orifice diameter:</b> 2 mm</li> <li>• <b>Crown diameter:</b> 80 mm</li> </ul>	10 f)	Kurchania et al. (2011)
7.	<ul style="list-style-type: none"> <li>• <b>Biogas burner head</b> (1.) Regular shaped, (2.) Cyclone-1 shaped</li> <li>• (3.) Cyclone-2 shaped</li> </ul>	10 g)	Syamsuri et al. (2015)
8.	<ul style="list-style-type: none"> <li>• <b>Material:</b> Sheet metal (2 mm thickness)</li> <li>• <b>Jet diameter:</b> 2.3 mm</li> <li>• <b>Primary air inlet:</b> No of holes- 2, Area of holes- 96 mm<sup>2</sup></li> <li>• <b>Gas air mixing tube:</b> Length 158 mm, Throat dia. 15.63 mm</li> <li>• <b>Port:</b> No. of port- 180, Dia. of port- 2 mm</li> <li>• <b>Manifold:</b> Cylindrical shape, 260 mm external dia.</li> </ul>	10 h)	Mulugeta et al. (2017)
9.	<ul style="list-style-type: none"> <li>• <b>Estimated gas flow rate:</b> 5.69 m<sup>3</sup>/h</li> <li>• <b>Jet diameter:</b> 11 mm</li> <li>• <b>Diameter of mixing pipe:</b> 66 mm</li> <li>• <b>Maximum length of air intake hole:</b> 462 mm</li> <li>• <b>Minimum length of air intake hole:</b> 89.1mm</li> <li>• <b>Diameter of mixing chamber:</b> 86 mm</li> <li>• <b>Length of mixing chamber:</b> 99 mm</li> <li>• <b>Number of holes:</b> 24</li> <li>• <b>Diameter of flame port hole:</b> 2.5 mm</li> </ul>	10 i)	Awulu et al. (2020)
10.	<ul style="list-style-type: none"> <li>• <b>Injector diameter:</b> 2.5 mm</li> <li>• <b>Internal throat diameter:</b> 18 mm</li> <li>• <b>Number of burner ports:</b> 71</li> </ul>	10 j)	Petro et al. (2020)

	<ul style="list-style-type: none"> <li>• <b>Mixing tube length:</b> 170 mm</li> <li>• <b>Internal manifold diameter:</b> 100 mm</li> <li>• <b>Flame port diameter:</b> 2.5 mm</li> <li>• <b>Air inlet diameter:</b> 5.0 mm</li> </ul>		
11.	<ul style="list-style-type: none"> <li>• <b>Porous Medium:</b> PZ (Al<sub>2</sub>O<sub>3</sub> Ceramic) - 90 mm diameter; 20 mm thickness and porosity 31% CZ (SiC foam) – 90 mm diameter, 20 mm thickness and porosity 90%</li> <li>• <b>Body Materials:</b> Casing : High-temperature-resistant castable cement</li> <li>• <b>Biogas supply pressure:</b> 1.2 bar</li> </ul>	10 k)	Kaushik et al. (2021)

### 2.1.2 Cook-stoves based on their performance with respect to the fuels

#### Liquefied Petroleum Gas (LPG)

LPG cook-stoves for commercial and large-scale applications require the operation of the burner at a higher power input rate and pressure compared to domestic scale burners. One such commercial LPG cook-stoves was developed under Technology Refinement and Marketing Programme (TREMAP) by Venture Center (Entrepreneurship Development Center), NCL Innovation Park, Pune (An Indigennous Design of LPG Burner for Commercial Cooking, Technology Refinement and Marketing Programme (TREMAP), Venture Center (Entrepreneurship Development Center), NCL Innovation Park, Pune, 2007). Cook-stove with swirl flow offered 55% thermal efficiency, which is 20% higher than its traditional counterpart. Parametric studies on commercial LPG cook-stoves (KB-5 burner) available in Thailand were conducted by Aroonjarattham (2016), by following the standard of TIS 2312-2549. The influence of the inclination and number of outer and inner ports on thermal efficiency was investigated. The increase of the number of inner and outer ports increased the thermal efficiency by 5 and 7%, respectively. The maximum thermal efficiency obtained at an outer port angle was 54.8%. While the outer port angle increased the thermal efficiency by 2%, the effect of the inner port angle was insignificant.

Shen et al. (2018) evaluated the performance of commonly available traditional domestic LPG cook-stoves in China, Uganda, Peru, and Cameroon by following ISO IWA-11 (International Organization for Standardization, International Workshop Agreement) test protocol. The average thermal efficiency of the cook-stoves was reported to be 51±6%. Emission factors were determined on useful energy delivered (MJd). Emission factors of THC, NO<sub>x</sub> and CO were reported to be 130 ± 196, 46 ± 9 and 0.77 ± 0.55 mg/MJd respectively. Most of the PM2.5

emission results were found to be below the detection limit of 0.11 mg/min. Fakinle et al. (2019) tested the thermal efficiency and emissions from domestic LPG cook-stoves operating on FFC available in Nigeria. As per the Nigerian standards, the average thermal efficiency obtained was  $66.2 \pm 7.21\%$  for power input  $1.5 \pm 0.3$  kW, and the toxicity potential of NO<sub>x</sub> and SO<sub>2</sub> was found to be below unity while the same was more than unity for CO and HC. Saad et al. (2019) investigated the performance of double ring-type burners with different patterns of swirling flow. The highest thermal efficiency of 57% was obtained from the counter-swirl type burner, while the least thermal efficiency of 56.3% was obtained from the radial burner. International Standard EN-30 was followed to evaluate the thermal efficiency and performance. However, the burners with swirl also produced higher CO emissions than the radial burners with no swirl. Another study was conducted by Sutar et al. (2020) to find the suitability of different pot sizes for efficient cooking at different flame settings. The use of optimum pot size, low flame setting, and a smaller burner was found to reduce the annual consumption of LPG by one cylinder. Studies conducted by Lather (2019) revealed that the existing domestic LPG cook-stove operates at a power input of 1.12 kW and a corresponding thermal efficiency to be 60.7%. Moreover, investigations for thermal efficiency improvement were conducted by changing the loading height. A loading height of 5 mm was found to be the optimum that facilitated the yield of the maximum efficiency and lowest fuel consumption. Thus, these studies on the performance of the cook-stoves led to the further development of clean cooking technologies like LPG-based PRB cook-stoves.

### ***PRB-based cook-stoves operated with LPG***

Very initial developments on the use of PRBs for cook-stove can be found in the research work of Jugjai and Sanitjai, (1996). Using PRRB design, they found that at a 4 kW combustion rate, primary air has a maximum value of temperature  $\sim 210^\circ\text{C}$ , leading to a significant increase in burner efficiency compared to PRB design. But in Porous Radiant Recirculated Burner (PRRB), at certain combustion rates, CO emission increases, whereas, in PRB, these values were nearly constant. Also, because PRRB operates at a higher flame temperature, it resulted in a sharp increase in NO<sub>x</sub> emission as the combustion rate increased. In their 5-30 kW cook-stove design (Jugjai and Rungsimuntuchart, 2002), throughout the tested capacity, the proposed PRRB(CB) was found to be about 12% more efficient than a CB. The maximum thermal efficiency of 44% was observed with PRRB(CB). The researchers further improved the thermal efficiency by replacing the ring burner (CB) with the swirling central flame ring burner (SB), i.e., PRRB(SB). The PRRB(SB) yielded a maximum thermal efficiency of about 60%. The

joint effects of efficient heat recirculation and the swirling central flame were the reasons behind the significant improvement in the case of PRRB(SB). Over the studied range of burner capacity, CO and NO<sub>x</sub> emissions were found to be higher for PRRB(SB). The relatively smaller port area and the resulting less amount of primary air led to incomplete combustion, which was the main cause behind higher emissions.

Later, major developments took place on PRB for domestic cooking; these developments comprised the exploration of various types of porous materials based on combustion and heat transfer performance, parametric studies, and studies on the surface and submerged combustion in PM. Pantangi et al. (2007) investigated the use of different types of PM for their improved thermal performance over a CB. The PRB of metal chips was found to yield the highest thermal efficiency of 73%, which was an improvement of 5% over the CB. In another study by the same research team (Pantangi et al., 2011), two-layered PRB cook-stoves were developed, and the thermal efficiency and emission were studied for burners of different sizes. The power ranges studied were 0.89 – 1.82 kW, 0.85 – 1.3 kW, 1.28 – 1.72 kW for PRB diameters of 60, 70, and 80 mm respectively, and 1.11-1.8 kW for PRB diameters of 90 and 100 mm. The highest thermal efficiency reported was 68% for an 80mm burner, against 65% for a comparable CB. The thermal efficiency was found to decrease with power input and equivalence ratio. The CO and NO<sub>x</sub> emissions were found to be 25-350 mg/m<sup>3</sup> and 12-25 mg/m<sup>3</sup>, lower than that of CB. Mujeebu et al. (2011) studied LPG combustion in domestic scale PRB in surface and submerged combustion modes at 0.62 kW power input. Operating the burner on surface combustion mode yielded thermal efficiency of 71%, which was more than that obtained from submerged combustion mode and the CB. Both surface and submerged combustion modes of operation reduced NO<sub>x</sub> emissions by up to 76% as compared to CB. The effect of PM porosity on the thermal performance of a domestic PRB was investigated by Muthukumar and Shyamkumar, (2013). Maximum thermal efficiency was obtained with a CZ porosity of 90%. The PRB yielded a maximum thermal efficiency of 75%. Wu et al. (2014) tested the feasibility of the LPG-operated flat flame burner for domestic application. The flame was stabilized on top of the PM, which allowed higher flame temperatures and therefore, higher heat transfer. The metal PM was composed of small bronze pellets, which formed a plug. Compared to a CB, the ratio of maximum to minimum output power with a stable flame (turndown ratio) was found to be higher in the flat flame burner. The flat flame burner showed a turndown ratio of 34 to 6.5, whereas it was only 6.2 to 3.17 for CB. The turndown ratio was reduced with decreasing equivalence ratio for both burners. The measured thermal efficiency

at an input power of 1 kW was found between 41% and 56% for the flat flame burner (equivalence ratio 1 to 0.7), whereas it was only 38 to 49% in the case of CB (equivalence ratio 1 to 0.9). Similarly, the NO<sub>x</sub> and CO emissions were generally lesser than that of CB. However, the distance between the burner exit and the pot/pan had only a nominal impact on the efficiency and emission of the flat flame burner. In another advancement, commercial cook-stoves developed by Mishra, (2015) generated a maximum thermal efficiency of 56% at an equivalence ratio of 0.56 at a power input of 5 kW, which was higher by 13% as compared to a CB. The thermal efficiency was observed to decrease with the equivalence ratio while the emissions of CO and NO<sub>x</sub> were observed to increase with the equivalence ratio. Meanwhile, Herrera et al. (2015) developed a PRB-based LPG-based heat input of 98.5 – 244 kW/m<sup>2</sup> and tested the burner on two modes of heat transfer: radiation-convection mode and conduction mode. They observed that the radiation-convection mode didn't increase the thermal efficiency, whereas the conduction mode test yielded thermal efficiency up to 14% higher than the CB. CO emissions lower than 25 ppm were observed for critical heat rates of 154 kW/m<sup>2</sup>, beyond which the CO emissions suddenly increased, due to quenching on the surface of the burner and moderate lift-off.

The self-aspirated cook-stove developed by Mishra and Muthukumar, (2018) showed a maximum thermal efficiency improvement of 15.5% and reductions in CO and NO<sub>x</sub> emissions with respect to CB. As an extension to this study, Kaushik et al. (2018) performed a techno-economic and cost-saving assessment, which showed an annual saving of US\$ 27.06 with a payback period of 6 months. Control cooking tests performed on the domestic PRB cook-stove (Mishra, 2015) revealed a total savings of 50 min of cooking time and 29% fuel consumption. Another study on the lifecycle and techno-economic assessment was conducted by Kaushik and Muthukumar, (2018) on the self-aspirated medium-scale PRB cook-stove developed by Mishra (2015). Life cycle energy efficiency was reported to be 38% at 5 kW, which amounted to an annual saving of US\$ 563.39 as compared to CB. The cumulative present worth was estimated to range between US\$ 4684.28 to US\$ 8102.1 for power inputs 5 – 10 kW. Deb and Muthukumar, (2021) developed a Cluster Porous Radiant Burner (CPRB) as an improvement over the medium-scale PRB cook-stove developed by Mishra (2015). Clustering of 3 single-PRBs (70 mm diameter) resulted in a thermal efficiency improvement of 13.8% and a reduction of CO emissions. IS 14612:1999 was followed for testing of the cook-stoves. The design was further improved by increasing the diameter and an optimum individual PRB diameter of 80 mm yielded a 27% improvement in thermal efficiency over CB (namely T-35, T-35, and M-

22). Maximum reduction of CO and NO<sub>x</sub> emissions up to 85% and 83% respectively were obtained with CPRB of 90 mm diameter.

In general, the studies reported so far portray that the thermal efficiency of LPG cook-stoves could be improved by appropriate design modifications to the FFC-based cook-stoves. The maximum thermal efficiency of domestic and commercial cook-stoves has been reported as 66.2% and 55%, respectively. These improvements were obtained by changing the loading height, port spacing, swirl angle, etc. However, with the introduction of PM, further improvements in thermal efficiency and reductions in emissions were obtained. The highest thermal efficiencies reported were 78% and 58% for PRB-assisted domestic and commercial cook-stoves, respectively. Also, the newly developed PRBs were further improved by optimizing the PM materials, burner geometry, operating conditions, etc.

### ***Biogas***

Chandra et al. (1991) tested the biogas cook-stoves of 14 different brands available in the Indian market. Efficiencies of these cook-stoves varied from 32 to 49% and 37 to 54%. Further, they studied the effects of the input pressure, pan size, and pan position over the burner head. The results showed that for optimal utilization of the heat available from the cook-stove, optimization of all the three above-mentioned parameters is very essential. Smith et al. (2000) studied the domestic biogas cook-stoves (operating at ~1.4 kW) available in India and estimated the nominal combustion efficiency, heat transfer efficiency, and total energy efficiency as 99.5%, 57.7%, and 57.4%, respectively. The Center for Energy Studies, Nepal, reported an efficiency of ~49.5% for biogas cook-stoves in Nepal, whereas it was ~45% for India (“A Study Report on Efficiency Measurement of Biogas, Kerosene and LPG Stoves, Center for Energy Studies Institute of Engineering Tribhuvan University Pulchowk, Lalitpur,” 2001).

Studies were not limited to the efficiency tests of biogas cook-stoves and few researchers performed their studies to test the feasibility of the design of the cook-stoves too. A report by Netherlands Development Organization (SNV) pointed out the problems associated with the poor design of Asian and African biogas cook-stoves (Khandelwal and Gupta, 2009). Using three different test standards viz. Chengdu Energy Environment International Cooperation (CEEIC), China, Department of Renewable Energy Sources (DRES), India, and Kiwa Gastec Certification (GASTEC), Apeldoorn, performance was assessed. Kurchania et al. (2010) developed a community-scale biogas cook-stove that could yield a cooking efficiency of 44%

for a fuel consumption of 1 m<sup>3</sup>/hr. The cook-stove showed thermal efficiency of ~60 % and CO<sub>2</sub> emission of ~150–180 ppm for fuel consumption of 0.375 m<sup>3</sup>/h. Kebede and Kiflu, (2014) developed a burner for injera baking application with biogas consumption and input power of 0.93 m<sup>3</sup>/h and 5.7 kW, respectively. The measured thermal efficiency was only 25%. Obada et al. (2014) developed a biogas burner for domestic cooking applications; the thermal efficiency recorded by Water Boiling Test (WBT) was 21% at a fuel consumption rate of 0.47 m<sup>3</sup>/hr, while it was 60% by cooking rice at 2.87 m<sup>3</sup>/hr. Tumwesige et al. (2014) studied eight different biogas stoves available in Sub-Saharan Africa and the average thermal efficiency of the tested stoves (KEJS, Reo, Tusk, Bremen, Ideal, Psem, Double, Psem L) ranged between 19.8% and 25.7% with input power in the range of 5.1-13 kW. Syamsuri et al. (2015) studied the impact of burner shape viz., regular and cyclone on thermal efficiency. Two cyclone-shaped burners were used for the experiments and were compared with the baseline regular burner. A maximum of 58.4% thermal efficiency at 1.53 kW was achieved with a cyclone-2 shaped burner. Decker et al. (2018) found higher thermal efficiency of 56.8% (at 3 kW) with the optimized design of the biogas stove; CO and total HC emissions were 1.103 g/MJ and 0.071 g, respectively. Unfortunately, these emissions were higher when compared to the baseline burner. Kaushik et al. (2021) estimated the thermal efficiency of a biogas stove (IS 8749: 2002) to be in the range of 51–62% for the biogas flow rate of 177-530 L/hr, and its maximum was observed at 0.75 equivalence ratio and 0.177 m<sup>3</sup>/hr flow rate of biogas. The CO and NO<sub>x</sub> emissions were 29–80 ppm and less than 4 ppm, respectively. Petro et al. (2020) achieved a thermal efficiency of 67% which was higher than the efficiency of the locally available burners. The specific fuel consumption of the developed burner was 736 g/L as compared to 920 g/L for CARMARTEC and 833 g/L for Simgas. In a different study of its kind, Awulu et al. (2020) measured the meantime for boiling water, cooking rice, yam and beans. The respective mean time obtained was 300 s, 2059.8 s, 2079.6 s, and 2959.8 s with biogas consumption of 0.474 m<sup>3</sup>, 3.254 m<sup>3</sup>, 3.285 m<sup>3</sup>, and 4.778 m<sup>3</sup>.

A study has been done on the PRB-based cook-stoves operated with biogas. As biogas is a fuel with low calorific value, it leads to ineffective combustion when cooking is done using an open flame burner / conventional burner. This can be addressed by using a Porous Radiant Burner (PRB), which has a Porous Medium. Biogas combustion in the porous media will extract it to its fullest potential, burning the low calorific value gases completely.

## 2.2 Literature on Medical Waste Incinerators

In the current scenario, the human population is growing day by day and there is a need for providing proper health care facilities to all people. In order to provide proper health care service to people of all categories, there is a need for improvement in the health care facilities and treatment techniques. Such improvisation in the medical sector will increase the generation of Medical Waste (MW) at a more rapid pace than at which the generated MW can be disposed of. Thus, the existing MW disposal system needs to undergo rapid expansion and modernization. MW is considered hazardous for both the environment and humans as it might be contaminated with disease-carrying pathogens. As per the World Health Organization (WHO) report, about 85% of MW generated is non-hazardous, 10% is infectious, and 5% is non-infectious but hazardous.

**Table 2.3** MW generated in different continents (Minoglou et al., 2017)

Name of the Continent	Countries considered	Total MW generated (kg/month per bed)
Africa	Tanzania, Sudan, Morocco, Mauritius Ethiopia, Egypt, Cameroon, Algeria	74.8
Asia	Vietnam, Kazakhstan, Turkey, Lebanese Republic, Nepal, Thailand, Palestine, Pakistan, Malaysia, Laos, Korea, Jordan, Japan, Iran, Indonesia India, China, Bangladesh	528.7
North America & South America	USA, El Salvador, Ecuador Canada, Brazil, Argentina	317.8
Europe	UK, Latvia, Spain, Norway Netherlands, Hellene, Germany France, Italy, Bulgaria	371.8

Therefore, it is necessary to treat MW with utmost care. During various pandemics like Severe Acute Respiratory Syndrome (SARS-2002), Middle East Respiratory Syndrome (MERS-2012), COVID-19 (2019), disposal of MW has been a major challenge all over the world. Various researchers around the world have done extensive studies related to the discarding of MW (Benson et al., 2021; Gören, 2011; Jaber et al., 2021; Kanyal et al., 2021; Manjula Bai,

2021; Olanrewaju and Fasinmirin, 2019; Shammi et al., 2021; Suryawan et al., 2019). The rate of MW generated at various continents across the globe in 2017 is presented in **Table 2.3**.

### 2.2.1 Medical Waste Management and its treatment across the globe

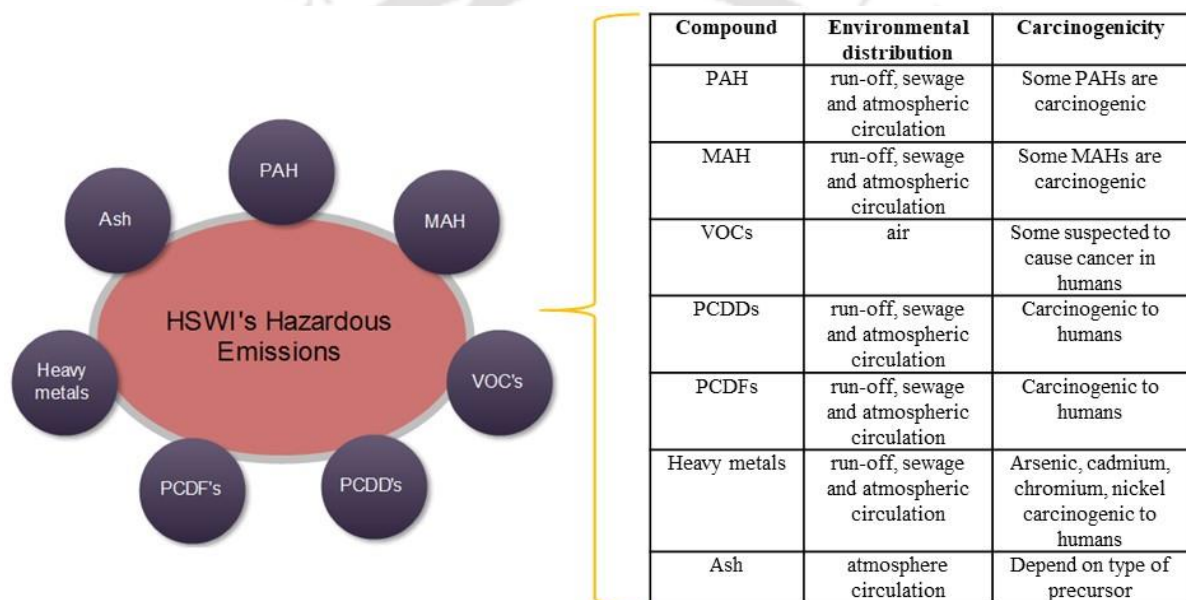
**Table 2.4** represents the status of MW disposal techniques in different countries, in which it can be observed that among the various disposal techniques, incineration is largely used for disposing of MW.

**Table 2.4** Types of MW disposal methods in developing countries

Name of the Country	Disposal method of MW
Republic of Botswana	Landfilling, incineration, open dump
Nigeria	Hydroclaving, incineration
Palestine	Incineration, landfilling
Pakistan	Landfilling, incineration, open dumping
Ethiopia	Incineration
Federative Republic of Brazil	Incineration, autoclaving, microwaving, sanitary landfill, skeptical ditching, open-air dumping
Hashemite kingdom of Jordan	Autoclaving, chemical disinfection, Incineration, landfill
China	Incineration, burning on-site
Turkey	Landfilling, incineration, autoclaving
Republic of India	Autoclave, Hydroclaving, microwave, vermiculture pyrolysis/gasification, incineration, landfill, pit burial
Republic of Bangladesh	Autoclaving, open place burning
Democratic Republic of	Incineration, chemical disinfection, on-site burial
Algeria	
South Africa	Incinerating, open dumping and landfilling, autoclaving

Ansari et al. (2019) presented a review on the composition of MW, how it is generated and the risk it poses to human health. Also, they stated that incineration is the widest method used for the disposal of solid MW in third world countries. But his report was limited to developing countries. Generally, the method of incineration has an inimitable advantage in reducing the waste volume up to 90% (Blahuskova et al., 2019). Besides, the incineration facility requires less floor space compared to the other methods for the disposal of MW (Govind Kharat et al., 2019).

Further, the burning of MW has numerous benefits like the use of the generated heat from the incinerators to heat up boilers, energy production, and the separation of noble metals for reusing (Makarichi et al., 2018). Regardless of the above-noted benefits, there are also worries associated with the use of Medical Waste Incinerators (MWIs). The major concerns associated with the use of incineration technique is the emission of hazardous matters as residual, which is harmful to the environment (Ansari et al., 2019). **Fig.2.4** shows various emissions from incinerators and their environmental distribution. The precarious emissions of MWIs may continue to persist in the environment for quite a longer duration, resulting in human health and environmental problems.



**Fig. 2.4** Environmental scattering and carcinogenicity of harmful emissions of MWIs (Ansari et al., 2019)

The Indian Government has implemented the Bio-Medical Waste Management (BMWM) rules (2016) for effective management and disposal of MW caused by Health Care Facilities (HCF) (Datta et al., 2018). The BMWM rules categorize MW into ten groups: Animal Waste, Human and Anatomical, Microbiology and Biotechnological Waste, Cast-off Medicines and Outmoded Drugs, Waste Sharp devices, Solid Waste, Soiled Waste, Liquid Waste, Chemical Waste and Incineration ash. As per BMWM rules (2016), the permissible limit for suspended Particulate Matter (PM), the residence time in the secondary chamber of the incinerator and criteria for dioxin and furans are  $50 \text{ mg/Nm}^3$ , 2 s and  $0.1 \text{ ngTEQ/Nm}^3$ , respectively (Datta et al., 2018). Manyele and Anicetus (2006) presented a survey on the prevailing systems of Medical Waste Management (MWM) in hospitals of Tanzanian in the course of a nationwide

healthcare waste management-training programme, piloted from 2003 to 2005. They reported that population increase, meager MWM systems, and the extended use of the disposables, are the central reasons for piling up of MWs in the hospitals. In a similar study done in Croatia, (Marinković et al., 2008) stated that incineration is the utmost appropriate technique for waste disposal, as it will be the most economical solution.

### ***2.2.2 Medical Waste Management and Disposal using Medical Waste Incinerators***

The rapid increase in MW generated from the health care system has led to a huge accumulation of MW. This accumulation had been causing a serious threat to societal health as well as to the environment (Mishra et al., 2016). “Incineration” is considered as one of the influencing ways of treating the MW (Rogers and Brent, 2006). It had been preferred for infectious MW treatment as it is effective in reducing the consequences of toxicity of infectious materials and also it reduces the amount of landfilled waste (Sukandar et al., 2006). Though it has been mentioned that incineration has a lesser impact on the people living in the surrounding areas, it is overlooked that the fact is that very few people live around incinerators (Rogers and Brent, 2006). There are other effects caused by incineration like the emission of toxic chemicals after combustion, mostly those from the solid residues and another concern is the leaching effect. Observations indicate that the duration of leaching is long-term in smaller particles when compared to larger particles (Sukandar et al., 2006). A study conducted by Matsui et al. (2003) also discussed the dioxins in the ashes and stack gas, which result after the incineration. It might also cause a public nuisance as the disposal of MW without proper treatment results in a foul smell (Kharat and Sharma, 2016).

### ***2.2.3 Types of Medical Waste Incinerators***

The design of the incinerators plays an imperative role in the efficient handling of MW and proper operation ensuring the efficient functioning of the incinerating unit. Various studies have been conducted across the globe focusing on the design and the thumb rules to be considered to come out with the optimal solutions to design an MWI for a specific purpose. Some of the merits and demerits of different types of incinerators are discussed in **Table 2.5**.

**Table 2.5** Merits and Demerits of incinerators

Incinerators	Merits	Demerits
<b>Double chamber incinerators</b>	<ul style="list-style-type: none"> <li>• Almost all the researchers reported that the emissions from the double chamber incinerators are clean and safe for the environment, as the treatment of MW is done in two stages.</li> <li>• MW is volatilized in the primary chamber and then the volatile gases are combusted in the secondary chamber, which will improve the combustion efficiency of the unit.</li> </ul>	<ul style="list-style-type: none"> <li>• It requires a sophisticated air supply arrangement for the proper incineration of MW.</li> <li>• There is a need for a separate burner arrangement in each chamber for maintaining the required temperatures.</li> </ul>
<b>Step grate incinerators</b>	<ul style="list-style-type: none"> <li>• It is simple in construction and saves the floor space and material requirements.</li> <li>• Fuel consumption is less compared to the double chamber incinerators, as the incineration takes place in a single chamber.</li> </ul>	<ul style="list-style-type: none"> <li>• Less combustion efficiency (86.5%) due to less operating temperature of 600 °C (Olisa et al., 2016).</li> <li>• The amount of CO produced in a step grate incinerator will be more than double chamber incinerators, as the incineration takes place in a single chamber in step by step manner.</li> </ul>
<b>Rotary grate incinerators</b>	<ul style="list-style-type: none"> <li>• Feasible to achieve the desired operating temperature (Xie et al., 2009).</li> <li>• There is no need for a separate burner arrangement in the secondary chamber as the heat lost from the primary chamber is recovered by the secondary chamber for maintaining the required temperature.</li> <li>• Higher destruction efficiency of CO in the secondary combustion chamber (100%).</li> </ul>	<ul style="list-style-type: none"> <li>• Not feasible for small scale applications.</li> <li>• Construction is complicated compared to a simple double chamber incinerator.</li> </ul>

### ***Double Chamber Incinerators***

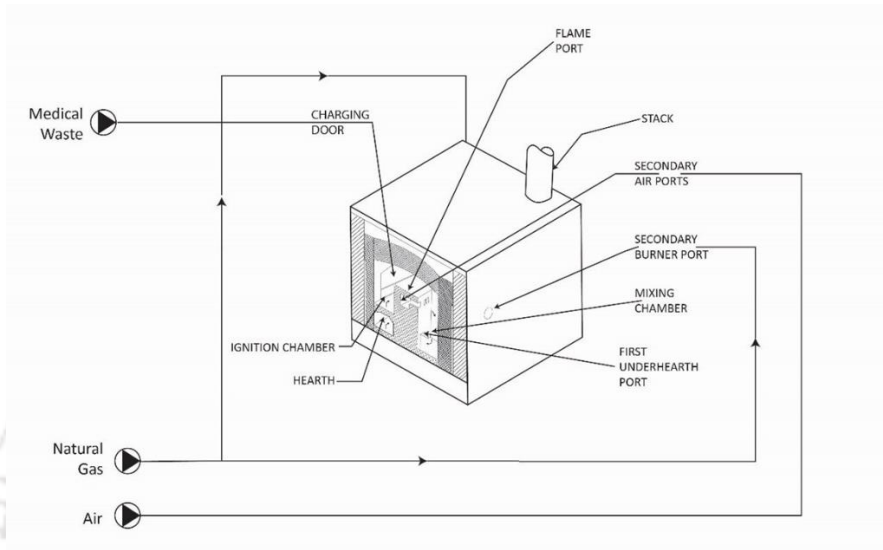
A study was conducted on a low-cost double chamber MWI at ‘The Federal Polytechnic Bida Niger State, Nigeria’ (Picken and Russell, 2012). The team observed that the functioning of the developed incinerator varied with the content of moisture in MW. Patel (2017) designed an incinerator to treat the MW with a capacity of 50 kg/hr using mass and heat balance analysis.

They designed an incinerator with a secondary chamber of volume  $1.0127 \text{ m}^3$  to have a detention time of 1s and a primary chamber of dimension  $1.26 \times 0.630 \text{ m}$  (L x D). However, this incinerator required a second retention in the active chamber volume. An innovative spread-sheet model for designing an MWI was presented by Nabizadeh et al. (2016). This model provides the procedure for the estimation of the volume, diameter, length, and residence time of the incinerator based on the thermodynamic and stoichiometric calculations. The developed MWI spread-sheet model was ordered into three quantities in MS Excel: input data, calculations and results output. This model can be taken as a reference for the design and development of incinerators as the researchers have given step-wise calculations to determine the required heat capacity for the process of incineration. But only components containing elements like hydrogen, chlorine and Sulphur were considered for the study, though the MW consists of other elements too.

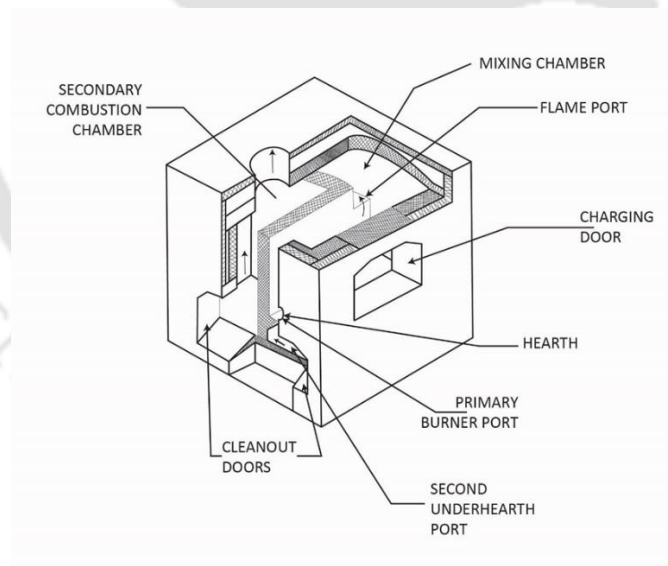
Easo and Swamy (2011) designed MWI to incinerate MW in Chikmangalur city that has a capacity of 100 kg/hr. From material and heat balance analyses, they designed a primary chamber of dimension  $1.8 \times 1.2 \times 2.2 \text{ m}$  and a secondary chamber with a volume of  $2.17 \text{ m}^3$  for a detention time of 1s. Another study conducted in Egypt presented an efficient and optimal Egyptian design of incineration plants for hospitals. The capacity of the unit was 100 kg/hr and also, they investigated the performance of the incinerator (Wahid, 2013). The author observed that the residue ash formed was 4-5% of the incinerator capacity. As per the Egyptian Environmental Affairs Agency, "Law No.4/1994 & Executed Regulations No. 338/1995" the emission level of Carbon Monoxide, Sulphuric Dioxide and Nitrogen Oxides should be less than 100, 50 and 200  $\text{mg}/\text{m}^3$ , respectively. The observed accumulations of Carbon Monoxide, Sulphur Dioxide and Nitrogen Oxides from the developed incinerator were found to be 87, 26.5 and 91  $\text{mg}/\text{m}^3$ , respectively, which is less than the permitted values.

A dual-chamber incinerator of 100 kg/hr capacity was developed to incinerate the MW generated in Bijnor city by Upadhyay (2017). Design calculations for primary and secondary chambers were made based on material and heat balance analyses. Based on the analyses, the desirable dimension of the primary chamber was found to be  $1.8 \times 1.2 \times 2.2$  and the volume of the secondary chamber was  $2.17 \text{ m}^3$  for a retention period of 1 s. In a later study conducted by Ganguly et al. (2017) in Shimla, a dual-chamber incinerator operating at 100 kg/hr capacity was developed. From mass and heat balance analyses, the dimensions of the primary chamber of the incinerator were found to be  $2.16 \times 1.23 \times 3 \text{ m}$ , and the design volume of the secondary

chamber was estimated as  $3.07 \text{ m}^3$  to maintain a retention time of 1 s. The required natural gas flow rate to maintain the temperature of  $1100 \text{ }^\circ\text{C}$  and neutralize the heat deficit was suggested to be  $29.52 \text{ m}^3/\text{hr}$ . A working design of an MWI with a combined combustion gas treatment component was put forward by Shaaban (2007). **Fig. 2.5** shows the combustion method in the multiple chambered incinerator.



a) Front-view of the incinerator

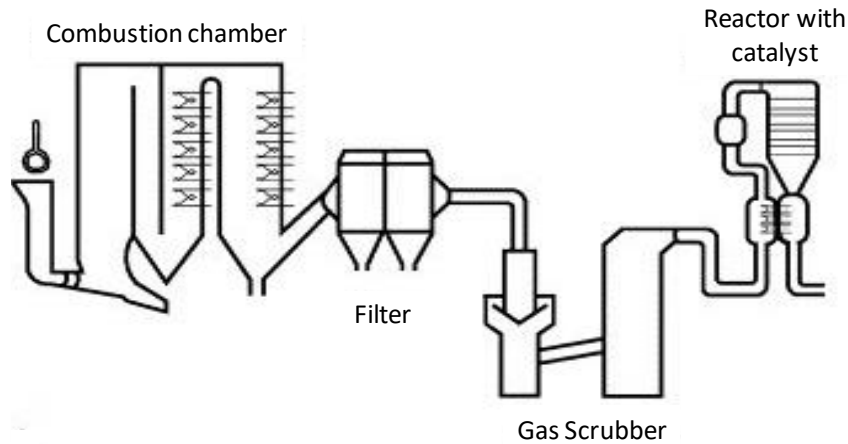


b) Top-view of the incinerator

**Fig. 2.5** Multiple-chamber pathological-waste incinerator (Shaaban, 2007)

In the combustion chamber, incineration proceeds in 2 stages viz., (i) primary/solid waste combustion which happens in the ignition chamber and (ii) secondary combustion in which

downdraft and updraft combustion happen. The heat from flue gases is collected in a heat exchanger that generates hot water at 75 °C and then the exhaust gas is treated in the treatment unit.

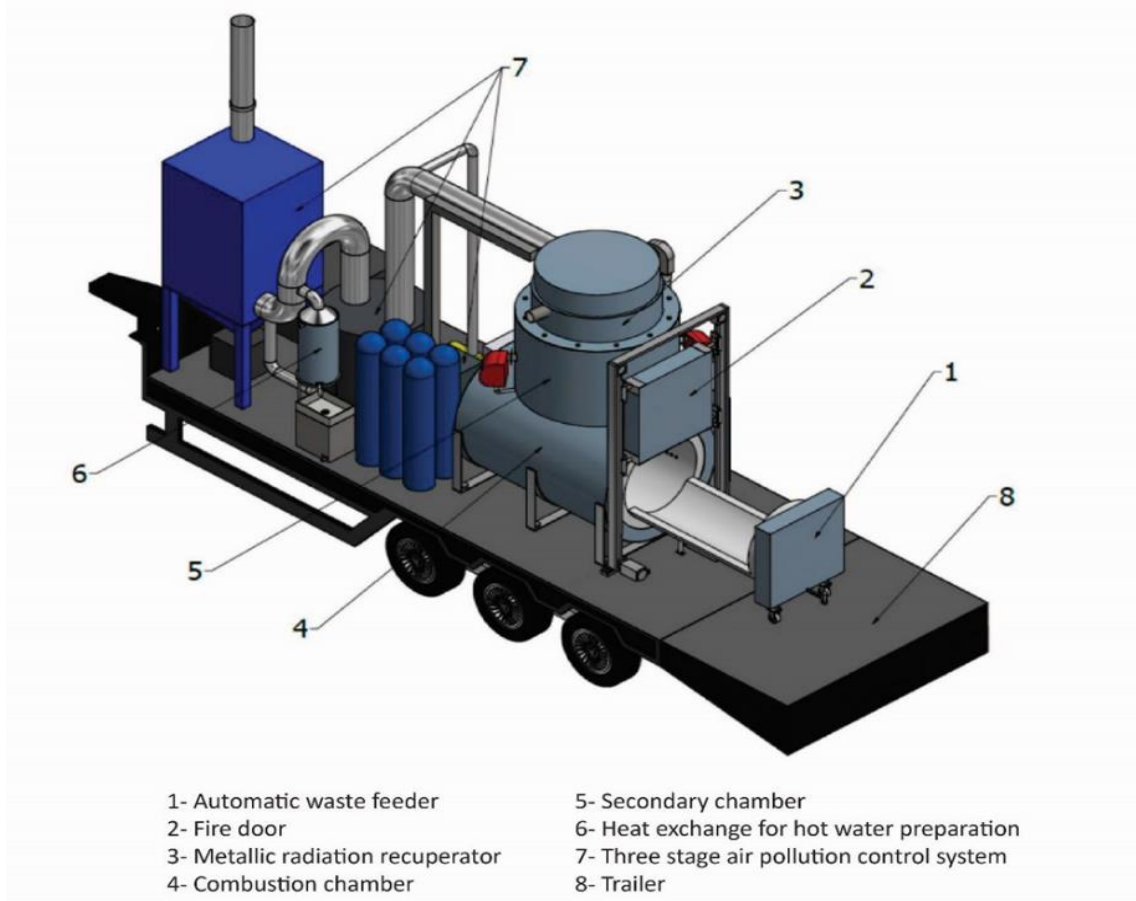


**Fig. 2.6** Flue gas treatment configuration (Shaaban, 2007)

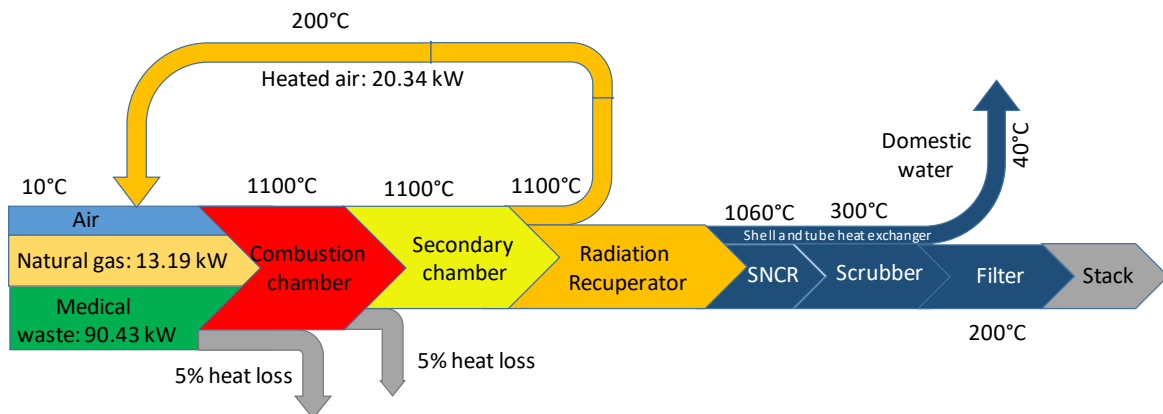
**Fig. 2.6** shows the flue gas treatment configuration used in the proposed incinerator. It comprises of filter, gas scrubber and catalytic converter. The catalytic reactor with Ammonia is positioned downstream of filter and gas scrubbers. Here, a heat exchanger is used to heat the flue gas. Using this flue gas treatment configuration, synchronized PCDD/Fs destruction and NO<sub>x</sub> reductions were observed.

One of the latest developments on the MWI which moved a step further from the traditional stationery incinerators is mobile MWIs. Wajs et al. (2019) proposed a mobile double chambered MWI for the disposal of MW in Poland. In this, the exhaust from the secondary chamber is sent to the treatment unit which consists of a Selective Non-Catalytic Reduction (SNCR) system, a spray scrubber that utilizes a wet exhaust gas cleaning method and a filter for separating the solid particles and dust.

**Fig. 2.7** shows the representation of the mobile incinerator, in which the primary chamber is horizontal while the secondary chamber is placed vertically above the primary chamber. Each combustion chamber is provided with two burners coupled with a natural gas supply system.



**Fig. 2.7** Schematic of the mobile MWI (Wajs et al., 2019)



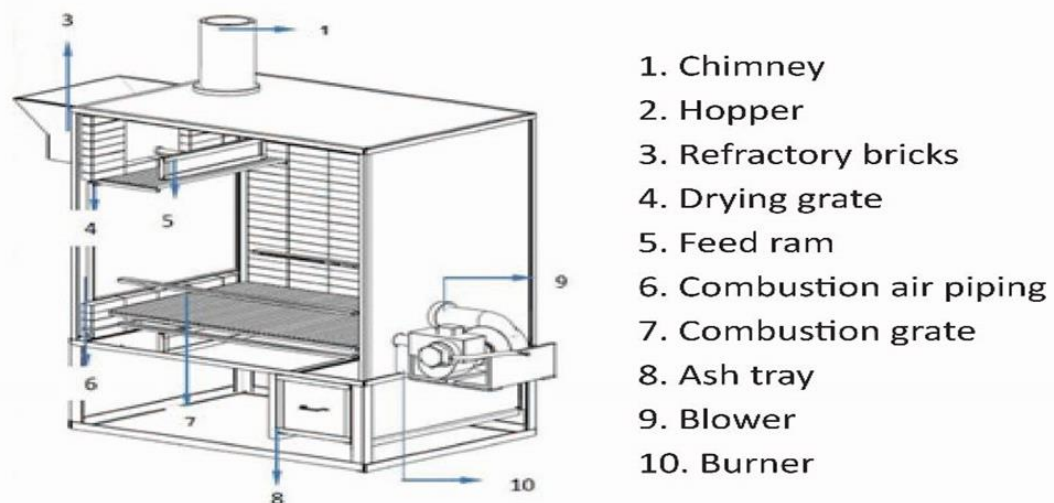
**Fig. 2.8** Graphical representation of energy flow in the mobile medical waste incinerator (Wajs et al., 2019)

**Fig. 2.8** represents the energy flow diagram of the mobile medical waste incinerator. They considered all rivulets of chemical energy, which is a substrate in the procedure. During the calculations, heat build-up in the construction materials of the two chambers and heat losses

were taken into account. The calculations also considered recuperation, as the supply of preheated air in the combustion chamber will reduce the demand for fuel.

The heat flow required to conduct the process at 1100 °C decreases from 102.99 kW to 62.42 kW, when the temperatures are measured (Wajs et al., 2019). Here, the heat energy is lost through water and flue gas is emitted. Because of its mobility, this MWI can be relocated depending on the intensity of the requirement. However, their necessity is limited to the temporary requirement.

### *Step Grate Incinerators*

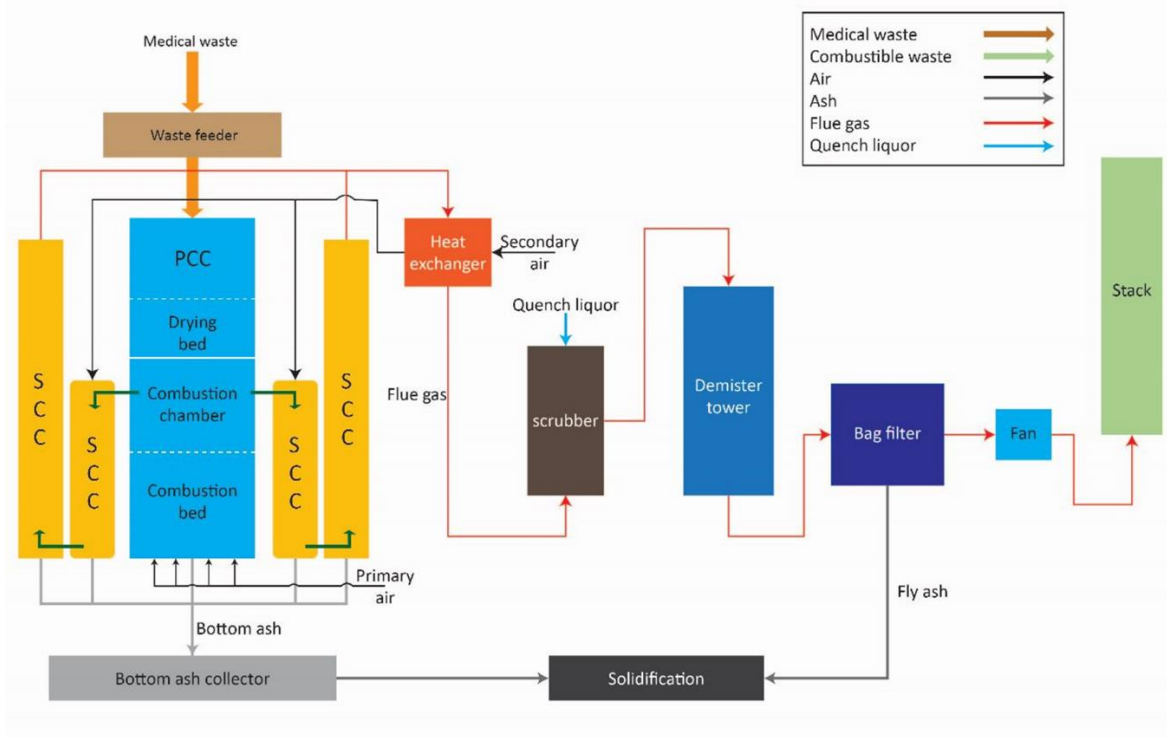


**Fig. 2.9** Pictorial and schematic view of the step grate package incinerator (Olisa et al., 2016)

In a step grate incinerator, the waste will be burnt by placing it on a grate. The waste moves in descending grate from an elevation to the ash pit in a step-by-step manner. A step grate package incinerator was designed and fabricated by Olisa et al. (2016), which was meant for thermal treatment of MW. It reduced the volume and destroyed the hazardous substances or pathogens present in the waste. **Fig. 2.9** represents the pictorial and schematic views of the step grate package incinerator, in which the waste is dumped into the hopper. From there it reaches the drying grate. The heat inside the chamber dries the waste that has reached the drying grate and then pushes it into the combustion grate. In the combustion grate, the waste is combusted by the burner and after combustion, the ash deposits at the bottom of the combustion grate. They obtained a combustion efficiency of 86.5% which is less, as they designed to operate at 600 °C.

### ***Rotary Grate Incinerators***

Rotary grate incinerators are the same as double-chamber incinerators with a primary and secondary chamber. A design was suggested for a rotary grate incinerator by Xie et al. (2009). The proposed rotary grate incinerator has a cylindrical chamber into which the waste is dumped and incinerated. This novel incinerator with a capacity of 10 tons/day consists of a feeder, a rotary grate, a primary combustion chamber (PCC) and a “coaxial” secondary combustion chamber (SCC). The authors have performed emission analysis following the incineration emission standards of China for the developed incinerator. PCC acted as a gasifier with an air excess level of 40% and excess air ratios of 1.0 in SCC for complete combustion of flue gas. As represented in **Fig. 2.10**, the waste from the waste feeder is fed into the PCC, where the waste gets dried and is combusted primarily in the combustion bed. Then the combustible gas from PCC reaches SCC. SCC has a unique cylinder arrangement with a coaxial structure. SCC surrounds PCC with the same vertical axis. The flue gas from SCC reaches the heat exchanger where the heat is rejected to air. From the heat exchanger, the flue gas passes through a scrubber, demister tower, bag filter and then the stack in a step-by-step manner. Maintaining the set temperature in the chambers is a challenge. But the authors achieved an operating temperature of 640°C in PCC which was near to the setting temperature (660°C). Also, the destruction efficiency of CO in the SCC was about 100%.



**Fig. 2.10** Operational flow chart rotary grate incinerator (Xie et al., 2009)

## 2.3 Literature Closure

### 2.3.1 Cook-stoves

Depending on the extensive literature review conducted on the cook-stoves and their operation with LPG and biogas fuels, the below mentioned concluding remarks can be made.

- The cook-stoves are basically designed to achieve an optimized combustion and heat transfer performance, which ensures maximum heat transfer to the load with minimal pollutant emissions.
- The combustion and heat transfer performance could be enhanced with careful design of burner geometry and external mixing chamber and judicious selection of the burner materials.
- The commercially available cook-stoves for gaseous and liquid fuels are designed on the free flame combustion principle. These cook-stoves offer higher thermal efficiency and reduced pollutant emissions as compared to biomass-based cook-stoves. However, due to stricter norms and increasing awareness about energy security and health concerns, the demand for better and advanced cook-stove technology has been growing.

- The porous media combustion technology is a viable manifestation of excess enthalpy/superadiabatic combustion by internal heat recuperation, where the heat is recovered to increase the inlet air temperature and raises the flame temperature locally and uniformly. It adds a novel dimension to the age-old combustion technology with manifold advantages. The development of Porous Radiant Burners (PRBs) for domestic as well as commercial cooking applications has found traction in the last decades. The performance of PRBs and their potentials to replace the conventional free flame burners (CBs) are being established. However, long-term stability is still a concern and the report in this direction is limited.
- Among the different cooking fuels, LPG has received prominence, and studies based on kerosene and natural gas are still sparse. Self-aspirated PRBs for biogas application are very limited. The recent development of self-aspirated PRBs for cook-stoves is promising as they can be a cleaner and energy-efficient alternative to CBs.

### 2.3.2 Medical Waste Incinerators

The studies conducted on MWM and MWIs by various researchers across the globe and their contributions are illustrated in **Table 2.6**.

Most of the reported articles on the MW disposal systems have focused mostly on the well-being of the people residing near the locality of the incinerators. Though Ansari et al. (2019) focused on the environmental impacts and the policy-making, the focus was given to the MWM and not on the MWI. Even though few studies on the health impacts of the MWI and MWM were reported, there is a lack of comprehensive survey on the guidelines to be followed while dealing with MW, selection of disposal location, design and construction of MWIs, various emissions associated with the incinerators and the strategies for reducing those emissions, proper maintenance of incinerators and corrosion preventive methods.

**Table 2.6** Various studies reported on incineration

Authors	Country	Study	Outcomes
K. Mishra et al., (2016)	India	Analyzed various techniques used in the segregation of MW	Biomedical waste could be segregated depending on the waste management treatments.

INCLEN Program Evaluation Network (IPEN) (2014)	India	Assessment of health facilities in primary, secondary and tertiary sectors	There is a necessity for greater binding at policy and programme levels for resource investments and capacity building in MW management.
Jang et al., (2006)	Korea	Segregation, composition, generation and disposal of MW	Suggests that efforts are required for minimization and salvaging of MW before the final disposal. Establishment of on-line mode manifestation system for tracking the waste-transport.
N. Singh et al., (2020)	China	Application of IoT in the tracking of MW disposal	During the outbreak of COVID-19 in Wuhan, three main changes were observed in MW disposal technology viz., from decentralization to centralization, from irregular to regular management, and from mostly incineration to non-incineration disposal technologies.
Rogers and Brent, (2006)	South Africa	Evaluation of low cost small-scale incinerators through qualitative and quantitative measures	The authors established protocol for low cost small scale incinerators and conducted a laboratory level trial.
Parmar and Rai, (2017)	India	Calculation of relative efficiency of 14 MW treatment plants using CCR and DEA	It was reported that that only one incinerator facility is fully efficient compared with others and the remaining facilities needed improvement. They suggested that the inefficient plants should comply with emission standards and optimize the resource allocation.
Kharat and Sharma, (2016)	India	Monitoring of the stack emission	With pollution control measures, and proper operation and maintenance care, it is possible to contain the air and water pollution problems from the incinerator.
Wang et al., (2019)	China	Clarification of the mechanism for the formation of PCDD/Fs	Strategies like strict regulation of the organochlorine content in feed material, frequent and thorough cleaning the Air Pollution Control Devices (APCD) and optimizing the injection rate of activated

			carbon can be adopted to control PCDD/F emissions.
Pandompatam et al., (1997)	Canada	Generating PCDD and PCDF release from the hog fuel boilers	Presence of inorganic chlorine in the feed material results in PCDD and PCDF formation/emission
Sukandar et al., (2006)	India	Study of metals leachability of medical waste incinerator fly ash in Japan based on particle size	Ba, Cd, Ni, Pb, and Zn in the medical waste incinerator fly ash showed high mobility. They tended to bind to carbonate and exchangeable fractions except for a range of particle sizes, 150–106 µm.
Domingo et al., (2020)	Spain	Review on the information of health effects including cancer occurrence and cancer mortality for the people residing in the vicinity of incinerator facility.	They suggested that details on the design of incinerator, the year of construction, years of operating, gas cleaning methods, level of maintenance and socioeconomic aspects of the population residing in the vicinity of incinerator facility are needed for critical review on the health effects associated with the respective population.
Karademir (2004)	Turkey	Health risks due to the exposure to the toxins like PCDD/F	Analysis were made to find the major exposure pathway for the pollutants in the area. Also, their analysis showed that the consumption of food products grown in that locality and Ambient air temperature are the most significant parameters in the exposure to PCDD/Fs in the area.
Bena et al., (2020)	Italy	Statistical analysis of Human Bio Monitoring of metals in the plant workers working in the incinerator facility	They reported that there was decrease in the concentration of most of the metals over time, except Mn, Pt, Sb, among the plant workers, which cannot be specifically attributable to the plant activity.

Emissions from MWIs still remain a threat to both humans and the environment. From the literature survey, different elements were identified in both the fly ash and bottom ash. Apart from this, it is also understood that there is no proper “one-agreed-standard” available all over the world for incinerating procedures and permissible emission limits. It is quite evident that further improvements in the design of MWIs, proper guidelines and emission handling systems

are needed for the effective functioning of MWI and lowering of the emission levels. Also, the excess heat produced during the incineration process can be effectively used for cogeneration, water heating purpose and so on, if the design and method of operation of MWIs are slightly modified with the proper equipment. CO, NO<sub>x</sub>, PM, PCDD, PCDF, PAH, PCB, REE and heavy metals in the bottom ash are identified as the major emissions from MWIs. Complete combustion of MW inside the incinerator indicates the efficiency of the incinerator to dispose of the MW and such improvement in efficiency can be achieved by modification in the design of the incinerator.

Various authors have tested different configurations of incinerators and reported improvement in the overall efficiency. However, no engineering approach has been adopted on the design of MWIs. Also, no work has been reported so far on the performance of the incinerators combined with heating device / burner, which is important as the thermal performance of the heating device / burner have an impact on the overall performance of the MWIs. Application of Porous Radiant Burner (PRB), which is highly efficient and produces less pollutants into the atmosphere can be explored as an alternative to the conventional burners used in MWIs.

## **2.4 Research Questions and Objectives**

The following research questions and objectives have been framed depending on the literature closure

### ***Research Questions***

- i. Is PRB more environmentally sustainable than conventional burner when used in cooking applications?
- ii. Is PRB environmentally a better sustainable product when used in industrial applications?
- iii. Is PRB's economical sustainability better than its counterparts?
- iv. If it is sustainable, what could be the organizational design for an entity to mass produce PRB?

### ***Objectives of the Thesis***

1. To conduct a detailed Life Cycle Assessment on Porous Radiant Burner used in
  - a) Cooking applications

- b) Medical Waste Incinerator
2. To perform Techno-Economic feasibility study on Porous Radiant Burner used in Commercial Cooking applications
  3. To propose an organizational structure or organizational design for an entity that manufactures a sustainable product like PRB considering all the stakeholders



## Chapter 3

### Methodology

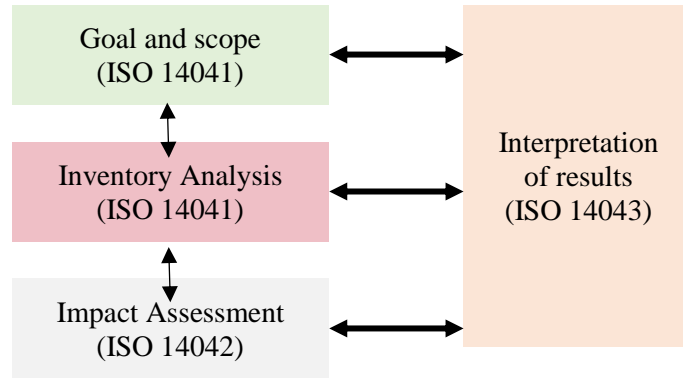
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In this chapter, the methodologies of conducting Life Cycle Assessment (LCA) and Techno-economic Assessment (TEA) are explained. Also, the methodology for the development of a business model for a firm aiming to start the mass production of PRB cook-stoves, based on the value the product creates for its customer/consumer base is presented.

#### 3.1 Methodology for LCA

The definition of LCA as given by ISO is “the compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle” (ISO\_354, 2003). LCA assesses environmental traits and the impacts of a service, process or product throughout its life (Adamczyk and Dzikuć, 2014; Ehtiwesh et al. 2016). Besides determining the environmental impacts, it will also categorize the environmental hotspots which affect the environmental impacts, hence giving an opportunity to choose better environmentally sustainable processes or products or services (Evangelisti et al., 2014; Abdelsalam et al., 2019). LCA can be performed by adopting different methods, depending on the requirement and the nature of the study. Methods of LCA include cradle-to-gate, gate-to-gate, gate-to-grave and cradle-to-grave. In the “cradle-to-gate” method, the environmental impacts of a product or a process are assessed partially, from the raw material extraction to their transportation to the factory gate. The “gate-to-gate” method also includes a partial environmental impact assessment since LCA is conducted only at one value-added process in the entire production chain. Whereas in the “gate-to-grave” method, LCA is done for the functional unit of the product or process or service, till the discard. These three methods of LCA are adopted for projects having a longer duration. The “Cradle-to-grave” method of LCA is the method in which the impact assessment of a product or service or process is done from the raw material extraction, its transportation, manufacturing, usage and till its discard.

LCA is a data-intensive process. For the accuracy of results, it is very important that the data input has to be taken care of with utmost accuracy. Generally, LCA process includes four steps, viz., 1) Goal and Scope, 2) Inventory Analysis, 3) Impact Assessment and 4) Interpretation of Results. **Fig. 3.1** represents the methodology adopted in conducting LCA.



**Fig 3.1** Methodology of LCA

### **3.1.1 Goal and Scope**

Goal and scope define and specify about which process or product or service, environmental assessment has to be conducted on. To frame goal and scope of the assessment, functional unit and system boundary has to be defined.

#### **Functional unit**

A functional unit is the utmost important comparative component while conducting an LCA study, which acts as a unit of reference to quantify the enactment of a service or process or product (Schwartz et al., 2018). To do an accurate comparison of the considered studies defined in the goal and scope, a clear functional unit has to be defined for the same (DeMarco and Fortier, 2021).

#### **System boundary**

The system boundary will define a system of different products or processes or services that are considered for the study, besides defining the quantity of energy and material inputs and their respective emission outputs while calculating the embodied energy of a particular product or service (Peuportier, 2001). A system boundary can be defined as one which separates the system of study from its adjacent systems (Zhao et al., 2018).

### **3.1.2 Inventory Analysis**

For conducting an LCA study, access to data about inputs, outputs, material requirements, etc., is crucial. For this, the compilation of data plays a significant role. In the Life Cycle Inventory (LCI) stage, the embodied energy involved in the material required for the set-up of the product,

service, or process including recycling of any of its parts, and all the respective emissions are defined in a quantitative representation.

### **3.1.3 Impact Assessment**

According to ISO 2006, a Life Cycle Impact Assessment (LCIA) seeks to evaluate the environmental impacts of a product or service or process and is the third stage of LCA. Though impact assessment methods have been developed since the early 1990s, there are quantitative differences between various LCIA methods. In the LCIA method, there are impact categories, which are environmental issues. The flows in the inventory which contribute to impact categories are called as substances. For each substance, the environmental impacts are quantified through the corresponding factors of characterization of the respective substances. The methods used for the studies are a multi-issue LCIA method viz., the ReCiPe method and IMPACT 2002+ method. In ReCiPe method, there are two indicators namely midpoint indicators which are problem oriented and endpoint indicators which are damage oriented. The midpoint indicators examine the impact of the cause and effect till the midpoint and the endpoint indicators examine the impact after the midpoint is reached till the end of the cause and effect chain. Environmental impacts are deciphered to “environmental themes” at the midpoint level, whereas they are deciphered to “issues of concern” at the endpoint level.

Midpoint approach is adopted to provide a clear understanding of PRB’s environmental impacts and compare it with CB. Midpoint categories adopted in ReCiPe Midpoint Hierarchist (H) version V1.13, are Climate change, Ozone depletion, Terrestrial acidification, Freshwater eutrophication, Marine eutrophication, Human toxicity, Photochemical oxidant formation, Particulate matter formation, Terrestrial ecotoxicity, Freshwater ecotoxicity, Marine ecotoxicity, Ionising radiation, Agricultural land occupation, Urban land occupation, Natural land transformation, Water depletion, Metal depletion and Fossil depletion.

The endpoint approach is adopted because certain assumptions are made because of the data gap throughout the cause and effect chain. Also, the endpoint approach is easier to communicate to decision-makers so that they can opt for the optimal/better alternatives. Endpoint categories adopted in ReCiPe Endpoint (H) V1.13, used in the present study, are Human Health, Ecosystems and Resources. The perspective adopted for the current research is H/H which refers to the normalization values with the weighting set belonging to the hierarchist perspective.

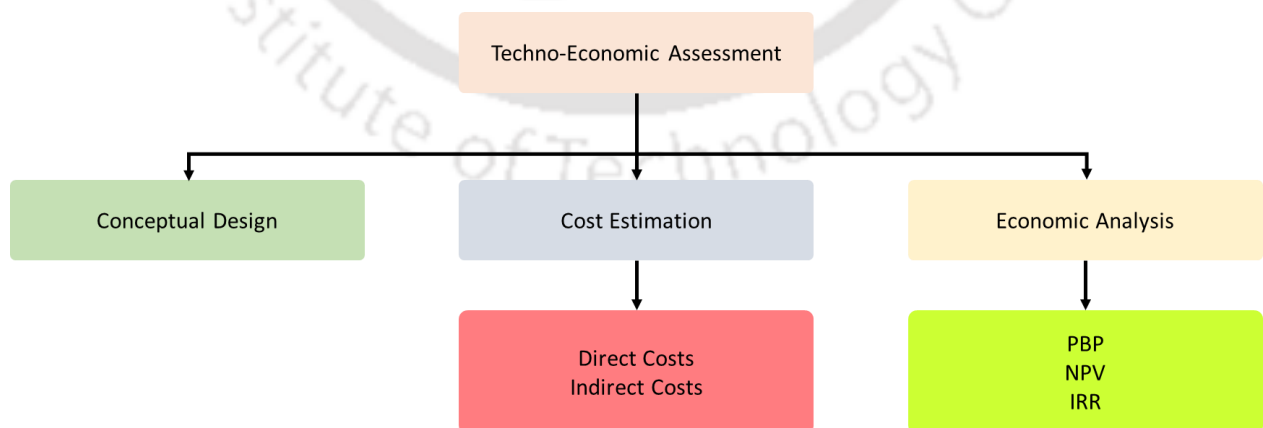
IMPACT 2002+ is an acronym of IMPact Assessment of Chemical Toxics which proposes a feasible implementation of a combined midpoint/damage approach, linking all types of life cycle inventory results (elementary flows and other interventions) via 14 midpoint categories to four damage categories. Midpoint categories of IMPACT 2002+ method include Human toxicity, Respiratory effects, Ionizing radiation, Ozone layer depletion, Photochemical oxidation, Aquatic ecotoxicity, Terrestrial ecotoxicity, Aquatic acidification, Aquatic eutrophication, Terrestrial acidification, Land occupation, Global warming, Non-renewable energy, and Mineral extraction. Whereas endpoint categories of IMPACT 2002+ method include, Human health, Ecosystem quality, Climate change and Resources.

### 3.1.4 Interpretation of Results

The results of LCA cannot be direct because all the stages of LCA, functional units, operational units, assessment methods, and assumptions may differ according to certain conditions like geographical areas, considered material, the energy required and given out, and so on. The last of the four steps in LCA is interpretation. This step includes a number of checks to test whether conclusions are adequately supported by the data and by the procedures used. Uncertainties can be handled in this step and this step will act as a decision-making tool on whether to go ahead with the product or process or service.

### 3.2 Methodology for TEA

Techno Economic Assessment provides an insight to check about the economic feasibility of a product or service or process. The methodology for TEA is shown in **Fig. 3.2**.



**Fig. 3.2** Techno-Economic Assessment methodology

### **3.2.1 Conceptual design**

Designing the concept and understanding the flow of the process have to be done before performing the economic assessment of any project. This step gives a clear understanding of the material used, equipment set up, and the flow of the operation or the procedural flow while the equipment is being operated. Designing the concept and procedural flow are developed into the Process Flow Diagram (PFD). A PFD is a diagrammatic representation of the process, which is normally drawn in a stylized pictorial form using international standards symbols (Shah et al., 2016).

### **3.2.2 Cost estimation and calculation**

In the cost estimation, the total costs required to set up the operational plant such as direct costs, indirect costs, fixed costs, variable costs, works costs are estimated. Cost of investment plays a major role in TEA of any plant involved in the manufacturing of a particular product or providing a dedicated service.

#### ***Direct costs***

Direct costs, also known as prime costs are those expenses that are directly related to producing the goods or services. The direct costs considered for the present study are the raw materials required for the manufacturing of PRB-based cook-stoves, accessories to fit the burners and stoves, transport inwards, wages of the floor level workers, engineers, and managers involved directly in the manufacturing of the PRB-based cook-stoves.

#### ***Factory costs***

Factory costs are the costs incurred for other expenses of the factory related to the product or the service other than the direct costs. These are indirect costs.

#### ***Administrative costs***

The administrative costs are the costs incurred for the business unit to run its operations. Similar to factory costs, administrative costs are not directly related to the manufacturing of the product or service.

#### ***Production cost***

The production cost is the total cost of all the direct and indirect costs a unit will incur in the due process of manufacturing a product or service.

### ***Sales cost***

The sales cost is the accumulated cost of the entire cost incurred till the production of the product or the service and also the costs incurred for the selling and distribution of the product or service. However, the sales cost does not include the profit. It has to be noted that the sales price may be decided by adding up the profit percentage to the sales cost.

Considering the direct, factory, administrative, production, and sales costs as CD, CF, CA, CP, CS  
then CS can be calculated as  $CS = CD + CF + CA + CP$ .

### ***3.2.3 Economic Analysis***

Economic Analysis is conducted to assess the economic viability of a project to confirm its profitability of the project. In the present study, Net Present Value (NPV), Internal Rate of Return (IRR) and Pay Back Period (PBP) analysis methods have been considered to test the economic viability.

#### ***Net Present Value (NPV)***

Net Present Value is obtained by considering the present value of all the cash flows calculated at the discounted value of the marginal tax after considering the initial investment. It is the difference of present values of cash inflows and present values of cash flows over a period of time and is used to analyze the profitability of a product or project. The projects with positive NPV may be taken up and the projects with NPV may be rejected.

#### ***Internal Rate of Return (IRR)***

Internal Rate of Return is a financial analysis metric that is obtained by estimating the profitability of the investments made in a project. It is the annual rate of growth an investment is expected to generate. It is calculated in the same way as NPV is calculated except that it sets the NPV value to zero. IRR is useful for the investors to estimate the return of various assets on which the investment is made.

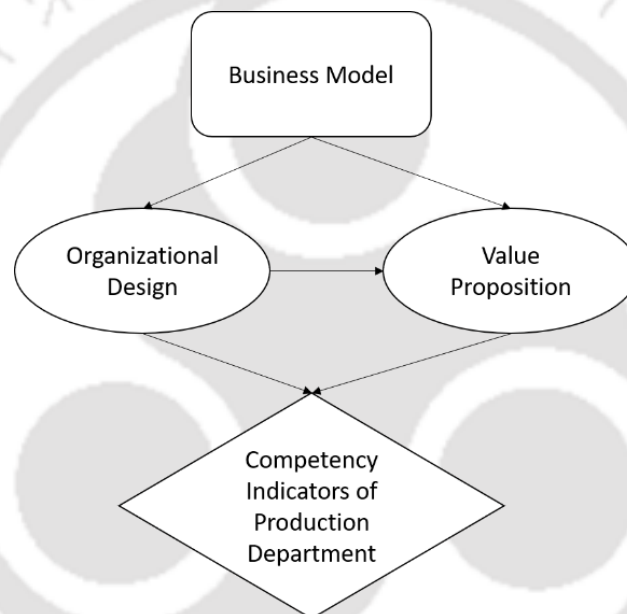
#### ***Pay Back Period (PBP)***

Pay Back Period is obtained by calculating the time period in which the initial investment is recovered.

### 3.3 Methodology for Organizational Design

The methodology adopted in the present study is the development of a business model for a firm aiming to start the mass production of a product, based on the value it creates to its customer/consumer base.

Also, the source of the value proposition is taken into consideration. Depending on the business model, an organogram or organizational design is proposed and value chain analysis is done for the same and accordingly, competency indicators have been proposed for the production department. The methodology is represented in **Fig. 3.3**.



**Fig. 3.3** Approach towards competency indicators

#### 3.3.1 Business Model

A business model is an expression of how the company performs its activities, operations and the value it creates for its stakeholders (Teece, 2010). There has been no definite definition for a business model, so far. According to Richardson, a business model is majorly based on three functions viz., proposition, generation, and capture of values (Richardson, 2011). Another definition of a business model is that it is an articulation of logic, data and other evidence that provides value to the customer and provides revenue and cost structure to the entity that provides the value to the customer (Teece, 2010).

The business model in the present study is developed by taking the business canvas model into reference (Parry, 2014). The business canvas model majorly comprises of three sections viz., the value the entity provides to its customers, the procurement of the necessities to provide those values, and the customer base and how to reach it.

### ***3.3.2 Organogram / Organizational Design***

An organizational design is the way an organization is put together, who does what, and how the communication takes place (Burton and Obel, 2004). In the industrial era, organizations were designed as vertically integrated structures to represent hierarchical authority because of the scarcity of resources and high interaction costs (Bryan and Joyce, 2007). However, organizations are adapting themselves to the changing environment. Each organization will have a unique design of its own depending on its type, the services it provides, its culture, communication, and the way it interacts with the external environment. In the present study, organizational design is proposed taking various aspects of the business model into consideration to provide the best output in the due course of the manufacturing of the product. In the organogram, both the line and staff functions have been analyzed thoroughly and represented.

### ***3.3.3 Value chain analysis and Competency Mapping***

Once the organogram is designed, the value chain for PRB cook-stove manufacturing is analyzed. Value chain analysis will open significant opportunities to any firm, which will potentially lead to the upgrading of their manufacturing and service (Morris, 2001). In the present study value chain is analyzed for the work procedure of manufacturing the product. After the analysis is done, the focus was given to the production department and competency indicators have been developed after conducting user studies at different levels of the department. After conducting the literature survey, all the skills have been analyzed and categorized into four broad skill sets at different levels of the organizations.

The different skill set types indicate interpersonal skills, conceptual skills, diagnostic skills, and technical skills (Griffin and Moorhead, 2010). Depending on these broad skills set types, sub-skill sets have been categorized for various positions in the organization and categorized accordingly, for the production department. After the categorization of the skill-set, questionnaires have been framed to understand the production department's working procedure. Telephonic interviews have been conducted with the employees working in similar

organizational units and performing similar roles in the production department. Depending on the results, competency indicators have been developed for mapping.

### 3.4 Summary

Mentioned methodologies may be applied to the product to test the environment, economic and social sustainability. Once the product is proved to be sustainable, Organizational Design methodology may be adapted to mass produce the product and the competencies may be framed for different levels of production department of the organization.



## Chapter 4

### Life Cycle Assessment of Porous Radiant Burner-based applications

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The present chapter describes the Life Cycle Assessment (LCA) of applications of Porous Radiant Burner (PRB), emphasizing cooking and industrial applications. Since, it is important to adapt to energy-efficient cooking technologies, using thermally efficient burners such as PRB is essential. This chapter is broadly divided into two sub-sections. In the first sub-section, LCA is done for the cooking applications of PRB, with the fuel inputs of biogas and LPG. For biogas, an extensive LCA is carried out using the cradle-to-grave approach to assess the environmental impacts of the biogas plant during its construction and operational phases. Also, the study is focused on comparing the environmental impacts of PRB and Conventional Burners (CB) during their entire operational life period when biogas is used as fuel input and the LCA method applied study is “cradle-to-grave” LCA. Whereas for LPG, a “cradle-to-grave” assessment is conducted, as it takes into consideration of the environmental impact at each stage from raw material procurement, transportation, making, usage, and discard. LCA is done for the cook-stoves with both PRB<sub>LPG</sub> and CB<sub>LPG</sub> that operate with LPG as fuel input. The environmental impact assessment of a 1-3 kW LPG operated Porous Radiant Burner (PRB<sub>LPG</sub>) based domestic cook-stove is compared to a Conventional Burner (CB<sub>LPG</sub>) based domestic cook-stove. The annual fuel consumption of both stoves is compared and the emissions are calculated and compared in order to make a decision on adapting to sustainable LPG domestic cooking applications. LCA has been performed for the cooking applications, using the ReCiPe method of eighteen midpoint and three endpoint levels.

In the second sub-section, LCA is done to compare the environmental impacts of a Small-scale Medical Waste Incinerator (SMWI) when used with Electric Heater (EH) and PRB. For this study, LCA has been performed using the Impact 2002+ method to determine the environmental impact caused by the SMWI. the IMPACT 2002+ LCA method is considered for the approximate prediction of environmental impact caused by the SMWI when equipped with different heating devices. The analysis is conducted on the SMWI with different heating devices to analyze the environmental impact of each heating device.

#### **4.1 Need for conducting LCA on biogas-operated Porous Radiant Burner**

In the urban regions of India, Liquefied Petroleum Gas (LPG) and Kerosene are used as cooking fuels mostly. But in rural areas, only 19% use LPG as a primary fuel for cooking, and the rest of the households still depend on biomass fuels or crop residues for cooking (Agarwal et al., 2019). Therefore, there is a risk of rural households becoming victims of harmful emissions such as Carbon dioxide, NO<sub>x</sub>, particulate matter and so on. These emissions not only are harmful for households, women and children but also add up to global warming. To provide a better cooking atmosphere to rural households, an adaptation of biogas as a cooking fuel can be one of the practical solutions, because biogas not only reduces the impact of global warming and climate change but, it is also renewable energy (Blenkinsopp et al., 2013). In India, the Ministry of New and Renewable Energy (MNRE) has come up with schemes like Biogas Power Generation (Off-Grid) and Thermal energy application Programme (BPGTP), New National Biogas and Organic Manure Programme (NNBOMP), to promote the generation and utilization of biogas in rural and semi-rural areas of the country. When a biogas plant is being constructed, it is equally important to check its environmental sustainability, lest the effort of providing a cleaner cooking solution for the rural household will not be productive.

Few studies on LCA of biogas plant operated with cattle manure for small and large have been reported across the globe. A study was conducted in Vietnam on LCA of biogas production in small-scale household digesters (Vu et al., 2015). The methodology adopted was ReCiPe 2008 in which the authors analyzed the impact on global warming potential, marine water eutrophication, freshwater eutrophication, and fossil fuel depletion as they are important factors for livestock manure. Singh et al. (2020) conducted an LCA of a large-scale biogas plant based on municipal sewage sludge. The methodology adopted by the authors is attributional LCA which details the environmental effects which are directly linked to the life cycle of the outcome. In Vietnam, an LCA was conducted on a rice-beef-biogas integrated system, which showed lesser environmental impact on climate change (Ogino et al., 2021) by adopting the IPCC impact assessment method. IPCC method developed by the International Panel on Climate Change lists the climate change factors of IPCC in 20, 100, and 500 years time frame. But, this system has to be limited only to rice-rich countries and also the method followed by the research team would not consider normalization and weighting. In a different attempt, Ali et al., (2019) conducted an analysis of both the energy and cost of 20 biogas plants and 20 solar Photo Voltaic cells in Bangladesh. The energy payback period of the study was found to be almost 8 years for PV cells, which is not very promising. Similar assessment studies were

conducted on small-scale biogas digesters in Colombia and Malaysia also (Aziz et al., 2019; Garfí et al., 2019)

A few studies have been conducted on the Porous Radiant Burner's performance individually. Kaushik and Muthukumar, (2018) conducted an environmental and economic assessment of a medium-scale two-layered PRB-based cook stove. The methodology adopted for LCA is the ReCiPe method to compare the performance of crude oil burners. The results of economic assessment indicated that considering 10-year life period of the stove, it's payback period was only a week, which was highly economical. Studies were conducted by the authors' research team to assess the performance of clustered PRB based stoves. Assessment was also done when vegetable oil and waste cooking oil were used as fuels to analyse the performance of PRB (Kaushik and Muthukumar, 2019, 2020). But no studies have been conducted so far combining the LCA of biogas plant operated with cow-dung and the LCA of the performance of the PRB associated with biogas produced from that plant, used for cooking and heating applications.

Hence, it is essential to conduct an environmental impact study of both the biogas plant as well as PRB combined with it so that the impact it makes on the environment can be clearly assessed and understood. Life Cycle Assessment (LCA) of the biogas plant and also when the plant is associated with PRB, helps in studying the environmental impact caused by both the plant and the PRB.

#### ***4.1.1 Goal, Scope and Functional unit for LCA of Biogas operated PRB***

##### ***Goal and Scope***

The main goals of this study are to identify, inspect and assess the environmental impacts of an indigenously developed PRB-embedded domestic biogas stove (BGS<sub>PRB</sub>), which was developed at IITG. In order to do the assessment, the comparison of BGS<sub>PRB</sub> is done with a CB-embedded domestic biogas stove (BGS<sub>CB</sub>). The current LCA also includes the assessment of a typical Deanbandhu-type 3 m<sup>3</sup> household biogas plant with a fixed dome, which is expressly set up at IITG for the experimental purpose to assess the performance of BGS<sub>PRB</sub>. The considered biogas plant is in the framework of the Ministry of New and Renewable Energy's (MNRE) program titled the New National Biogas and Organic Manure Programme (NNBOMP). It aims to provide clean cooking fuels to kitchens, to improve bio-slurry by setting up plants in rural and semi-urban areas, and to mitigate the drudgery of women, besides a few

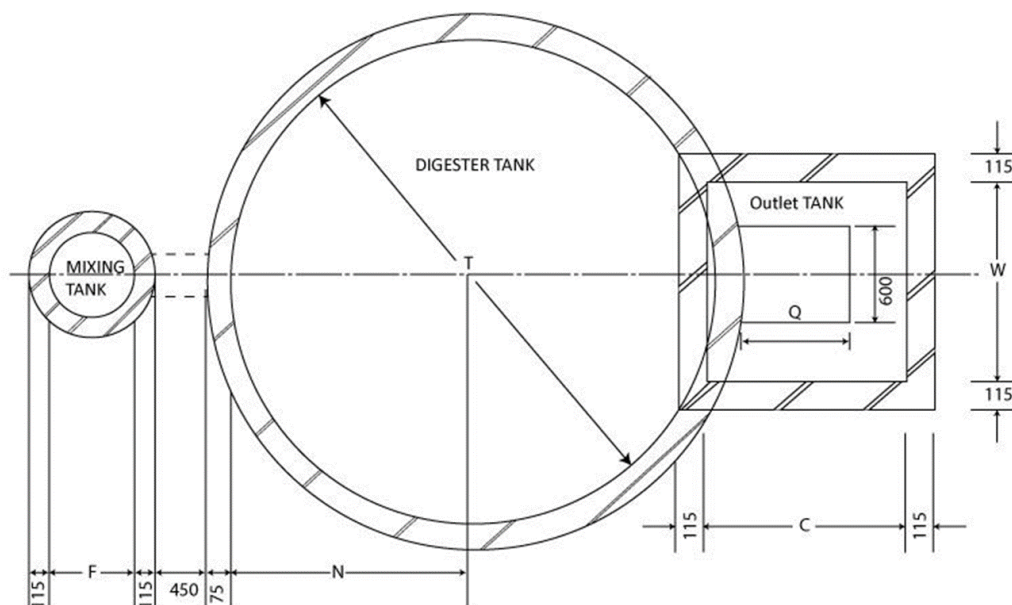
other objectives (Testimony of Biogas Technology Development Division Government of India Ministry of New and Renewable Energy, 2020).

### **Functional Unit**

The functional unit of this study is 1 m<sup>3</sup> biogas, typically used for cooking. The whole unit can be seen as a production and consumption unit. In order to determine the impact of the functional unit chosen along with the impact of products and co-products, attributional LCA (aLCA) is adapted here (Rehl et al., 2012; Weidema et al., 2018). The production plant has a life of 25 years in which biogas is produced using cow-dung and water in the ratio of 1:1 as input and the volume of the digester or the fixed dome plant is 3m<sup>3</sup> (Sangha, 2013). The consumption unit consists of a stove that has a life span of 10 years with a PRB, i.e., BGS<sub>PRB</sub> or Conventional burner, i.e., BGS<sub>CB</sub>, for which the study considered is of 1 unit.

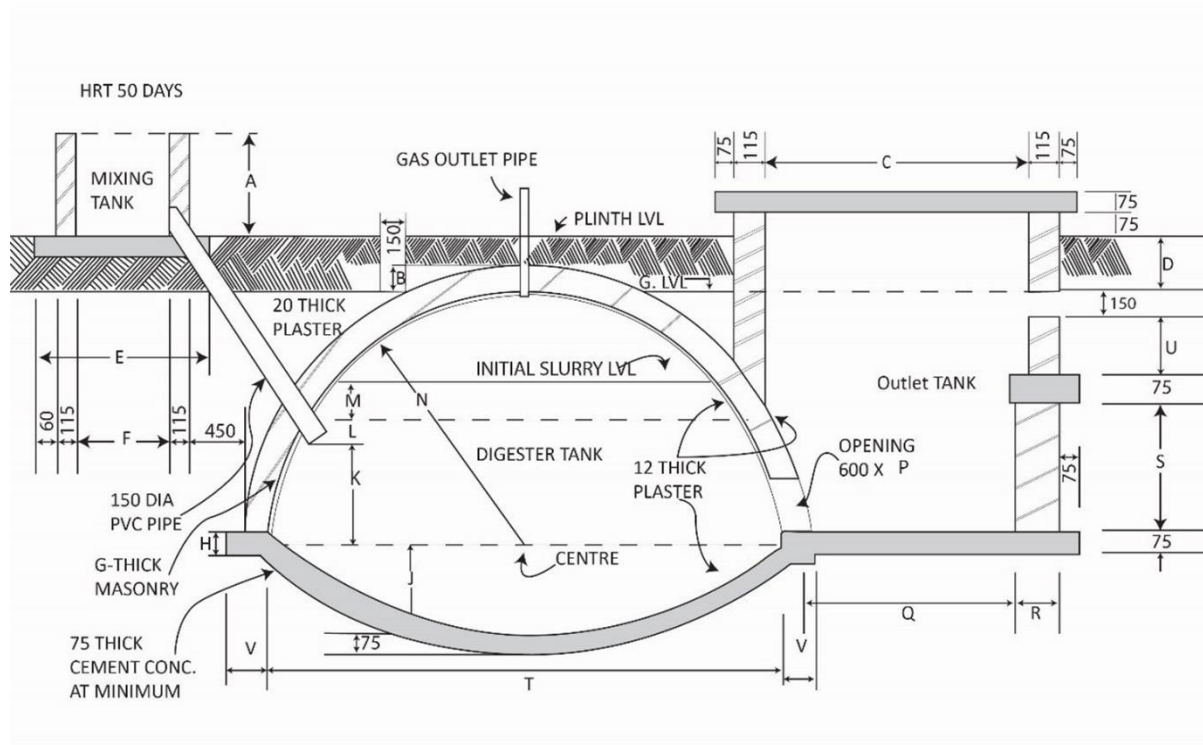
#### **4.1.2 Description of Deenbandhu type Biogas dome plant**

A deenbandhu-type biogas plant is built in such a way that it has a closed gas chamber which is in a cylindrical shape, which acts as a gas holder and is buried under the ground. This is also called a digester tank and it has a connecting pipe coming from the mixing tank or inlet tank through which feed is given; also, a digestate tank or outlet tank is constructed at the other end of the tank, which acts as a displacement pit (Sangha, 2013).



**Fig. 4.1** Top view of constructional plan of Deenbandhu-type biogas plant (Sangha, 2013)

**Fig. 4.1** shows the construction plan of the Deenbandhu-type biogas plant unit, **Fig. 4.2** represents the typical unit and **Table 4.1** represents the dimensions of the plan.



**Fig. 4.2** Sectional representation of Deenbandhu-type biogas plant (Sangha, 2013)

**Table 4.1** Dimensions of constructional plan of biogas plant

Description	Digester capacity 3 M <sup>3</sup>
A – Height of the Mixing Tank	60
B – Thickness of Digester at GI Nipple level	10
C – Width of the Displacement Tank	100
D – Displacement tank height above the hole bottom	45
E – Width of the mixing tank concrete base	100
F – Width of mixing tank	60
G – Thickness of digester masonry work	7
H – Thickness of base concrete at digester base	8
J – Height of the taper portion or height of the centre pillar	60
K – Height of the inlet pipe inner edge from the base concrete	45
L – Height of the arch from the bottom inner tip of the inlet pipe	25
M – Initial slurry level height from the arch	90
N – Radius of the Digester	150

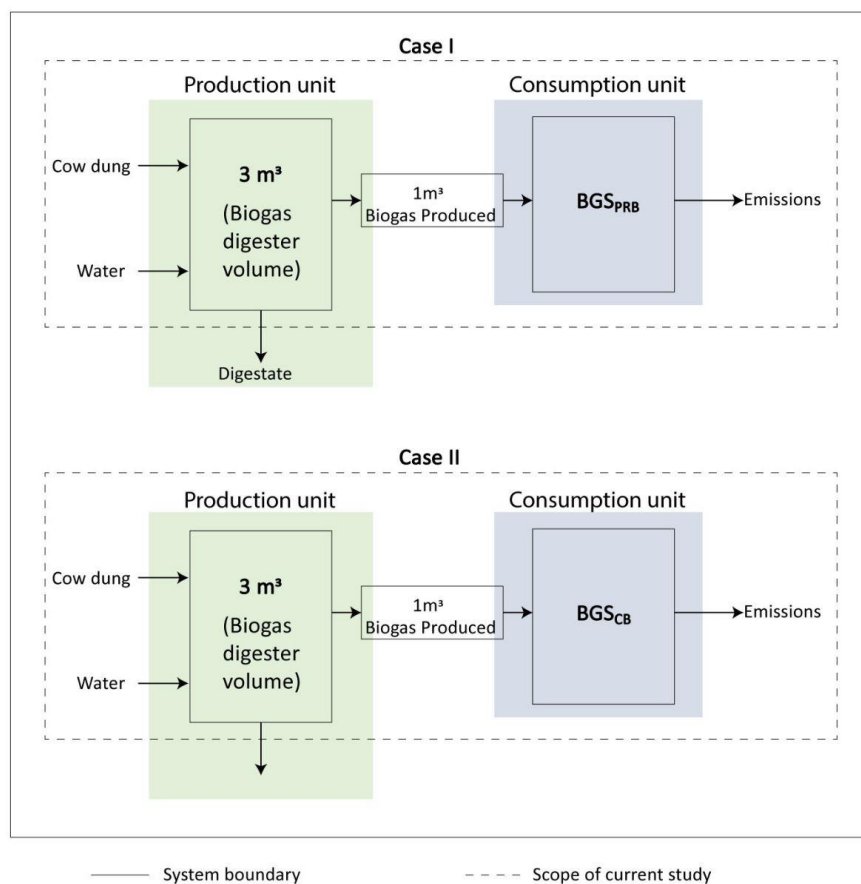
P – Arch height from arch tank concrete base	63
Q – Length of the arch tank	70
R – Thickness of arch tank wall under the displacement tank wall	22
S – Arch tank height until the bottom of the concrete base of the displacement tank	76
T – Diameter of the digester	600
U – Height of the slurry exit hole from the bottom of the displacement tank	40
V- Width of the concrete under the digester base	25
V- Width of the concrete under the digester base	250

Biogas that is generated in the digester tank is stored in the upper part of the tank and at the lower part of the tank, waste is accumulated and decomposed. The biogas that is generated can be directly used for cooking after Hydraulic Retention Time (HRT) depending on the plant size and volume (Rajendran et al., 2012). Due to the difference in the levels of slurry and the expansion chamber, gas pressure is created (Garfí et al., 2016). After the production of the biogas is started, the slurry is forced to move to the digestate tank (Garfí et al., 2014). The construction of these plants should be such that they are air-tight and should be waterproof (Garfí et al., 2019). While operating the digesters, they have to be fed on a daily basis with an equal proportion of cow-dung and water (Garfí et al., 2016). Once the biogas is produced, the slurry is moved to the digestate tank. The slurry has to be managed so that it will not cause any environmental pollution by being discharged into soil or water. Instead, this digestate can be used as a bio-fertilizer for agriculture (Garfí et al., 2011). Plant maintenance is done bi-annually, which includes checking of any gas leakages, sludge removal and so on. Since the Deenbandhu-type plant is a fixed dome plant, comparatively, it has low construction and maintenance costs while still having a longer life span; because for construction, no rusting material is used (Ocwieja, 2010).

#### **4.1.3 System Boundary for biogas operated cook-stoves**

The system boundary will define a system of different products or processes or services that are considered for the study, besides defining the quantity of energy and material inputs and their respective emission outputs while calculating the embodied energy of a particular product or service (Peuportier, 2001). In the current study, BGS<sub>PRB</sub> and BGS<sub>CB</sub> are included in the system boundary to analyze the environmental impact of making and emissions of each burner while they use the same quantity of biogas generated from this plant. Respective materials used for making both the burners, extraction and manufacturing are included in the system boundary.

Also, typical Deenbandhu-type household biogas with all the primary inputs and respective outputs, the building of the plant, usage of the land, maintenance, transportation and emissions to soil, air, and water are taken for analysis, which is represented in **Fig. 4.3**. In this study, two cases, namely CASE I, where the analysis focused on the biogas based PRB stove ( $BGS_{PRB}$ ) and CASE II, in which the analysis focused on the biogas-based CB stove ( $BGS_{CB}$ ), are considered as system boundary. In both cases, production unit and consumption unit are considered for the scope of the study. The production unit is the  $3m^3$  biogas plant which will take cow dung and water as inputs and  $1m^3$  biogas and digestate are generated as outputs, for one complete fill of the inputs. Digestate is out of the scope.  $1 m^3$  biogas is considered as input to the consumption units in both CASE I and CASE II. Then the impacts are compared for both cases to make an optimal decision. The generated  $1 m^3$  biogas can be used for up to a cooking time of 1 hour in a day. The biogas that is produced can be utilized for cooking either continuously or can be stored and used all through the day, depending on the requirement of the user.



**Fig. 4.3** Scope of the study and system boundary of biogas operated cook-stoves

At the end of 25 years of the plant's life, the plant is demolished and certain materials used for the construction of the plant are recycled, all of which are included in the system boundary of the current study. Along with biogas, digestate is also generated, which can be used as agricultural manure. Sensitivity analysis is done for digestate leakage and biogas leakage. To map the input and output data for the usage of BGS<sub>PRB</sub> and BGS<sub>CB</sub> with biogas, the database used is "Ecoinvent v3". The scope and the system boundary of the present study are represented in **Fig. 4.3**.

#### ***4.1.4 Inventory Analysis for LCA of Biogas operated PRB***

For conducting an LCA study, access to data about inputs, outputs, material requirements, etc., is crucial. For this, the compilation of data plays a significant role. In the Life Cycle Inventory (LCI) stage, the embodied energy involved in the material requirement for the set-up of the product, service or process including recycling of any of its parts and all the respective emissions are defined in a quantitative representation. In the present study, the primary data of the inventory for the making of stoves (PRB and CB) and their operation with biogas, along with the construction of the plant and its operation, is collected from the field investigation. In the cases where the data is not readily available, it is obtained from the literature. For the environmental modeling, the software used is "SimaPro 8.3.0.0" with "Ecoinvent v3" as the preferable database.

#### ***Material used for PRB, CB, and the plant***

All the material required for the making of PRB is locally available and obtained from the local market, which is not far from 25 km. There is the usage of Silicon carbide and Alumina usage to make the layers of the burner. Along with these, refractory Alumina is used in order to avoid rusting of the product. Along with these, there is also the usage of other metals, viz., copper, cast iron, and alloyed steel. Apart from metals, general-purpose polystyrene is used and also synthetic rubber for the entire manufacture or making of PRB. As mentioned earlier, all these materials are procured from the local market. Hence, the transport for the procurement of the material for PRB is assumed to be 25 km, and also, as the material quantity is significantly less, it is brought on a light motor vehicle. So, the data from Ecoinvent v3 is considered for 25 km, considering the emission standards of Euro 6 for a light motor vehicle. The conventional burner is also obtained from the local market as the product is readily available in the market. For the making of the CB, the metals used are brass, low-alloyed steel, and cast iron. Along with these metals, there is also the usage of polystyrene and synthetic rubber. Though all these materials

are used for the making of CB, the product is readily available in the market and so it is directly got from the local market. Hence, the assumptions made for it also are the same as PRB, considering 25 km with Euro 6 emission standards for light motor vehicles in Ecoinvent v3.

The material required for constructing the biogas plant is considered such that the bricks, portland cement, sand, and gravel are locally available. The details of the material are given in **Table 4.2**. As sand is considered, two types of sand (fine and coarse) are assumed to be used in the construction. Since iron wire and the binding wire were not directly available, an equivalent amount of cast iron for them is considered and also the processing of it under metalworking is considered. The same is the case for GI pipe; alloyed and hot-rolled steel of equivalent amount is regarded along with metalworking of its manufacturing and processing, after which it is coated with zinc. There is a usage of GI nipples in the construction. So it is assumed that the same process is adapted for it as for GI pipe and the same is considered. Brass nipples used in the construction are also deemed to be based on the assumptions of brass production, its metalworking, and its average for product manufacturing and processing. The PVC ball valve used is assumed to be of 3/4<sup>th</sup> inch, for which assumptions are made of Polyvinylchloride production, its bulk polymerization, and its injection molding. Transportation adapted for the transport of the entire material is assumed to be brought in a lorry, so it is considered as per Euro 6 standards for a 3.5 to 7.5 metric ton lorry. The water used for the construction of the plant is also taken from the water readily available at the IITG campus. The amount of water required is assumed to be according to IS 4562000 standard of M20 nominal mixes. Since the biogas unit has a shallow impact on the land use of 25 m<sup>2</sup> for 25 years, no land-use change is considered. It is assumed that biannual maintenance is needed for the smooth functioning of the plant; hence it is considered for 25 years throughout the plant life, for twice in a year, where the transportation of the person is assumed from 25 km distance, away from the plant set up area.

Inputs given to the plant are cow-dung and water in the ratio 1:1. Cow-dung is diluted with water and is fed into the mixing tank. Here, 37.5 kg of cow-dung is diluted with 37.5 L of water, which will produce 1 m<sup>3</sup> biogas, which is assumed to be consisting of 60% of CH<sub>4</sub>, 35% of CO<sub>2</sub> and 5% of the other gases (Vu et al., 2015). Though, biogas is produced taking all the precautionary measures and standards, it has to be noted that all the gas produced is not consumable. A particular part of biogas (10%) produced is lost due to leakages because of cracks in the digester unit or pipes, when there is larger amount of biogas production than its consumption as the pressure builds up in the digester (Vu et al., 2015). In the present case, 10%

biogas leakage has been considered. Along with the biogas production, there is also a production of digestate. In general, the digestate produced is used as a fertilizer because of its rich nutrient composition. However, digestate as a replacement of the fertilizer is out of the boundary and scope of the present study. It is assumed that of the total digestate produced, a maximum of 5% of it is lost due to leakages. Of the remaining digestate, 50% is supposed to be water-born emission and the rest as soil-born emission.

#### ***4.1.5 Impact Assessment for Biogas operated PRB***

According to ISO 2006, a Life Cycle Impact Assessment (LCIA) seeks to evaluate the environmental impacts of a product or service, or process and is the third stage of LCA. Though impact assessment methods have been developed since the early 1990s, there are quantitative differences between various LCIA methods. In the LCIA method, there are impact categories, which are environmental issues. The flows in the inventory which contribute to impact categories are called substances. For each substance, the environmental impacts are quantified through the corresponding factors of characterization of the respective substances. The method used in the present study is a multi-issue LCIA method viz., the ReCiPe method. In this method, there are two indicators namely midpoint indicators which are problem-oriented, and endpoint indicators which are damage oriented. The midpoint indicators examine the impact of the cause and effect till the midpoint and the endpoint indicators examine the impact after the midpoints reached till the end of the cause and effect chain. Environmental impacts are deciphered to “environmental themes” at the midpoint level, whereas they are deciphered to “issues of concern” at the endpoint level.

In the present study midpoint approach is adopted to provide a clear understanding of PRB’s environmental impacts and compare it with CB. Midpoint categories adopted in ReCiPe Midpoint Hierarchist (H) version V1.13, are Climate change, Ozone depletion, Terrestrial acidification, Freshwater eutrophication, Marine eutrophication, Human toxicity, Photochemical oxidant formation, Particulate matter formation, Terrestrial ecotoxicity, Freshwater ecotoxicity, Marine ecotoxicity, Ionising radiation, Agricultural land occupation, Urban land occupation, Natural land transformation, Water depletion, Metal depletion, and Fossil depletion.

The endpoint approach is adopted because certain assumptions are made because of the data gap throughout the cause-and-effect chain. Also, the endpoint approach is easier to communicate to decision-makers so that they can opt for the optimal/better alternatives.

Endpoint categories adopted in ReCiPe Endpoint (H) V1.13, used in the present study, are Human Health, Ecosystems, and Resources. The perspective adopted for the current research is H/H which refers to the normalization values with the weighting set belonging to the hierarchist perspective.

#### ***4.1.6 Sensitivity Analyses***

Sensitivity analysis shows how the target variables are affected based on the changes of other input variables. In the present study, it is done for biogas and digestate leakages. It is carried out to inspect the performance of the system at different volumes of biogas and digestate leakages. It is imperative to do sensitivity analysis as it gives a clear idea for the analysts or decision-makers where to focus on the system design to ensure accuracy across the range of inputs given to a system. The base biogas leakage considered in this study is 10% of the total produced biogas, and sensitivity analyses is done for 5% and 7.5% leakages of the total biogas produced. Whereas the base digestate leakage taken for the study is 5% of the total digestate produced and the sensitivity analyses is done for 3.5% and 2% leakages of the digestate of the total digestate produced.

#### ***4.1.7 Results Interpretation***

The results of LCA cannot be direct because all the stages of LCA, functional units, operational units, assessment methods, assumptions may differ according to certain conditions like geographical areas, considered material, the energy required and given out and so on. The present study focuses on the environmental superiority of PRB when compared to CB, which is operated from the biogas output at IITG biogas plant and can be shown as a solid recommendation to the analysts or decision makers when environmental sustainability is considered. Hierarchist version of ReCiPe is adopted to normalize the results applying the world's normalization values. Even though it is not a compulsory step in LCIA, this is done to provide a clear picture of the relative magnitude of the scores represented. In order to provide an easier understanding of the analysis, the entire system is represented in two sub-systems, of which the first sub-system is about the constructional phase of the plant and the comparison of the constructional phases of stoves with CB and PRB, including their disposal or recycling after the useful life is reached; and the second sub-system is about the operational phase of the stoves with PRB and CB and biogas plant including the leakages of biogas and digestate.

### *ReCiPe at midpoint level*

Midpoint level results of ReCiPe (H) V1.13 method for plant construction are shown first and later the consequences of making of cookstoves with PRB and CB are shown. Material content used for the construction of the plant is already mentioned in **Table 4.2**.

It is evident from **Table 4.2** that the largest quantity used for the construction is sand which has an impact on certain midpoint categories with the highest on the Climate change followed by human toxicity. The same is the case with gravel, which is the second-highest used quantity which shows an enormous impact of around 43 kgCO<sub>2</sub>eq on Climate change and around 18.5 kg 1,4-DBeq on human toxicity, whereas for sand, it is around 74 kgCO<sub>2</sub>eq for Climate change and around 30 kg 1,4-DBeq for human toxicity. Even the clay bricks and cement followed a similar pattern of having the highest impact on Climate change with approximately 750 kgCO<sub>2</sub>eq and 890 kgCO<sub>2</sub>eq, respectively, followed by human toxicity in the quantities of around 215 kg 1,4-DBeq and 120 kg 1,4-DBeq, respectively.

**Table 4.2** Material used for the biogas plant construction

Materials/assemblies	Quantity	Unit
Clay brick	2280	kg
Cement, Portland	950	kg
Sand	6160	kg
Gravel, crushed	2400	kg
6 mm iron wire	10	kg
Binding iron wire	0.1	kg
PVC pipe	8.0	kg
GI pipe	0.5	kg
GI nipple 20 mm diameter	0.2	kg
Brass nipples	0.6	kg
HDPE pipes	8	kg
PVC ball valve	0.25	kg
Synthetic rubber	0.08	kg

It is evident that these materials are having such an impact because of the high amount used in the construction, but what is of concern is of the metals like iron and brass and plastics like valves and pipes, though they are used in very minute quantities, they are

having a significant impact on specific midpoint categories. It is understood that metals will have a natural impact on the metal depletion category, but the concern is about the impact that brass nipple has on Human toxicity, which is around 130 kg 1, 4-DB eq.

Of all the materials used for plant construction, brass has the highest impact on human toxicity. In the other metals used, the iron wire has an impact of around 11 m<sup>2</sup>a on agricultural land occupation. The most profound concern is of pipes used in the construction of the plant. PVC pipes and HDPE pipes show the highest impact on climate change with ~25 kg CO<sub>2</sub> eq and ~20 kg CO<sub>2</sub> eq, respectively; after which they have a major impact on fossil depletion with ~10 kg oil eq and ~14 kg oil eq, respectively. However, certain material used for the construction of the plant is recycled.

It is shown in **Table 4.3**, how both the constructional phase and recycling phase together of 1 m<sup>3</sup> biogas functional unit will influence the ReciPe method's characterization midpoint impact categories.

**Table 4.3** Impact of constructional phase and recycling phase on the midpoint categories

Impact category	Unit	Plant Construction without Recycling	Plant Construction with Recycling
Climate change	kg CO <sub>2</sub> eq	2052	1976
Ozone depletion	kg CFC-11 eq	0.000141	0.000138
Terrestrial acidification	kg SO <sub>2</sub> eq	6	5.5
Freshwater eutrophication	kg P eq	0.6	0.5
Marine eutrophication	kg N eq	0.3	0.26
Human toxicity	kg 1,4-DB eq	697	522
Photochemical oxidant formation	kg NMVOC	5.5	5.25
Particulate matter formation	kg PM10 eq	3.5	3.2
Terrestrial ecotoxicity	kg 1,4-DB eq	0.19	0.17
Freshwater ecotoxicity	kg 1,4-DB eq	15	12
Marine ecotoxicity	kg 1,4-DB eq	15	12
Ionising radiation	kBq U235 eq	52	51
Agricultural land occupation	m <sup>2</sup> a	185	175
Urban land occupation	m <sup>2</sup> a	32	31
Natural land transformation	m <sup>2</sup>	0.5	0.5
Water depletion	m <sup>3</sup>	19	18
Metal depletion	kg Fe eq	177	122
Fossil depletion	kg oil eq	409	382

It can be seen from the data that in the entire life period of the plant and its recycling, the highest impact is on Climate change with 1976 kg CO<sub>2</sub> eq. The following highest impact is on Human toxicity factor with 522 kg 1, 4-DB eq, followed by Fossil depletion, Agricultural land occupation and Metal depletion with 382 kg oil eq, 175 m<sup>2</sup>a and 122 kg Fe eq, respectively. Whereas among all the midpoint factors, the impact of the plant after its life, including the recycling phase, the lowest impact is on Ozone depletion with 0.000138 kg CFC-11 eq.

When it comes to the comparison of the construction phase and recycling of PRB with that of CB, **Table 4.4** shows the impact on the environment each of them will have. It is shown through the ReCiPe midpoint categories. It is clearly visible from the tabulated data that PRB has a lesser impact when compared to CB on most of the ReCiPe midpoint categories.

**Table 4.4** Comparison of the impacts of construction and recycling of PRB and CB on midpoint categories

Impact category	Unit	Construction and recycling of PRB	Construction and recycling of CB
Climate change	kg CO <sub>2</sub> eq	0.0014	0.0013
Ozone depletion	kg CFC-11 eq	1.82E-10	1.57E-10
Terrestrial acidification	kg SO <sub>2</sub> eq	6.63E-06	7.61E-06
Freshwater eutrophication	kg P eq	1.05E-06	2.05E-06
Marine eutrophication	kg N eq	3.61E-07	5.39E-07
Human toxicity	kg 1,4-DB eq	0.002	0.004
Photochemical oxidant formation	kg NMVOC	2.38E-05	2.32E-05
Particulate matter formation	kg PM10 eq	4.11E-06	4.89E-06
Terrestrial ecotoxicity	kg 1,4-DB eq	1.89E-07	2.94E-07
Freshwater ecotoxicity	kg 1,4-DB eq	3.7E-05	6.83E-05
Marine ecotoxicity	kg 1,4-DB eq	3.76E-05	7.01E-05
Ionising radiation	kBq U235 eq	-5.22E-06	3.48E-05
Agricultural land occupation	m <sup>2</sup> a	0.000239	0.000243
Urban land occupation	m <sup>2</sup> a	1.48E-05	1.65E-05
Natural land transformation	m <sup>2</sup>	3.57E-07	3.36E-07
Water depletion	m <sup>3</sup>	1.02E-05	1.15E-05
Metal depletion	kg Fe eq	0.0008	0.0012
Fossil depletion	kg oil eq	0.0005	0.0004

Among the 18 midpoint categories, the impact of PRB is lesser than CB on 12 factors, the rest being Climate change, Ozone depletion, Photochemical oxidant formation, Natural land transformation and Fossil depletion. The Ionising radiation impact of PRB is in negative because of the refractory aluminium oxide used in the making of PRB, which has a negative Ionizing radiation. It is noteworthy that though both PRB and CB have a high impact on Human toxicity with PRB 0.002 kg 1, 4-DB eq and CB 0.004 kg 1, 4-DB eq, respectively, PRB shows much lesser impact on Human toxicity when compared to CB, which is approximately 48% lesser.

The frame of the stove used accounts for around 55% of Climate change impact factor, which is the highest impact factor among all the midpoint categories. PRB also has much lesser impact than CB on Freshwater eutrophication with PRB 1.05E-6 kg P eq and CB 2.05E-6 kg P eq impacts which mean PRB's impact is almost 49% lesser than that of CB on Freshwater eutrophication. Also, PRB has lesser impact than CB on Freshwater ecotoxicity and Marine ecotoxicity, both being approximately 46% lesser than CB. One of the few crucial factors to be considered among the environmental impacts is Particulate matter formation. PRB's Particulate matter formation is 4.11E-6 kg PM10 eq whereas it is 4.89E-6 kg PM 10 eq in the case of CB; which means the Particulate matter formation is almost 16% lesser in PRB than in CB.

For the operation of the plant, cow-dung and water are given as inputs to the digester unit in equal proportions. They are fed on a daily basis to produce the biogas. There is utilization of the biogas produced from this plant by the BGS<sub>PRB</sub> and BGS<sub>CB</sub>. The environmental impact of the burners on the midpoint categories of ReCiPe method are shown in **Table 4.5**.

Through the tabular representation of the comparison of the operation of BGS<sub>PRB</sub> with that of the operation of BGS<sub>CB</sub> and their respective impacts on the midpoint ReCiPe categories, it is evident that the impact of BGS<sub>PRB</sub> operation on all the ReCiPe midpoint categories is definitely lower than that of the impact of BGS<sub>CB</sub> operation. Both the burners show a major impact on the Climate change factor, with the operation of BGS<sub>PRB</sub> contributing to 1.23 kg CO<sub>2</sub> eq, whereas it is 1.23 kg CO<sub>2</sub> eq for BGS<sub>CB</sub>.

**Table 4.5** Impact of the operation of BGS<sub>PRB</sub> and BGS<sub>CB</sub> on midpoint characterization environmental factors

Impact category	Unit	Operation of BGS <sub>CB</sub>	Operation of BGS <sub>PRB</sub>
Climate change	kg CO <sub>2</sub> eq	1.229	1.226
Ozone depletion	kg CFC-11 eq	2.62E-09	1.99E-09
Terrestrial acidification	kg SO <sub>2</sub> eq	0.0002	0.00018
Freshwater eutrophication	kg P eq	8.38E-06	6.38E-06
Marine eutrophication	kg N eq	1.59E-05	1.52E-05
Human toxicity	kg 1,4-DB eq	0.024	0.023
Photochemical oxidant formation	kg NMVOC	0.0007	0.0006
Particulate matter formation	kg PM10 eq	9.29E-05	8.17E-05
Terrestrial ecotoxicity	kg 1,4-DB eq	5.68E-07	4.49E-07
Freshwater ecotoxicity	kg 1,4-DB eq	0.0003	0.00029
Marine ecotoxicity	kg 1,4-DB eq	0.00032	0.00028
Ionising radiation	kBq U235 eq	0.002	0.001
Agricultural land occupation	m <sup>2</sup> a	0.0013	0.001
Urban land occupation	m <sup>2</sup> a	9.29E-05	7.07E-05
Natural land transformation	m <sup>2</sup>	5.55E-06	4.22E-06
Water depletion	m <sup>3</sup>	0.04	0.035
Metal depletion	kg Fe eq	0.0005	0.0004
Fossil depletion	kg oil eq	0.019	0.017

Also, there is no major difference on the water depletion factor by both the burners as BGS<sub>PRB</sub> shows an impact of 0.035 m<sup>3</sup> whereas BGS<sub>CB</sub> shows 0.04 m<sup>3</sup>; so is the situation with Photochemical oxidant formation as BGS<sub>PRB</sub> has an impact factor of 0.0006 kg NMVOC while the impact factor of BGS<sub>CB</sub> is 0.0007 kg NMVOC. But there is a considerate reduction on the other impact categories as BGS<sub>PRB</sub> has 24% lesser impact on Ozone depletion, 7% lesser on Terrestrial acidification, 23.87% lesser on Freshwater eutrophication, 4.4% lesser on Marine eutrophication, 6.07% lesser on Human toxicity, 12% lesser on particulate matter formation, 20.95% lesser on Terrestrial ecotoxicity, 13% lesser on Freshwater ecotoxicity, 12.77% lesser on Marine ecotoxicity. It is approximately 24% lesser impact on Ionising radiation, Agricultural land occupation, Urban land occupation, Natural land transformation and Metal depletion, and 8.4% lesser impact on Fossil depletion than the operational impact of BGS<sub>CB</sub>. Hence it is clearly evident that the operation of BGS<sub>PRB</sub> with the same fuel input of biogas is much beneficial

in the operational phase when compared to BGS<sub>CB</sub> as BGS<sub>PRB</sub> has a lesser environmental impact on all the 18 ReCiPe midpoint categories.

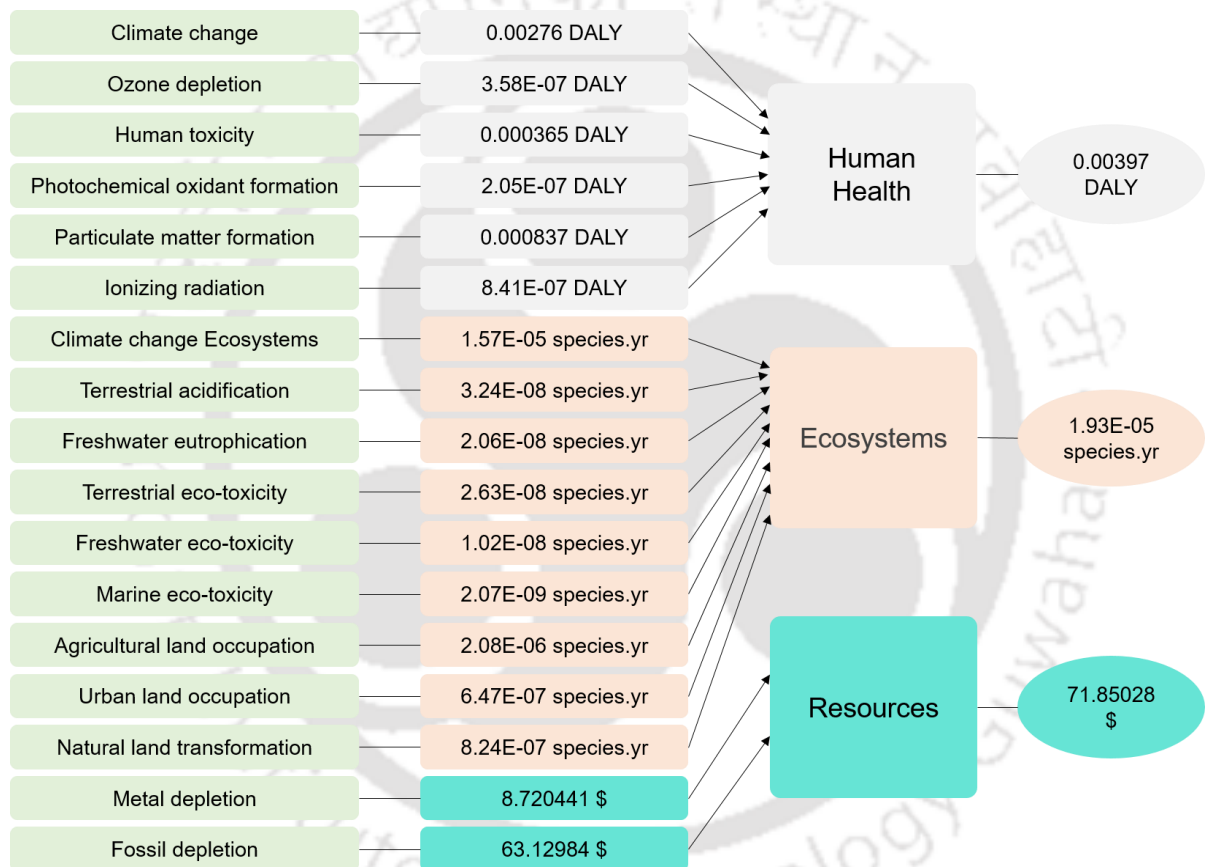
### ***ReCiPe at endpoint level***

The environmental impact that construction and operation will have on the environment is also shown through ReCiPe endpoint impact categories besides midpoint impact categories, so that it will become easy for the decision-makers and analysts to reach to a decision or conclusion about the choice or alternate options of a product, service or process. The characterization categories of the impact factors of ReCiPe endpoint level leading to the damage assessment is shown in **Fig. 4.4** for the construction stage of the plant along with its useful life period and recycling after its life.

In the flow-chart, it is shown how different midpoint characterization categories will have their respective impacts on the ReCiPe endpoint damage categories. The midpoint characterization categories of Climate change, Ozone depletion, Human toxicity, Photochemical oxidant formation, Particulate matter formation and Ionising radiation indicate the damage caused to “Human health” endpoint characterization category. It is measured in DALY units. One DALY represents the loss of the equivalent one year of full health. DALYs for a disease or a health condition are the sum of the years of life lost due to premature mortality and the years lived with a disability due to prevalent cases of the disease or health condition in a population. Similarly, Climate change ecosystems, Terrestrial acidification, Freshwater eutrophication, Terrestrial ecotoxicity, Fresh water ecotoxicity, Marine ecotoxicity, Agricultural land occupation, Urban land occupation, Natural land transformation midpoint characterization factors indicate the damage caused to “Ecosystems” endpoint characterization factor measured in “species.yr” units. Species.yr indicate one species disappearing in one year. However, “Water depletion” midpoint characterization factor is not represented in **Fig. 4.4** as there is no water depletion reported in the process. The midpoint characterization factors viz., Metal depletion and Fossil Depletion indicate the damage caused to “Resources” endpoint characterization factor which is measured in “\$” units which indicate the monetary value of resource depletion. From the damage assessment categories, it is quite evident that the construction, usage and recycling of the biogas plant will have a major impact on the Resources with 71.85 \$ impact factor.

However, it will have a significantly less impact on Human health of about 0.0039 DALY impact factor based on the material selection and utilization which is appreciable. Furthermore, it will be negligible on Ecosystems with an impact factor of 1.933E-05 Species.yr.

The construction and recycling stage of both the burners, i.e. PRB and CB is compared and the environmental impact on the midpoint characterization categories is shown in **Table 4.6**, from which the endpoint damage assessment categories are projected.

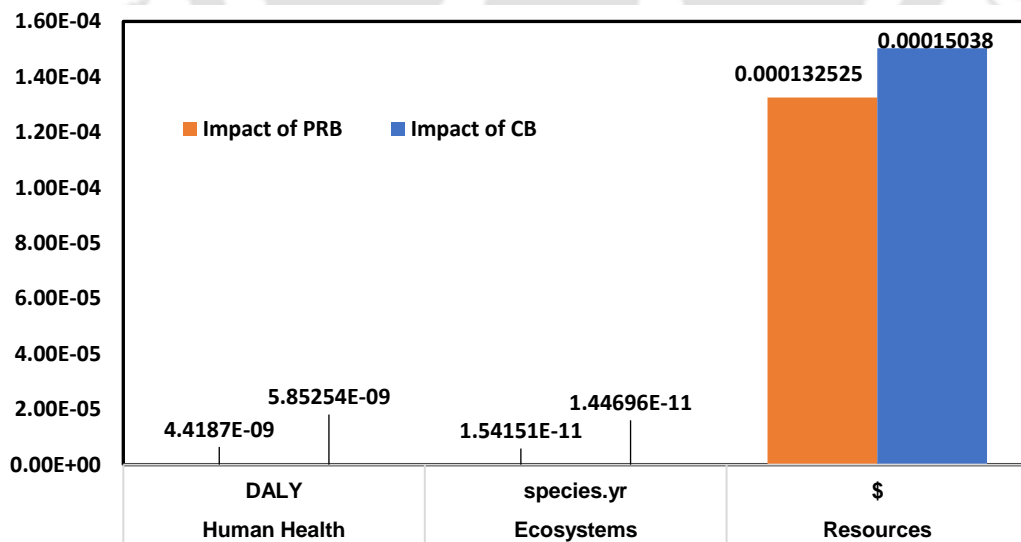


**Fig. 4.4** Cradle-to-grave endpoint characterization and damage assessment categories of the plant

The damage assessment categories from the characterization impact categories in the endpoint level are represented in **Fig. 4.5**.

**Table 4.6** Impact of the construction and recycling of PRB and CB on midpoint characterization environmental factors

Impact category	Unit	Impact of PRB	Impact of CB
Climate change Human Health	DALY	2.02E-09	1.83E-09
Ozone depletion	DALY	4.89E-13	4.16E-13
Human toxicity	DALY	1.32E-09	2.75E-09
Photochemical oxidant formation	DALY	9.29E-13	9.06E-13
Particulate matter formation	DALY	1.07E-09	1.27E-09
Ionising radiation	DALY	-8.57E-14	5.71E-13
Climate change Ecosystems	species.yr	1.15E-11	1.04E-11
Terrestrial acidification	species.yr	3.85E-14	4.41E-14
Freshwater eutrophication	species.yr	4.69E-14	9.15E-14
Terrestrial ecotoxicity	species.yr	2.85E-14	4.42E-14
Freshwater ecotoxicity	species.yr	3.18E-14	5.87E-14
Marine ecotoxicity	species.yr	6.63E-15	1.24E-14
Agricultural land occupation	species.yr	2.88E-12	2.92E-12
Urban land occupation	species.yr	3.06E-13	3.41E-13
Natural land transformation	species.yr	6.12E-13	5.84E-13
Metal depletion	\$	5.58E-05	8.52E-05
Fossil depletion	\$	7.67E-05	6.52E-05



**Fig. 4.5** Impact of the endpoint characterization factors on damage assessment categories

It is clear that both PRB and CB have the highest impact on Resources among all the damage assessment categories. But PRB has a much lesser impact on CB on two damage assessment categories, one being the Resources category as PRB's impact is 0.000133 \$ whereas the same for CB is 0.00015 \$; other being Human health PRB accounted for 4.42E-09 DALY whereas it is 5.85E-09 DALY for CB. Whereas the impact of PRB on Ecosystems is 1.54E-11 species.yr, and the impact CB has is 1.45E-11 species.yr, which indicate that here the impact of PRB is slightly more than CB.

Considering the operation of BGS<sub>PRB</sub> and BGS<sub>CB</sub>, the endpoint ReCiPe level's characterization of the operation of both the burners is shown in **Table 4.7**.

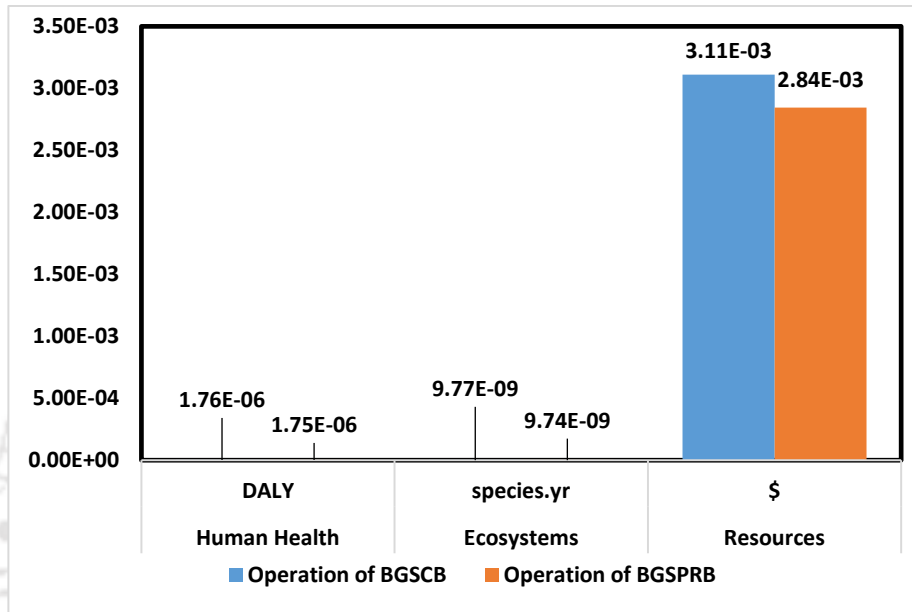
**Table 4.7** Impact of the operation of BGS<sub>PRB</sub> and BGS<sub>CB</sub> on endpoint characterization environmental factors

Impact category	Unit	Operation of BGS <sub>CB</sub>	Operation of BGS <sub>PRB</sub>
Climate change Human Health	DALY	1.72E-06	1.72E-06
Ozone depletion	DALY	6.76E-12	5.15E-12
Human toxicity	DALY	1.72E-08	1.62E-08
Photochemical oxidant formation	DALY	2.65E-11	2.62E-11
Particulate matter formation	DALY	2.42E-08	2.13E-08
Ionising radiation	DALY	3.29E-11	2.5E-11
Climate change Ecosystems	species.yr	9.74E-09	9.72E-09
Terrestrial acidification	species.yr	1.16E-12	1.07E-12
Freshwater eutrophication	species.yr	3.73E-13	2.84E-13
Terrestrial ecotoxicity	species.yr	8.56E-14	6.77E-14
Freshwater ecotoxicity	species.yr	2.88E-13	2.51E-13
Marine ecotoxicity	species.yr	5.66E-14	4.94E-14
Agricultural land occupation	species.yr	1.62E-11	1.23E-11
Urban land occupation	species.yr	1.92E-12	1.46E-12
Natural land transformation	species.yr	9.66E-12	7.35E-12
Metal depletion	\$	3.9E-05	2.97E-05
Fossil depletion	\$	0.003073	0.002815

In view of the characterization impact factors, the damage assessment points of ReCiPe endpoint level can be shown in **Fig. 4.6**.

From the results, it can be witnessed that the impact of BGS<sub>PRB</sub> when compared to BGS<sub>CB</sub> in the operational phase unlike in the construction and recycling phase, is lower in all the

damage assessment categories.  $BGS_{PRB}$  shows a lesser impact than  $BGS_{CB}$  in the Human health damage assessment category with  $7.69E-09$  DALY lesser than CB. Whereas in the Ecosystems damage assessment category,  $BGS_{PRB}$ 's impact is  $2.79E-11$  species.yr lesser than  $BGS_{CB}$ 's impact. Sadly, both burners show a considerable impact on the Resources damage assessment category; still,  $BGS_{PRB}$ 's impact is lesser by  $2.67E-04$  \$ than  $BGS_{CB}$ .



**Fig. 4.6** Damage assessment factors due to the operation of  $BGS_{PRB}$  and  $BGS_{CB}$

#### 4.1.8 Interpretation of Sensitivity Analyses Results

Sensitivity analysis is performed to compare the impacts of biogas and digestate leakage on the overall environmental performance of the biogas system (Plant and burner) considering the performance in both the midpoint and endpoint categories of ReCiPe method so that it can contribute to providing the decision-makers with useful information to make the optimal decisions. In the sensitivity analysis, the base leakage for biogas is taken as 10%, of the entire biogas produced in the digester unit throughout the plant life, and the base digestate leakage is taken as 5% of the whole digestate produced throughout the plant life. Sensitivity analyses are done for 7.5% and 5% biogas leakage and 3.5% and 2% digestate leakage. The respective environmental impacts are measured and compared when the rest of the biogas is consumed by the  $BGS_{PRB}$  and  $BGS_{CB}$ , respectively.

**For 7.5% biogas leakage and 3.5% digestate leakage**

Comparison of performances and impacts of biogas system on ReCiPe midpoint characterization categories at 7.5% biogas leakage and 3.5% digestate leakage is shown in **Table 4.8**.

**Table 4.8** Impact of the operation of BGS<sub>PRB</sub> and BGS<sub>CB</sub> on midpoint characterization environmental factors for 7.5% biogas leakage and 3.5% digestate leakage

Impact category	Unit	Operation of BGS <sub>CB</sub> (7.5% BL and 3.5% DL)	Operation of BGS <sub>PRB</sub> (7.5% BL and 3.5% DL)
Climate change	kg CO <sub>2</sub> eq	0.91	0.9
Ozone depletion	kg CFC-11 eq	2.62E-09	1.99E-09
Terrestrial acidification	kg SO <sub>2</sub> eq	0.00019	0.00018
Freshwater eutrophication	kg P eq	8.38E-06	6.38E-06
Marine eutrophication	kg N eq	1.41E-05	1.34E-05
Human toxicity	kg 1,4-DB eq	0.024	0.023
Photochemical oxidant formation	kg NMVOC	0.00055	0.00054
Particulate matter formation	kg PM10 eq	9.17E-05	8.05E-05
Terrestrial ecotoxicity	kg 1,4-DB eq	5.66E-07	4.47E-07
Freshwater ecotoxicity	kg 1,4-DB eq	0.0003	0.0002
Marine ecotoxicity	kg 1,4-DB eq	0.0003	0.0002
Ionising radiation	kBq U235 eq	0.002	0.001
Agricultural land occupation	m <sup>2</sup> a	0.001	0.001
Urban land occupation	m <sup>2</sup> a	9.29E-05	7.07E-05
Natural land transformation	m <sup>2</sup>	5.55E-06	4.22E-06
Water depletion	m <sup>3</sup>	0.0341	0.034
Metal depletion	kg Fe eq	0.0005	0.0004
Fossil depletion	kg oil eq	0.018	0.017

From the values, it is clearly evident that the performance of BGS<sub>PRB</sub> is better than BGS<sub>CB</sub> as it has a lesser impact on all the midpoint damage assessment categories in characterization. There is a high impact on Climate change, Human toxicity, Water depletion, and Fossil depletion categories by both burners. But it is noteworthy that the impact of BGS<sub>PRB</sub> on Ozone depletion, Freshwater eutrophication, Ionizing radiation, Agricultural land occupation, Urban

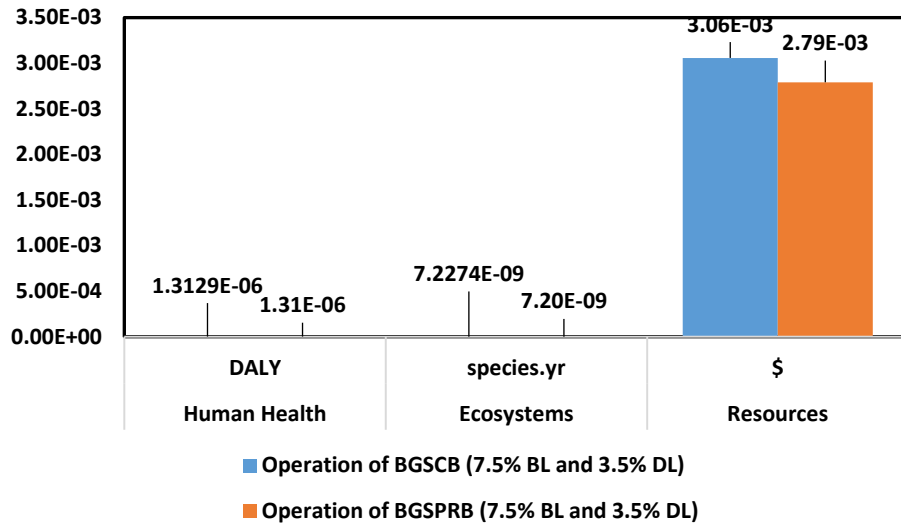
land occupation, Natural land transformation, and Metal depletion categories is approximately 23% lesser than the impact of BGS<sub>CB</sub> on the same categories. BGS<sub>PRB</sub>'s impact on Human toxicity is 0.023 kg 1,4-DB eq, whereas it is 0.024 kg 1,4-DB eq, which means the impact of BGS<sub>PRB</sub> is approximately 6% lesser than BGS<sub>CB</sub>, which is a good development. Also, BGS<sub>PRB</sub> has a lesser impact of 8.05E-05 kg PM10 eq on Particulate matter formation, which is approximately 12% lesser than the impact BGS<sub>CB</sub> has on particulate matter formation. On the Terrestrial ecotoxicity category, BGS<sub>PRB</sub> has approximately 21% lesser impact than BGS<sub>PRB</sub> as its impact is 4.47E-07 kg 1,4-DB eq.

Endpoint characterization for 7.5% biogas leakage and 3.5% digestate leakage is shown in **Table 4.9**, for which the damage assessment is shown in **Fig. 4.7**.

**Table 4.9** Impact of the operation of BGS<sub>PRB</sub> and BGS<sub>CB</sub> on endpoint characterization environmental factors for 7.5% biogas leakage and 3.5% digestate leakage

<b>Impact category</b>	<b>Unit</b>	<b>Operation of BGS<sub>CB</sub> (7.5% BL and 3.5% DL)</b>	<b>Operation of BGS<sub>PRB</sub> (7.5% BL and 3.5% DL)</b>
Climate change Human Health	DALY	1.27E-06	1.27E-06
Ozone depletion	DALY	6.76E-12	5.15E-12
Human toxicity	DALY	1.69E-08	1.58E-08
Photochemical oxidant formation	DALY	2.16E-11	2.13E-11
Particulate matter formation	DALY	2.38E-08	2.09E-08
Ionising radiation	DALY	3.29E-11	2.5E-11
Climate change Ecosystems	species.yr	7.2E-09	7.18E-09
Terrestrial acidification	species.yr	1.14E-12	1.05E-12
Freshwater eutrophication	species.yr	3.73E-13	2.84E-13
Terrestrial ecotoxicity	species.yr	8.53E-14	6.74E-14
Freshwater ecotoxicity	species.yr	2.85E-13	2.47E-13
Marine ecotoxicity	species.yr	5.59E-14	4.87E-14
Agricultural land occupation	species.yr	1.62E-11	1.23E-11
Urban land occupation	species.yr	1.92E-12	1.46E-12
Natural land transformation	species.yr	9.66E-12	7.35E-12
Metal depletion	\$	3.9E-05	2.97E-05
Fossil depletion	\$	0.003019	0.002761

From all the three damage assessment categories, BGS<sub>PRB</sub> has shown lesser impact, with BGS<sub>PRB</sub> having 1.30521E-06 DALY on Human health when BGS<sub>CB</sub> has 1.3129E-06 DALY. Whereas in the Ecosystems damage assessment category, BGS<sub>PRB</sub> has 2.79E-11 species.yr lesser impact than BGS<sub>CB</sub>. In the Resources category, PRB shows approximately 9% lesser impact than BGS<sub>CB</sub> as BGS<sub>PRB</sub>'s impact is 0.00279 \$, and the impact of BGS<sub>CB</sub> is 0.00306 \$.



**Fig. 4.7** Damage assessment due to the operation of BGS<sub>PRB</sub> and BGS<sub>CB</sub> at 7.5% biogas leakage and 3.5% digestate leakage

***For 5% biogas leakage and 2% digestate leakage***

Performances of BGS<sub>PRB</sub> and BGS<sub>CB</sub> on the impact of ReCiPe midpoint characterization categories at 5% biogas leakage and 2% digestate leakage are compared and shown in **Table 4.10**. Tabulated data give evidence that the impact of both BGS<sub>PRB</sub> and BGS<sub>CB</sub> on all the midpoint characterization factors of the ReCiPe method for 5% biogas leakage and 2% digestate leakage is almost similar to the ones for 7.5% biogas leakage and 3.5% digestate leakage, except for the Climate change category.

**Table 4.10** Impact of the operation of BGS<sub>PRB</sub> and BGS<sub>CB</sub> on midpoint characterization environmental factors for 5% biogas leakage and 2% digestate leakage

Impact category	Unit	Operation of BGS <sub>CB</sub> (5% BL and 2% DL)	Operation of BGS <sub>PRB</sub> (5% BL and 2% DL)
Climate change	kg CO <sub>2</sub> eq	0.605	0.602
Ozone depletion	kg CFC-11 eq	2.62E-09	1.99E-09
Terrestrial acidification	kg SO <sub>2</sub> eq	0.00019	0.00018
Freshwater eutrophication	kg P eq	8.38E-06	6.38E-06
Marine eutrophication	kg N eq	1.24E-05	1.17E-05
Human toxicity	kg 1,4-DB eq	0.024	0.022
Photochemical oxidant formation	kg NMVOC	0.00044	0.00043
Particulate matter formation	kg PM10 eq	9.05E-05	7.93E-05
Terrestrial ecotoxicity	kg 1,4-DB eq	5.64E-07	4.46E-07
Freshwater ecotoxicity	kg 1,4-DB eq	0.0003	0.0002
Marine ecotoxicity	kg 1,4-DB eq	0.0003	0.0002
Ionising radiation	kBq U235 eq	0.002	0.001
Agricultural land occupation	m <sup>2</sup> a	0.0013	0.001
Urban land occupation	m <sup>2</sup> a	9.29E-05	7.07E-05
Natural land transformation	m <sup>2</sup>	5.55E-06	4.22E-06
Water depletion	m <sup>3</sup>	0.0332	0.0331
Metal depletion	kg Fe eq	0.0005	0.0004
Fossil depletion	kg oil eq	0.018	0.016

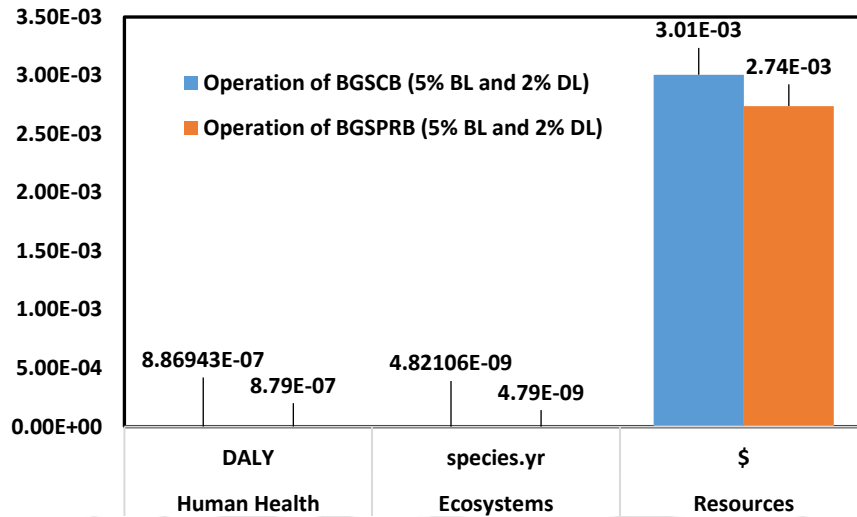
Considering the same for 5% and 2% leakages of biogas and digestate, respectively, the endpoint characterization values that are obtained are shown in **Table 4.11**.

**Table 4.11** Impact of the operation of BGS<sub>PRB</sub> and BGS<sub>CB</sub> on endpoint characterization environmental factors for 5% biogas leakage and 2% digestate leakage

Impact category	Unit	Operation of BGS <sub>CB</sub> (5% BL and 2% DL)	Operation of BGS <sub>PRB</sub> (5% BL and 2% DL)
Climate change Human Health	DALY	8.47E-07	8.43E-07
Ozone depletion	DALY	6.76E-12	5.15E-12
Human toxicity	DALY	1.65E-08	1.55E-08
Photochemical oxidant formation	DALY	1.7E-11	1.66E-11
Particulate matter formation	DALY	2.35E-08	2.06E-08
Ionising radiation	DALY	3.29E-11	2.5E-11
Climate change Ecosystems	species.yr	4.79E-09	4.77E-09
Terrestrial acidification	species.yr	1.12E-12	1.03E-12
Freshwater eutrophication	species.yr	3.73E-13	2.84E-13
Terrestrial ecotoxicity	species.yr	8.5E-14	6.71E-14
Freshwater ecotoxicity	species.yr	2.82E-13	2.44E-13
Marine ecotoxicity	species.yr	5.52E-14	4.8E-14
Agricultural land occupation	species.yr	1.62E-11	1.23E-11
Urban land occupation	species.yr	1.92E-12	1.46E-12
Natural land transformation	species.yr	9.66E-12	7.35E-12
Metal depletion	\$	3.9E-05	2.97E-05
Fossil depletion	\$	0.002968	0.00271

Endpoint characterization values shown in **Table 4.11**, when converted into endpoint damage assessment categories can be represented in **Fig. 4.8**.

The graphical representation makes it evident that BGS<sub>PRB</sub>'s impact on all the three endpoint damage assessment categories is lesser than BGS<sub>CB</sub>, with BGS<sub>PRB</sub> having 0.86% lesser impact than BGS<sub>CB</sub> on Human health factor. In the Ecosystems, the impact of BGS<sub>PRB</sub> is 2.79392E-11 species.yr lesser than BGS<sub>CB</sub>. In the Resources category, the impact of BGS<sub>PRB</sub> is 0.00274 \$ whereas it is 0.00301 \$.



**Fig. 4.8** Damage assessment due to the operation of BGS<sub>PRB</sub> and BGS<sub>CB</sub> at 5% biogas leakage and 2% digestate leakage

From the midpoint and endpoint characterization factors and endpoint damage assessment factors, it is clear that the BGS<sub>PRB</sub> has a lesser impact on the environmental factors than BGS<sub>CB</sub>. So, in order to see the change in performance of BGS<sub>PRB</sub> at different biogas and digestate leakage percentages, the performance of BGS<sub>PRB</sub> are tabulated and graphs are plotted accordingly.

**Table 4.12** shows the performance of BGS<sub>PRB</sub>'s impact for midpoint characterization values. From the values it can be said that there is no difference in the impact of BGS<sub>PRB</sub> on midpoint characterization categories at different levels of biogas and digestate leakages, except for Climate change, Water depletion and Metal depletion. For these three factors, the impact is more on the larger quantity of leakages and is lesser for the lower quantity of leakages. The performance of BGS<sub>PRB</sub> for damage assessment categories obtained from endpoint characterization categories is represented in **Fig. 4.9**.

The graph tells that BGS<sub>PRB</sub>'s impact on endpoint damage assessment categories for different leakages of biogas and digestate, is not at all similar to midpoint damage categories, as in all the endpoint damage assessment categories the impact of BGS<sub>PRB</sub> on the environment reduces for the lesser amount of biogas and digestate leakages. For 7.5% biogas leakage and 3.5% digestate leakage, there is a decrease of 25.6%, 26.1%, and 1.9% on Human health, Ecosystems, and Resources categories, respectively than the base biogas and digestate leakages. Whereas for 5%

biogas leakage and 2% digestate leakage, the decrease is 49.9%, 50.8%, and 3.7% in Human health, Ecosystems, and Resources categories, respectively than the base biogas and digestate leakages.

**Table 4.12** Impact of BGS<sub>PRB</sub> for different biogas and digestate leakages

Impact category	Unit	10% BL and 5% DL	7.5% BL and 3.5% DL	5% BL and 2% DL
Climate change	kg CO <sub>2</sub> eq	1.226686852	0.90601107	0.602213
Ozone depletion	kg CFC-11 eq	1.99157E-09	1.9915E-09	1.99E-09
Terrestrial acidification	kg SO <sub>2</sub> eq	0.000184589	0.00018089	0.000177
Freshwater eutrophication	kg P eq	6.37853E-06	6.3785E-06	6.38E-06
Marine eutrophication	kg N eq	1.52285E-05	1.3434E-05	1.17E-05
Human toxicity	kg 1,4-DB eq	0.023118441	0.0226223	0.022152
Photochemical oxidant formation	kg NMVOC	0.000669237	0.0005443	0.000426
Particulate matter formation	kg PM <sub>10</sub> eq	8.17373E-05	8.0492E-05	7.93E-05
Terrestrial ecotoxicity	kg 1,4-DB eq	4.49257E-07	4.4734E-07	4.46E-07
Freshwater ecotoxicity	kg 1,4-DB eq	0.000291889	0.00028777	0.000284
Marine ecotoxicity	kg 1,4-DB eq	0.000280227	0.00027618	0.000272
Ionising radiation	kBq U235 eq	0.00152536	0.00152536	0.001525
Agricultural land occupation	m <sup>2</sup> a	0.001024275	0.00102427	0.001024
Urban land occupation	m <sup>2</sup> a	7.07099E-05	7.071E-05	7.07E-05
Natural land transformation	m <sup>2</sup>	4.22183E-06	4.2218E-06	4.22E-06
Water depletion	m <sup>3</sup>	0.035018341	0.03407411	0.03318
Metal depletion	kg Fe eq	0.000415626	0.00041563	0.000416
Fossil depletion	kg oil eq	0.017022391	0.01669655	0.016388

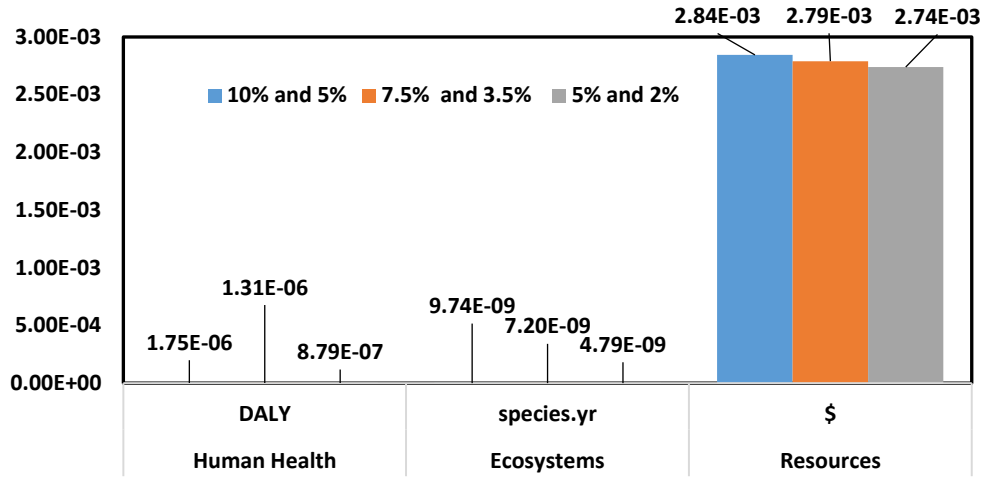


Fig. 4.9 Performance of BGS<sub>PRB</sub> at different biogas and digestate leakages

#### 4.2 Need for conducting LCA on LPG-operated Porous Radiant Burner

Liquefied Petroleum Gas (LPG) is one of the most used cooking fuels in India and other nations. The consumption of LPG alone has increased by a 7 % Compound Annual Growth Rate in the last ten years. Considering the Geospatial Energy Map of India released by the National Institution for Transforming India (NITI) Ayog, it is evident that the reserves of fossil fuels in our country are limited. In order to meet the energy requirement, India imports 50% of its LPG fuel. A significant amount of the generated revenue is utilized in importing fuel to meet the day-to-day needs of cooking, and heating applications. It has become necessary after the oil crisis of 1973 that the nations should shift to energy-efficient technologies, renewable fuels, and better cooking technologies. Dynamic research is being conducted across the world to come up with technologies to address the energy crisis. One such energy-efficient product is Porous Radiant Burner (PRB) (Mishra and Muthukumar, 2018b; Panigrahy et al., 2016). Studies were conducted on PRB to test its emissions, thermal efficiency, and fuel consumption. Only one study was conducted on the environmental viability of PRB and the study was done focusing on the energy efficiency of the product (Kaushik and Muthukumar, 2018d). However, no studies were reported about environmental sustainability in terms of fabrication and recycling, and the operation of PRB. So, in the present study, the environmental impact of a 1-3 kW LPG operated Porous Radiant Burner (PRB<sub>LPG</sub>) based domestic cook-stove is compared with that of a Conventional Burner (CB<sub>LPG</sub>) based domestic cook-stove of the same capacity available in the Indian market, to test the environmental sustainability.

#### ***4.2.1 Goal, Scope, and Functional unit for LCA of LPG operated cook-stoves***

##### ***Goal and Scope***

The major goal of the present study includes conducting LCA for 1-3 kW PRB<sub>LPG</sub> based domestic cook-stove with that of a CB<sub>LPG</sub> based domestic cook-stove available in the Indian market. This is to assess and compare the environmental impacts of PRB<sub>LPG</sub> and CB<sub>LPG</sub> to make a decision on a better environmentally sustainable product. PRB<sub>LPG</sub> is indigenously developed at IITG by the corresponding author's research team. The environmental impacts of both products are to be thoroughly studied so that the best sustainable product can be adopted on a wider scale in the nation. The goal also includes the comparison of both making and recycling, and the operation of 1-3 kW PRB<sub>LPG</sub> and CB<sub>LPG</sub> cook-stoves. Also, to analyze and compare the impacts of PRB<sub>LPG</sub> and CB<sub>LPG</sub> at the operation of both minimum and maximum power output ranges of 1 kW and 3 kW LPG.

##### ***Functional Unit***

The functional unit considered in the present study is the operation of PRB<sub>LPG</sub> and CB<sub>LPG</sub> cook-stoves with the fuel consumption of 10 cylinders annually. The cylinders are meant for domestic cooking applications, with a 14.2 kg LPG capacity. The total period considered for the functional unit is of 10 years which is the active life of the cook-stove. The fuel input considered for the functional unit is 1 kW and 3 kW for both PRB<sub>LPG</sub> and CB<sub>LPG</sub> cook-stoves. From the field experiment, the thermal efficiency obtained for CB<sub>LPG</sub> is 68% and the CO and NO<sub>x</sub> emissions are 220 ppm and 5 ppm, respectively at a 1 kW power output. And at 3 kW power output, there is a thermal efficiency of 64% and the emissions of CO and NO<sub>x</sub> are 550 ppm and 25 ppm, respectively. Whereas for PRB<sub>LPG</sub>, the thermal efficiency obtained at 1 kW power output is 80% and the respective CO and NO<sub>x</sub> emissions are 30 ppm and 0.2 ppm. At 3 kW power output, the achieved thermal efficiency for PRB<sub>LPG</sub> is 78% with CO and NO<sub>x</sub> emissions of 140 ppm and 3.5 ppm, respectively. With the mentioned thermal efficiency of CB<sub>LPG</sub>, it consumed 10 cylinders per annum each with 14.2 kg capacity for a household giving 1223.24 operating hours for 1 kW power output and 383.76 operating hours for 3 kW power output.

**Table 4.13** Fuel consumption and emissions of PRB<sub>LPG</sub> and CB<sub>LPG</sub> for 10 years

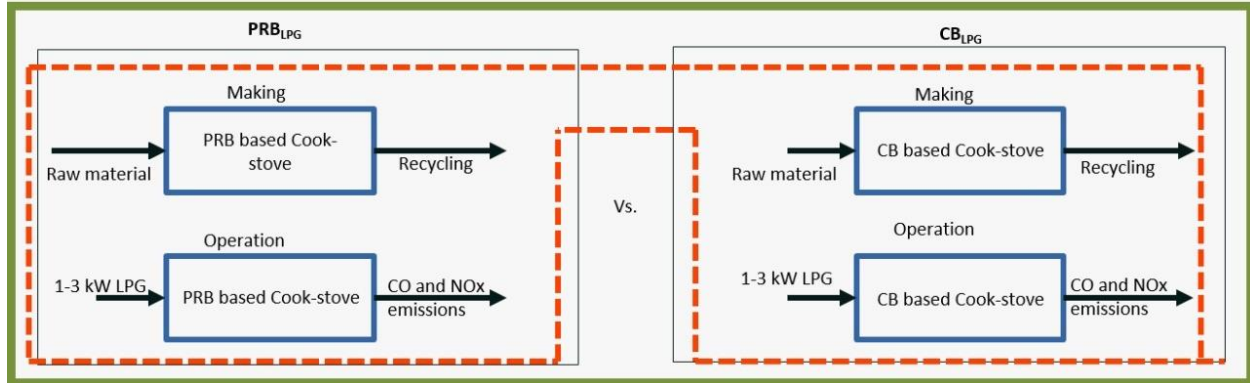
<b>For time period of 10 years</b>	<b>PRB<sub>LPG</sub></b>	<b>CB<sub>LPG</sub></b>
Fuel consumption for 1 kW power output (kg) and 1223.24 operating hours	1207	1420
Fuel consumption for 3 kW power output (kg) and 383.76 operating hours	1165.13	1420
CO emissions for 1 kW power output (g)	385.1	2824.1
CO emissions for 3 kW power output (g)	4.21	105.2
NO <sub>x</sub> emissions for 1 kW power output (g)	1691.43	6644.89
NO <sub>x</sub> emissions for 3 kW power output (g)	69.31	495.05

Taking the operating hours of CB<sub>LPG</sub> as base, the fuel consumption and CO and NO<sub>x</sub> emissions are calculated for PRB<sub>LPG</sub>, for comparison. For the convenience to assess the impact factors, ppm values of emissions are converted into grams. Details of fuel consumption and emissions for PRB<sub>LPG</sub> and CB<sub>LPG</sub> at 1 kW and 3 kW power outputs for 10 years is given in **Table 4.13**.

From the obtained values, the annual reduction of CO emissions from PRB<sub>LPG</sub> are lesser than CB<sub>LPG</sub> by 86.4% for 1 kW power output. Whereas, the reduction obtained for PRB<sub>LPG</sub> at 3 kW power output in CO emissions is 96% lesser than that of CB<sub>LPG</sub>. The annual reduction in NO<sub>x</sub> emissions of PRB<sub>LPG</sub> at 1 kW power output is 74.5 % lesser when compared to the NO<sub>x</sub> emissions of CB<sub>LPG</sub>. At 3 kW power output also, NO<sub>x</sub> emissions of PRB<sub>LPG</sub>, when compared to CB<sub>LPG</sub> are 86 % lesser.

#### **4.2.2 System Boundary**

A system boundary can be defined as the one which separates the system of study from its adjacent systems. It will also define the amount of material requirement for the making of the product or process or service including its embodied energy requirement and respective output emissions. **Fig. 4.10** represents the system boundary of the current study, in which the scope of the study is indicated by a red dashed line and the system boundary is represented by thick green line. In the present study, PRB<sub>LPG</sub> and CB<sub>LPG</sub> are considered for the system boundary for analyzing environmental impact for the making of the respective cook-stoves. Also, the environmental impact each would have during the operation when the same fuel input is given to each of them.



**Fig. 4.10** System boundary and scope of the study of LPG based cook-stoves

As represented in Fig 4.10, for both  $PRB_{LPG}$  and  $CB_{LPG}$ , the raw material used for the fabrication of the cook-stoves are considered in the system boundary. Also, after the lifetime of the cook-stoves for a period of 10 years, some amount of material is recycled, which is also included in the system boundary. Along with the fabrication, the operation of  $PRB_{LPG}$  and  $CB_{LPG}$  are also considered for the minimum and maximum power outputs of 1 kW and 3 kW LPG to analyze and compare the environmental impacts of these burners. The boundary and scope are also considered to measure and compare the impacts of the emissions of these burners on the environment at different fuel inputs, with the help of the Ecoinvent V3 database.

#### **4.2.3 Life Cycle Inventory Analysis of LPG based cook-stoves**

Life Cycle Inventory Analysis (LCIA) is done to analyze the inputs and outputs of making, recycling and utilization of any product or service or process. Data compilation plays a crucial role for conducting LCIA. The total energy required for fabrication and recycling is represented quantitatively in LCIA in step-by-step manner. For this study, “SimaPro 8.3.0.0” is the tool used for the environmental modelling and the database considered is “Ecoinvent V3”. The required inventory data for the making of  $PRB_{LPG}$  and  $CB_{LPG}$  cook-stoves, and their functioning with 1-3 kW LPG power output and their respective emissions are collected from the field-study experiments. The emissions considered are CO and NO<sub>x</sub> emissions for  $PRB_{LPG}$  and  $CB_{LPG}$  operating at different power outputs.

#### **Inventory of $PRB_{LPG}$ Cook-stove**

To make the upper layer of  $PRB_{LPG}$ , also known as combustion layer, SiC is used and to make the lower layer, Alumina is used. There is also usage of refractory Alumina to bind the layers of the

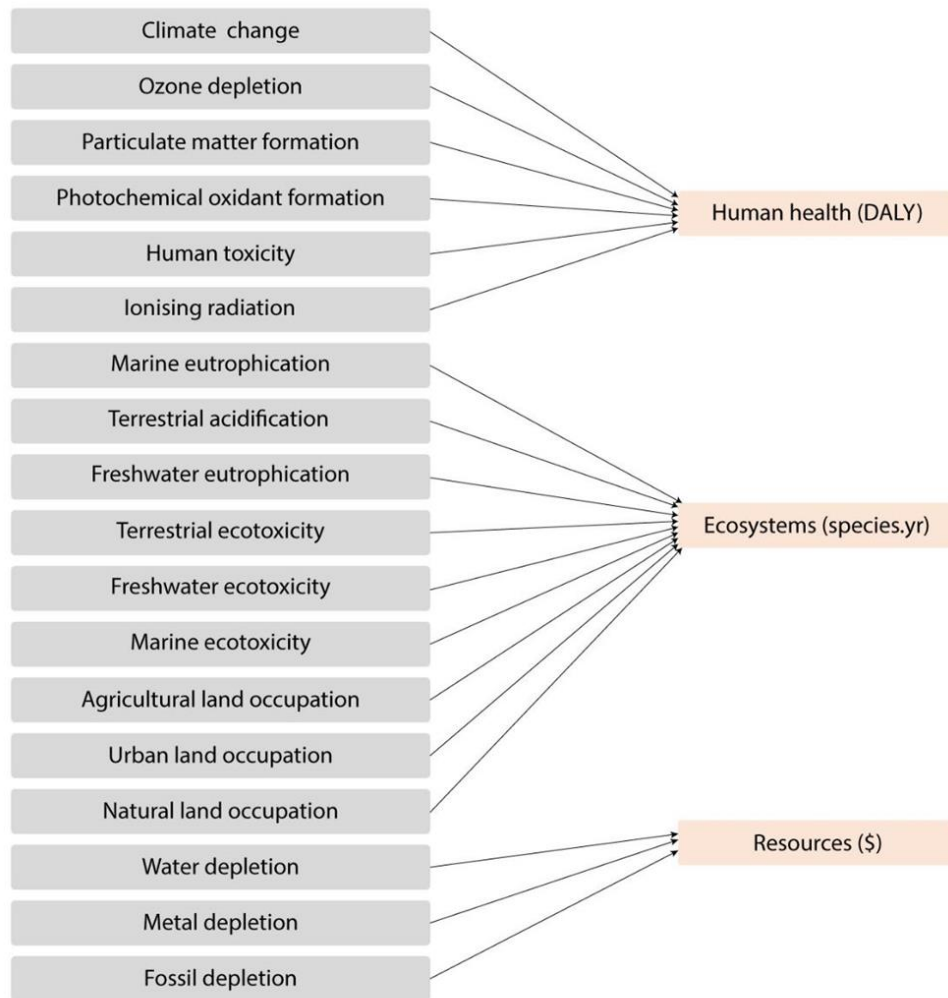
burner together and also to prevent the rust. For the cook-stove, and it to be integrated with PRB<sub>LPG</sub>, other materials like copper, cast iron, polysterene, stainless steel, synthetic rubber etc., are used. As all these materials are available locally, they were brought from a distance of 25 km to the location of experimental setup. Also, as the quantity is less, it is brought on a light motor vehicle. The emission standards considered for the vehicle are Euro 4 standards from the Ecoinvent 3 database, which are equivalent to Bharat Stage IV emission standards.

#### ***Inventory of CB<sub>LPG</sub> Cook-stove***

The material used for the making of CB<sub>LPG</sub> constitutes mainly of brass, cast iron, and low-alloyed steel. Whereas, the material used for the cook-stove for CB<sub>LPG</sub> to be integrated with, is the same as it has been used for PRB<sub>LPG</sub> cook-stove, such as copper, cast iron, polysterene, stainless steel, synthetic rubber. Since all the materials are available locally, they have been brought on a light motor-vehicle for a distance of 25 km to the experimental place. The same Euro 4 emission standards are considered for CB<sub>LPG</sub> as have been considered for PRB<sub>LPG</sub>, in Ecoinvent 3 database.

#### ***4.2.4 Life Cycle Impact Assessment of LPG based cook-stoves***

A multi-issue method known as ReCiPe method is used in the present study to assess the impacts. Both the indicators of the ReCiPe method viz., midpoint indicators and endpoint indicators are used in the study to analyse the impacts. As the names suggest, the midpoint indicators will analyse the impacts of the cause and effect chain till the midpoint and these indicators are the problem-oriented indicators. Whereas, the endpoint indicators will analyse the impacts of the cause and effect chain from the midpoint till the end. The endpoint indicators are the damage-oriented indicators. The midpoint indicators construe the environmental themes and the endpoint indicators construe the issues of concern. For the environmental modelling, the ReCiPe method has been chosen as it includes both the problem-oriented approach and the damage-oriented approach. As this method includes a problem-oriented approach, there is less uncertainty of results; but because it also includes many factors, it is complex to reach a conclusion for the decision making. In order to overcome this, damage-oriented approach is also included in this method to easily reach decision-making on the impact of the product or process or process on the factors.



**Fig. 4.11** Midpoint and endpoint assessment categories

The midpoint categories of ReCiPe Midpoint Hierarchist (H) version V1.13, are Climate change, Human health, Ozone depletion, Human toxicity, Photochemical oxidant formation, Particulate matter formation, Ionising radiation, Climate change ecosystems, Terrestrial acidification, Freshwater eutrophication, Terrestrial ecotoxicity, Freshwater ecotoxicity, Marine ecotoxicity, Agricultural land occupation, Urban land occupation, Natural land transformation, Metal depletion and Fossil depletion. Whereas, the endpoint categories adopted in ReCiPe Endpoint (H) V1.13, are Human Health, Ecosystems and Resources. H/H is the perspective adopted for the current research, which refers to the hierarchist perspective weighing set of normalization values. The endpoint approach makes it easier for the decision makers to choose the optimal or better product

or process or service. The approaches considered in the present study are to assess the environmental impacts of PRB<sub>LPG</sub> and compare them with that of CB<sub>LPG</sub>. The ReCiPe method impact assessment categories of both midpoint and endpoint categorization are represented in **Fig. 4.11**.

#### ***4.2.5 Results of Assessment of LPG based cook-stoves***

The results of LCA depend on the assessment strategies, fabrication and recycling and operation of the products, processes, or services; functional units, assumptions made while selecting the inventory (if data is not readily available in the database) and so on. The current study focuses on comparing PRB<sub>LPG</sub> based domestic cook-stove with that of a CB<sub>LPG</sub> based domestic cook-stove available in the Indian market for their fabrication and recycling, and operation. The operation of both the stoves is compared with same power output of 1-3 kW and for both minimum and maximum power output of 1 kW and 3 kW, respectively.

The analysis is done individually for the fabrication and recycling phase, and the operation phase of the cook-stoves, so that a clear understanding can be provided about the study. Both midpoint analysis and endpoint analysis are done for fabrication and recycling, and operation of the cook-stoves. ReCiPe's Hierarchist version is adopted for normalizing the results. Results are normalized using world's normalization values. Normalization in LCIA is to provide the clear comparison of the impact factors of the scores.

#### ***ReCiPe at midpoint level for the fabrication and recycling of LPG based cook-stoves***

For the midpoint analysis of the fabrication and recycling of PRB<sub>LPG</sub> and CB<sub>LPG</sub> cook-stoves, the ReCiPe (H) V1.13 method is adopted. **Table 4.14** shows the details of the midpoint environmental impact factors for the fabrication and recycling of PRB<sub>LPG</sub> and CB<sub>LPG</sub> cook-stoves. It is understood from the results obtained that the impact of PRB<sub>LPG</sub> cook-stove on most of the midpoint characterization values of environmental impact factors are lesser compared to CB<sub>LPG</sub> cook-stove. Significant reduction of ~11 kg 1,4-DB eq is observed in PRB<sub>LPG</sub> cook-stove than CB<sub>LPG</sub> cook-stove in Human toxicity and also there is a significant amount of reduction in Metal depletion impact category of ~2 kg Fe eq for PRB<sub>LPG</sub> cook-stove than that of CB<sub>LPG</sub> cook-stove. Approximately 55% reduction in both Freshwater ecotoxicity and Marine ecotoxicity for PRB<sub>LPG</sub> cook-stove than CB<sub>LPG</sub> cook-stove is observed, as PRB<sub>LPG</sub> cook-stove's impacts for these factors

stand at 0.142 and 0.144 kg 1,4-DB eq, respectively. For certain other factors like Ozone depletion, Photochemical oxidant formation, Terrestrial ecotoxicity and Natural land transformation, the environmental impacts of both the PRB<sub>LPG</sub> and CB<sub>LPG</sub> cook-stoves are similar. However, for Ionising radiation impact factor, PRB<sub>LPG</sub> cook-stove has an impact of -0.029 and this negative value is because of the refractory aluminium used in the fabrication of PRB<sub>LPG</sub>. The only impact factor in which PRB<sub>LPG</sub> cook-stove has more environmental impact than CB<sub>LPG</sub> cook-stove is Fossil depletion, with PRB<sub>LPG</sub> cook-stove having ~1.8 kg oil eq.

**Table 4.14** Midpoint characterization values of fabrication and recycling of PRB<sub>LPG</sub> and CB<sub>LPG</sub> cook-stoves

Impact category	Unit	CB <sub>LPG</sub> cook-stove fabrication and recycling	PRB <sub>LPG</sub> cook-stove fabrication and recycling
Climate change	kg CO <sub>2</sub> eq	5.2	5.5
Ozone depletion	kg CFC-11 eq	0.000	0.000
Terrestrial acidification	kg SO <sub>2</sub> eq	0.033	0.025
Freshwater eutrophication	kg P eq	0.009	0.004
Marine eutrophication	kg N eq	0.002	0.001
Human toxicity	kg 1,4-DB eq	18	7
Photochemical oxidant formation	kg NMVOC	0.092	0.092
Particulate matter formation	kg PM10 eq	0.021	0.015
Terrestrial ecotoxicity	kg 1,4-DB eq	0.001	0.001
Freshwater ecotoxicity	kg 1,4-DB eq	0.315	0.142
Marine ecotoxicity	kg 1,4-DB eq	0.323	0.144
Ionising radiation	kBq U235 eq	0.137	-0.029
Agricultural land occupation	m <sup>2</sup> a	0.981	0.929
Urban land occupation	m <sup>2</sup> a	0.070	0.056
Natural land transformation	m <sup>2</sup>	0.001	0.001
Water depletion	m <sup>3</sup>	0.046	0.039
Metal depletion	kg Fe eq	5	3
Fossil depletion	kg oil eq	1.6	1.8

***ReCiPe at endpoint level for the fabrication and recycling of LPG based cook-stoves***

ReCiPe (H) V1.13 method is also the method used for endpoint analysis of the fabrication and recycling of PRB<sub>LPG</sub> and CB<sub>LPG</sub> cook-stoves. **Table 4.15** shows the endpoint characterization values for the fabrication and recycling of PRB<sub>LPG</sub> and CB<sub>LPG</sub> cook-stoves.

**Table 4.15** Endpoint characterization values of fabrication and recycling of PRB<sub>LPG</sub> and CB<sub>LPG</sub> cook-stoves

Impact category	CB <sub>LPG</sub> cook-stove	PRB <sub>LPG</sub> cook-stove
	fabrication and recycling	fabrication and recycling
Climate change Human Health	7.29E-06	7.67E-06
Ozone depletion	1.64E-09	1.87E-09
Human toxicity	1.29E-05	5.12E-06
Photochemical oxidant formation	3.59E-09	3.61E-09
Particulate matter formation	5.35E-06	4.03E-06
Ionising radiation	2.25E-09	-4.78E-10
Climate change Ecosystems	4.13E-08	4.34E-08
Terrestrial acidification	1.94E-10	1.43E-10
Freshwater eutrophication	4.22E-10	1.8E-10
Terrestrial ecotoxicity	1.96E-10	1.1E-10
Freshwater ecotoxicity	2.70E-10	1.22E-10
Marine ecotoxicity	5.69E-11	2.54E-11
Agricultural land occupation	1.18E-08	1.11E-08
Urban land occupation	1.44E-09	1.16E-09
Natural land transformation	2.33E-09	2.37E-09
Metal depletion	0.37	0.22
Fossil depletion	0.26	0.29

Note: Units of Impact category are given in **Fig. 4.11**

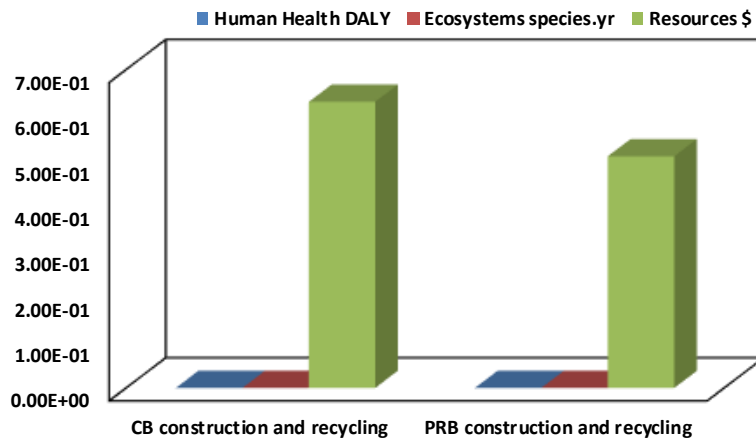
The endpoint characterization values when represented as endpoint damage assessment categories, the obtained impact factors can be grouped into three damage assessment categories of Human health, Ecosystems and Resources categories that are represented in **Table 4.16**.

From the values obtained in **Table 4.16**, it is evident that the impact of PRB<sub>LPG</sub> cook-stove is definitely lesser than that of CB<sub>LPG</sub> cook-stove on Human health and Resources damage assessment categories. It is noteworthy that PRB<sub>LPG</sub> cook-stove fabrication and recycling will reduce the impact on Human health damage by up to 34% more than CB<sub>LPG</sub> cook-stove, which is remarkable. Also, there is a reduction of 19% damage on Resources when PRB<sub>LPG</sub> cook-stove is fabricated and recycled when compared to CB<sub>LPG</sub> cook-stove.

**Table 4.16** Endpoint damage assessment categories - fabrication and recycling of PRB<sub>LPG</sub> and CB<sub>LPG</sub> cook-stoves

Damage category	CB <sub>LPG</sub> cook-stove fabrication and recycling	PRB <sub>LPG</sub> cook-stove fabrication and recycling
HumanHealth (DALY)	2.55E-05	1.68E-05
Ecosystems (species.yr)	5.79E-08	5.87E-08
Resources (\$)	0.63	0.51

However, there is slightly more damage of 1.2% caused to Ecosystems through PRB<sub>LPG</sub> cook-stove than CB<sub>LPG</sub> cook-stove due to fabrication and recycling. The same is represented in **Fig. 4.12**.



**Fig. 4.12** Damage assessment categories - fabrication and recycling of PRB<sub>LPG</sub> and CB<sub>LPG</sub> cook-stoves

#### 4.2.6 ReCiPe at midpoint characterization

##### *For cook-stoves operating at 1 kW LPG power output*

To compare the performance of PRB<sub>LPG</sub> cook-stove with that of CB<sub>LPG</sub> cook-stove when they are operated with the same capacity of power outputs, different power outputs are given to the cook-stoves and their performance is assessed. For the domestic cooking application, at the power output of 1 kW LPG is given to the cook-stoves and their impact assessment categories are observed at midpoint characterization levels. **Table 4.17** represents the midpoint characterization values of PRB<sub>LPG</sub> and CB<sub>LPG</sub> cook-stoves when they are operated at 1 kW LPG power output.

Values represented indicate that during the operation phase with 1 kW LPG power output, PRB<sub>LPG</sub> cook-stove has lesser environmental impacts that of CB<sub>LPG</sub> cook-stove on all the midpoint characterization factors. Particularly, there is a major reduction in the impacts of PRB<sub>LPG</sub> cook-stove on Climate change factor with 201.45 kg CO<sub>2</sub> eq lesser than that of CB<sub>LPG</sub> cook-stove. And also on Human toxicity, where the impact of PRB<sub>LPG</sub> cook-stove is 153.16 kg 1,4-DB eq lesser than CB<sub>LPG</sub> cook-stove. There is also significant decrease of the PRB<sub>LPG</sub> cook-stove's impact on Agricultural land occupation and Fossil depletion categories with CB<sub>LPG</sub> cook-stove having 165.9 m<sup>2</sup>a and 307.32 kg oil eq more than the impacts of PRB<sub>LPG</sub> cook-stove, respectively. Except for the Ozone depletion category where there is a negligible impact of both the cook-stoves, the impact of PRB<sub>LPG</sub> cook-stove is notably lesser than CB<sub>LPG</sub> cook-stove on all other midpoint characterization factors also.

**Table 4.17** Midpoint characterization values of operating PRB<sub>LPG</sub> and CB<sub>LPG</sub> cook-stoves at 1 kW LPG power output

Impact category	Unit	CB <sub>LPG</sub> - Impact for 1 kW LPG power output	PRB <sub>LPG</sub> - Impact for 1 kW LPG power output
Climate change	kg CO <sub>2</sub> eq	1317.421	1115.973
Ozone depletion	kg CFC-11 eq	0.001	0.0009
Terrestrial acidification	kg SO <sub>2</sub> eq	13.532	11.471
Freshwater eutrophication	kg P eq	1.354	1.143
Marine eutrophication	kg N eq	0.504	0.426
Human toxicity	kg 1,4-DB eq	947.558	794.413
Photochemical oxidant formation	kg NMVOC	7.428	6.312
Particulate matter formation	kg PM10 eq	7.551	6.396
Terrestrial ecotoxicity	kg 1,4-DB eq	0.14	0.118053
Freshwater ecotoxicity	kg 1,4-DB eq	17.76	14.88706
Marine ecotoxicity	kg 1,4-DB eq	17.28	14.47908
Ionising radiation	kBq U235 eq	192.89	162.9424
Agricultural land occupation	m <sup>2</sup> a	1103.02	937.1225
Urban land occupation	m <sup>2</sup> a	16.21	13.73942
Natural land transformation	m <sup>2</sup>	2.06	1.745713
Water depletion	m <sup>3</sup>	35.006	29.69955
Metal depletion	kg Fe eq	43.157	35.09337
Fossil depletion	kg oil eq	2033.339	1726.024

**For cook-stoves operating at 3 kW LPG power output**

Midpoint characterization values for PRB<sub>LPG</sub> and CB<sub>LPG</sub> cook-stoves of domestic cooking applications are also assessed for 3 kW LPG power output. The resultant values are tabulated as indicated in **Table 4.18**.

**Table 4.18** Midpoint characterization values of operating PRB<sub>LPG</sub> and CB<sub>LPG</sub> cook-stoves at 3 kW LPG power output

<b>Impact category</b>	<b>Unit</b>	<b>CB<sub>LPG</sub> - Impact for 3 kW LPG power output</b>	<b>PRB<sub>LPG</sub> - Impact for 3 kW LPG power output</b>
Climate change	kg CO <sub>2</sub> eq	1327.807	1119.189
Ozone depletion	kg CFC-11 eq	0.001	0.0008
Terrestrial acidification	kg SO <sub>2</sub> eq	13.59	11.49
Freshwater eutrophication	kg P eq	1.4	1.15
Marine eutrophication	kg N eq	0.51	0.43
Human toxicity	kg 1,4-DB eq	953.16	796.18
Photochemical oxidant formation	kg NMVOC	7.46	6.32
Particulate matter formation	kg PM10 eq	7.59	6.41
Terrestrial ecotoxicity	kg 1,4-DB eq	0.14	0.12
Freshwater ecotoxicity	kg 1,4-DB eq	17.93	14.94
Marine ecotoxicity	kg 1,4-DB eq	17.44	14.53
Ionising radiation	kBq U235 eq	194.72	163.51
Agricultural land occupation	m <sup>2</sup> a	1104.05	937.47
Urban land occupation	m <sup>2</sup> a	16.29	13.77
Natural land transformation	m <sup>2</sup>	2.06	1.75
Water depletion	m <sup>3</sup>	35.14	29.74
Metal depletion	kg Fe eq	43.65	35.25
Fossil depletion	kg oil eq	2038.87	1727.82

The tabular values indicate that even for 3 kW LPG power output, PRB<sub>LPG</sub> cook-stove has lesser environmental impacts than that of CB<sub>LPG</sub> cook-stove on all the midpoint characterization factors, except for Ozone depletion. In the Ozone depletion impact factor, just as is the case for 1 kW LPG power output, both PRB<sub>LPG</sub> and CB<sub>LPG</sub> cook-stoves have negligible impact factors while being operated with 3 kW LPG power output. The resultant impact factors of the cook-stoves are almost

similar to that of their operation with 1 kW LPG power output. There is a decrease on the impact factors like Terrestrial acidification, Photochemical oxidant formation, Particulate matter formation, Freshwater ecotoxicity and Marine ecotoxicity for up to 0.02 kg SO<sub>2</sub> eq, 1.14 kg NMVOC, 1.18 kg PM<sub>10</sub> eq, 2.98 kg 1,4-DB eq and 2.91 kg 1,4-DB eq, respectively with the operation of PRB<sub>LPG</sub> cook-stove than CB<sub>LPG</sub> cook-stove when the same power output of 3 kW LPG is given to both the cook-stoves.

#### 4.2.7 ReCiPe at endpoint characterization

##### *For cook-stoves operating at 1 kW and 3 kW LPG power outputs*

The method adopted for calculating ReCiPe endpoint characterization values is also ReCiPe (H) V1.13 method. The impact assessment categories obtained for endpoint characterization category at 1 kW LPG power output are shown in **Table 4.19**. And impact assessment categories obtained for endpoint characterization category at 3 kW LPG power output are shown in **Table 4.20**.

**Table 4.19** Endpoint characterization values of operating PRB<sub>LPG</sub> and CB<sub>LPG</sub> cook-stoves at 1 kW

Impact category	CB <sub>LPG</sub> - Impact for 1 kW LPG power output	PRB <sub>LPG</sub> - Impact for 1 kW LPG power output
Climate change Human Health	0.001844	0.001562
Ozone depletion	2.67E-06	2.27E-06
Human toxicity	0.000663	0.000556
Photochemical oxidant formation	2.9E-07	2.46E-07
Particulate matter formation	0.001963	0.001663
Ionising radiation	3.16E-06	2.67E-06
Climate change Ecosystems	1.04E-05	8.85E-06
Terrestrial acidification	7.85E-08	6.65E-08
Freshwater eutrophication	6.03E-08	5.09E-08
Terrestrial ecotoxicity	2.1E-08	1.78E-08
Freshwater ecotoxicity	1.53E-08	1.28E-08
Marine ecotoxicity	3.04E-09	2.55E-09
Agricultural land occupation	1.32E-05	1.12E-05
Urban land occupation	3.36E-07	2.84E-07
Natural land transformation	3.55E-06	3.02E-06
Metal depletion	3.086053	2.509499
Fossil depletion	336.2602	285.4386

Note: Units of the Impact category are given in **Fig 4.11**

Values obtained from the endpoint characterization tables of 1 kW and 3 kW LPG power outputs clearly indicate that the impact on the respective endpoint factors of PRB<sub>LPG</sub> cook-stove is lesser

in all categories than CB<sub>LPG</sub> cook-stove. Operating the cook-stoves at both the minimum power output of 1 kW and maximum power output of 3 kW LPG indicate that even when the power output is varied, PRB<sub>LPG</sub> cook-stove has lesser environmental impact at each respective power output.

**Table 4.20** Endpoint characterization values of operating PRB<sub>LPG</sub> and CB<sub>LPG</sub> cook-stoves at 3 kW LPG power output

<b>Impact category</b>	<b>CB<sub>LPG</sub> - Impact for 3 kW LPG input</b>	<b>PRB<sub>LPG</sub> - Impact for 3 kW LPG input</b>
Climate change Human Health	0.001859	0.001567
Ozone depletion	2.67E-06	2.27E-06
Human toxicity	0.000667	0.000557
Photochemical oxidant formation	2.91E-07	2.47E-07
Particulate matter formation	0.001974	0.001666
Ionising radiation	3.19E-06	2.68E-06
Climate change Ecosystems	1.05E-05	8.87E-06
Terrestrial acidification	7.88E-08	6.66E-08
Freshwater eutrophication	6.07E-08	5.1E-08
Terrestrial ecotoxicity	2.11E-08	1.78E-08
Freshwater ecotoxicity	1.55E-08	1.29E-08
Marine ecotoxicity	3.07E-09	2.56E-09
Agricultural land occupation	1.32E-05	1.12E-05
Urban land occupation	3.37E-07	2.85E-07
Natural land transformation	3.56E-06	3.02E-06
Metal depletion	3.121018	2.520543
Fossil depletion	337.1743	285.7351

Note: Units of the Impact category are given in Fig. 4.11

### ***Comparison of damage assessment categories of cook-stoves***

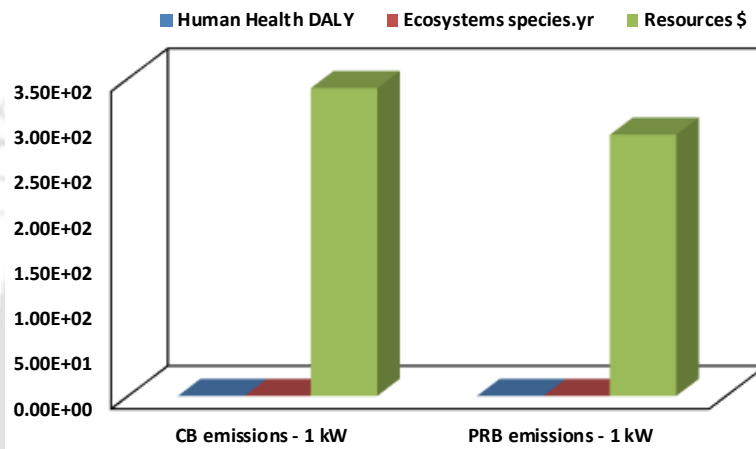
The endpoint characterization values for PRB<sub>LPG</sub> and CB<sub>LPG</sub> cook-stoves for 1 kW LPG power output obtained from Table 7 when converted into endpoint damage assessment categories are represented in **Table 4.21**.

From the obtained values of **Table 4.21**, it can be represented that the damage assessment categories of PRB<sub>LPG</sub> cook-stove are lesser by approximately 15%, 15% and 15% on Human health

(measured in Death Average Limiting Years – DALY unit), Ecosystems and Resources categories, respectively than CB<sub>LPG</sub> cook-stove. The graphical representation of the data is shown in **Fig. 4.13**.

**Table 4.21** Endpoint damage assessment of operating PRB<sub>LPG</sub> and CB<sub>LPG</sub> cook-stoves at 1 kW LPG power output

Impact category	CB <sub>LPG</sub> - Impact for 1 kW LPG input	PRB <sub>LPG</sub> - Impact for 1 kW LPG input
Human Health (DALY)	0.004	0.003
Ecosystems (species.yr)	2.77E-05	2.35E-05
Resources (\$)	339.35	287.95



**Fig. 4.13** Damage assessment categories – operation of PRB<sub>LPG</sub> and CB<sub>LPG</sub> cook-stoves at 1 kW LPG power output

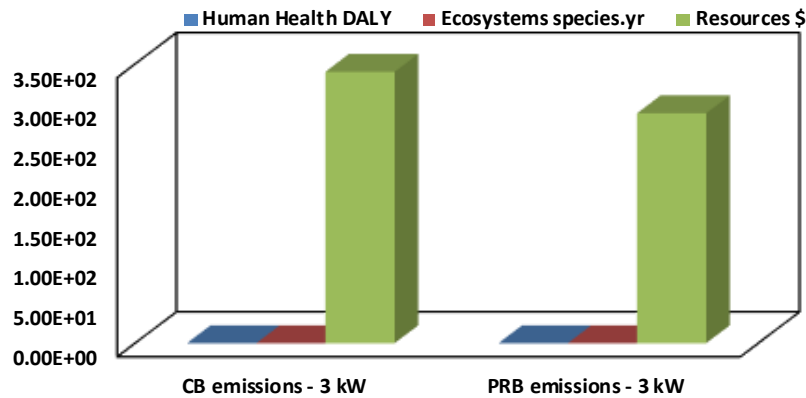
The endpoint characterization values for PRB<sub>LPG</sub> and CB<sub>LPG</sub> cook-stoves for 3 kW LPG power output obtained from **Table 4.20** when converted into endpoint damage assessment categories are represented in **Table 4.22**.

**Table 4.22** Endpoint damage assessment of operating PRB<sub>LPG</sub> and CB<sub>LPG</sub> cook-stoves at 3 kW LPG power output

Damage category	CB <sub>LPG</sub> - Impact for 3 kW LPG power output	PRB <sub>LPG</sub> - Impact for 3 kW LPG power output
Human Health (DALY)	0.005	0.004
Ecosystems (species.yr)	2.785E-05	2.357E-05
Resources (\$)	340.29	288.26

The values of **Table 4.22** indicate that the damage assessment categories of PRB<sub>LPG</sub> cook-stove are lesser by approximately 15%, 15% and 15% on Human health, Ecosystems and Resources

categories, respectively than  $CB_{LPG}$  cook-stove for 3 kW LPG power output. The graphical representation of the data is shown in **Fig 4.14**.



**Fig. 4.14** Damage assessment categories – operation of  $PRB_{LPG}$  and  $CB_{LPG}$  cook-stoves at 3 kW LPG power output

### 4.3 Need for conducting LCA on Small Scale Medical Waste Incinerator

In India, most of the remote areas have no access to formal medical waste disposal facilities. In such places, disposing of locally generated medical waste remains a challenging task. In most of remote locations, open-pit burning or landfilling of health care waste is practiced, which is not safe for human health and the environment. Hence, there is a need for developing a small-scale incinerator for serving such remote places to enable them to dispose of medical waste on their own. Westland Incinerator Corp. (Canada), Mediburner Ltd. (Finland), De Montfort University (England), and various companies and research groups all over the globe, have designed small-scale incinerators varying in the design aspect. Trials with Small-scale Medical Waste Incinerators (SMWI) in remote places in South Africa have been reported to be successful (Rogers & Brent, 2006). There is no need for pre-treatment of stock before feeding it into the incinerator, as the quantity of medical waste to be disposed of in SMWI is less (Generally, less than 50 kg). Yet, there is a need for further improvement in the design of SMWI. Further, no studies have been reported on the environmental impact caused by SMWI, starting from their construction phase to the operational phase. This thesis presents the design of 5 kW SMWI equipped with Liquefied Petroleum Gas (LPG)-operated Porous Radiant Burner (SMWI-PRB) with a capacity of 20 kg/hr. Also, the environmental impact caused by SMWI-PRB is studied and compared with SMWI equipped with an Electric heater (SMWI-EH).

Life Cycle Assessment (LCA) recommended by ISO has been performed using SimaPro software to analyze the environmental impact. In this paper, the IMPACT 2002+ LCA method is considered for the approximate prediction of environmental impact caused by SMWI-PRB and SMWI-EH. LPG operated PRB (PRB<sub>LPG</sub>) developed by Kaushik with a combustion efficiency of around 99%, has been considered for the present study. Also, CO and NO<sub>x</sub> emissions from PRB<sub>LPG</sub> are only 34 ppm and 2 ppm at 5 kW, respectively, whereas the same for the conventional burner are 335 ppm and 28 ppm, respectively. In order to avoid emissions generated from the burner, PRB<sub>LPG</sub> is chosen as an auxiliary heating device in SMWI. This investigation would contribute to the knowledge in the field of efficient waste management.

#### ***4.3.1 Design specifications of Small-scale Medical Waste Incinerator***

The SMWI is designed with a primary and a secondary chamber and the with the capacity of burning 20 kg/hr of medical waste (Easo and Swamy, 2011). The volume of the primary chamber is estimated as 1 m<sup>3</sup> and the secondary chamber is estimated to be 0.754 m<sup>3</sup>. The volume of the secondary chamber is calculated based on the flue gas volumetric flow rate and residence time required for the retention of flue gas at a given temperature. An auxiliary heating device is required to maintain a temperature of 1050 °C in the secondary chamber to sustain the incineration process. In the primary chamber, the waste is thermally treated to produce ash and volatile gases through an oxygen deficit-combustion process at a temperature of 800–900°C. The primary chamber includes a heating device, which is used to start the process. The volatile gases produced in the primary chamber reach the secondary chamber, where they get combusted under excess air conditions around 1000–1100°C. The temperature inside the secondary chamber is maintained constant throughout the process by an auxiliary heating device. The exhaust from the secondary chamber is treated in air pollution control devices before being released into the atmosphere. Though incinerators vary in design, the multi-chamber system using “controlled air” is the most commonly used incinerator type all over the globe. The high temperature incinerator chambers ensure the complete combustion of the toxins and pathogens, and the elimination of odors without damaging the components of the system. The end products after the incineration process are primarily CO<sub>2</sub>, water, and residual ash (Kharat et al., 2019). Some of the notable advantages of incinerators are complete sterilization and disinfection of medical waste, remarkable volume

reduction, operability in any weather condition, less floor space requirement, production of heat which can be easily recovered by a recovery system, etc.

Medical wastes are generally classified as A1 class (red bag), A2 (orange bag), A3(a) (yellow bag), A3(b) (Yellow bag), A3(c) (Yellow bag), and B1 (Blue bag). In the present work, for simplification in design calculation, a red bag containing tissue, water, and ash and a yellow bag containing polyethylene, polyvinylchloride, cellulose, and ash is considered in the ratio of 30:70, respectively.

The classification of medical waste segregation is given in **Table 4.23** and the components of each bag, their weight and their heat content are summarized in **Table 4.24**.

**Table 4.23** Classification of Medical Waste (Easo and Swamy, 2011)

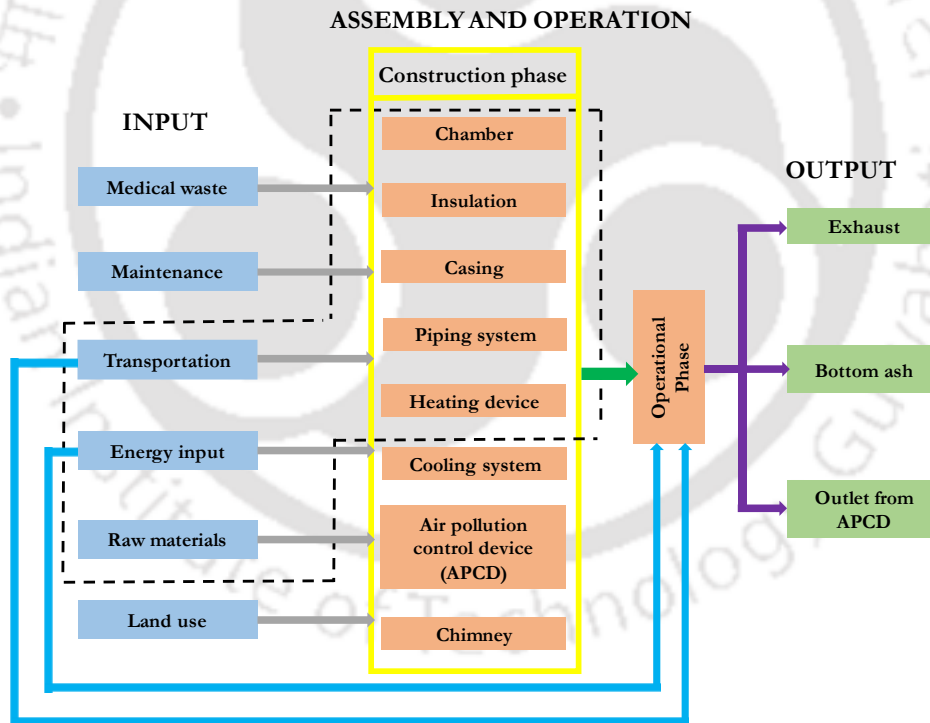
Waste Class	Components
A1 (Red bag)	Human anatomical waste, Plastic swabs, Absorbents, Alcohol, Disinfectants
A2 (Orange bag)	Animal anatomical waste, Plastics, Glass, Beddings, Shavings
A3(a) (Yellow bag)	Paper, Swabs, Cellulose, Plastics, PVC, Sharps, Needles, Alcohol, Disinfectants, Fluids, Residuals
A3(b)-Lab waste (Yellow bag)	Plastics, Sharps, Cellulosic material, Fluids, Residuals, Alcohol, Disinfectants, Glass
A3(c) (Yellow bag)	Swabs, Pads, Plastics, Sharps, Glass, Fluids
B1 (Blue bag)	Non-infected animal anatomical waste, Plastics, Glass, Beddings, Shavings

**Table 4.24** Composition of the medical waste considered and its heat content (Easo and Swamy, 2011)

Bag	Component	Heat content (kJ/kg)	Input (kg)	Total Heat flow (kJ/hr)
Red bag	$C_5H_{10}O_3$	20471	0.9	18424
	$H_2O$	0	4.8	0
	Ash	0	0.3	0
Yellow bag	$(C_2H_4)_x$	46304	4.9	226890
	$(C_2H_3Cl)_x$	22630	0.56	12673
	$C_6H_{10}O_5$	18568	7.14	132576
	Ash	0	1.4	0
Total			20 kg	390563 kJ/hr

### 4.3.2 Life Cycle Assessment of Small-scale Medical Waste Incinerator

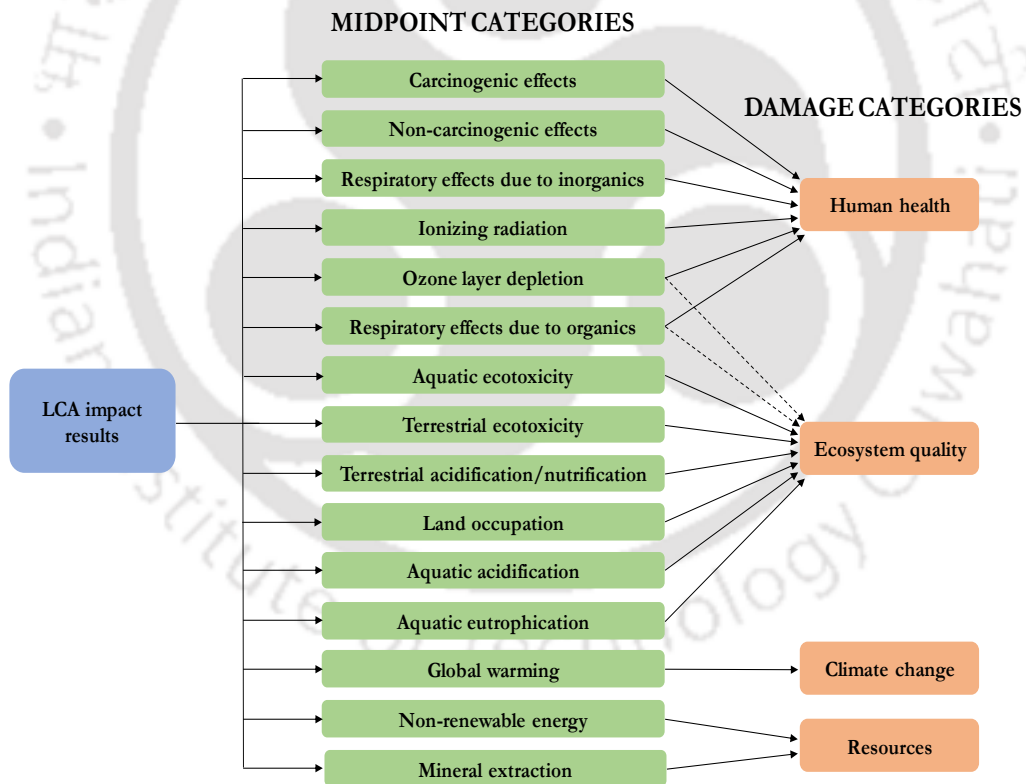
In this section, LCA has been performed to determine the environmental impact caused by SMWI since it is a systematic analytical method to identify, evaluate, and minimize the environmental impacts of SMWI. Material and energy utilization are considered for SMWI to evaluate the resource depletion, emissions, and energy consumption of all the processes, starting from transforming raw materials into useful products and their byproducts to their final disposal. The environmental impact caused by the construction of SMWI and its operation with PRB<sub>LPG</sub>, and an Electric heater is analyzed and compared using “SimaPro 8.3.0.0” LCA software embedded with the “Ecoinventv3” database. The standard LCA method as prescribed by ISO 14040-14044, is adopted for the analysis. The system boundary considered for LCA, as shown in **Fig. 4.15** comprises a chamber, insulation, casing, piping system, and the heating devices of the secondary chamber.



**Fig. 4.15** System boundary (within the dashed lines) considered for LCA of SMWI

The overall scheme of the IMPACT 2002+ LCA method is represented in **Fig. 4.16**. The impact results are linked to 4 damage categories (Human health, Ecosystem quality, Climate change, and Resource utilization). The endpoint damage categories are linked through 15 midpoint categories

which are Human toxicity-carcinogenic effects, Human toxicity-non-carcinogenic effects, Respiratory effects due to inorganics, Ionizing radiation, Ozone layer depletion, Respiratory effects due to organics, Aquatic ecotoxicity, Terrestrial ecotoxicity, Terrestrial acidification/nitrification, Land occupation, Aquatic acidification, Aquatic eutrophication, Global warming, Non-renewable energy consumption, and Mineral extraction (Wilson, 1907). SMWI with a 1 m<sup>3</sup> volume primary chamber and a 0.754 m<sup>3</sup> volume secondary chamber is considered for the assessment. PRB<sub>LPG</sub> and Electric heaters are considered as heating devices used to supply required heat energy to the secondary chamber for the completion of the incineration process. The environmental impacts caused by the construction of SMWI and the operation of the heating device used in the secondary chamber are considered for the assessment in this study. The present study can provide a holistic view of PRB<sub>LPG</sub>'s ability to curb the influence on the environment when compared to that of an Electric heater.



**Fig. 4.16** Scheme of IMPACT 2002+ method (Wilson, 1907)

### 4.3.3 Energy requirement for the fabrication of SMWI

The EcoInvent database is used to calculate the cumulative demand of energy required for the construction of the incinerator. The total energy required for SMWI construction is estimated as ~48286 MJ. The energy required for the materials used for the fabrication of the chamber is nearly 90% of the total energy required for the fabrication of SMWI. The estimated energy required for the fabrication of each component of the SMWI is given in **Table 4.25**.

**Table 4.25** Total energy required for fabrication of SMWI

SMWI component	Total Energy (MJ)
Primary and secondary chamber	43300
Outer casing	989
Insulation	2982
Piping system	1015
<b>Total</b>	<b>48286</b>

### 4.3.4 Comparison of environmental impacts of SMWI equipped with different heaters

The method adopted to compare the environmental impacts caused by SMWI-PRB and SMWI-EH in the present study is IMPACT 2002+ LCA method. The assumed efficiency of both the heating devices is 95% since the heat generated from both the PRB<sub>LPG</sub> and Electric heater is almost utilized totally in the primary and secondary chambers. The assessment of SMWI is done taking fabrication and power consumption of SMWI into consideration when equipped with PRB<sub>LPG</sub> and an Electric heater. For the fabrication of SMWI, the parts considered are both the chambers, casing, insulation, piping system, and heating devices.

The resultant environmental impacts of SMWI are shown in **Figs. 4.17** and **4.18** through which it is clear that power consumption devices contribute more to the share of the total environmental impact of SMWI. When SMWI is equipped with heating devices, the environmental impact of the SMWI for fabrication is almost equal for both PRB and EH. However, the environmental impact of fuel consumption by heating devices varies.

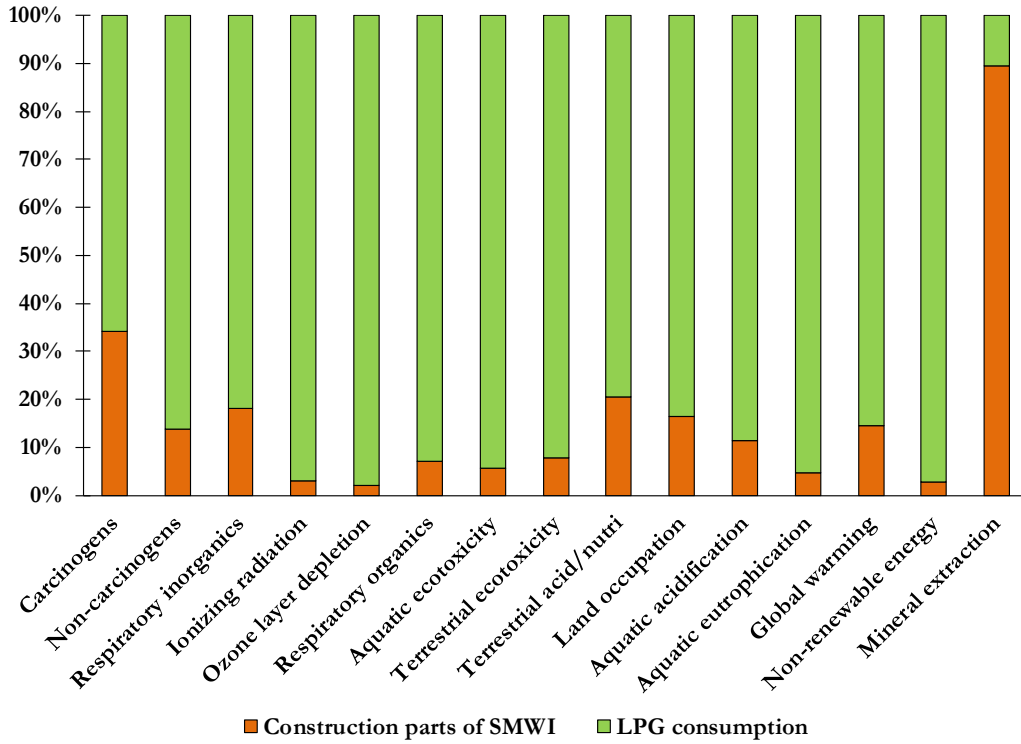


Fig. 4.17 Characterized data on SMWI-PRB (Impact category)

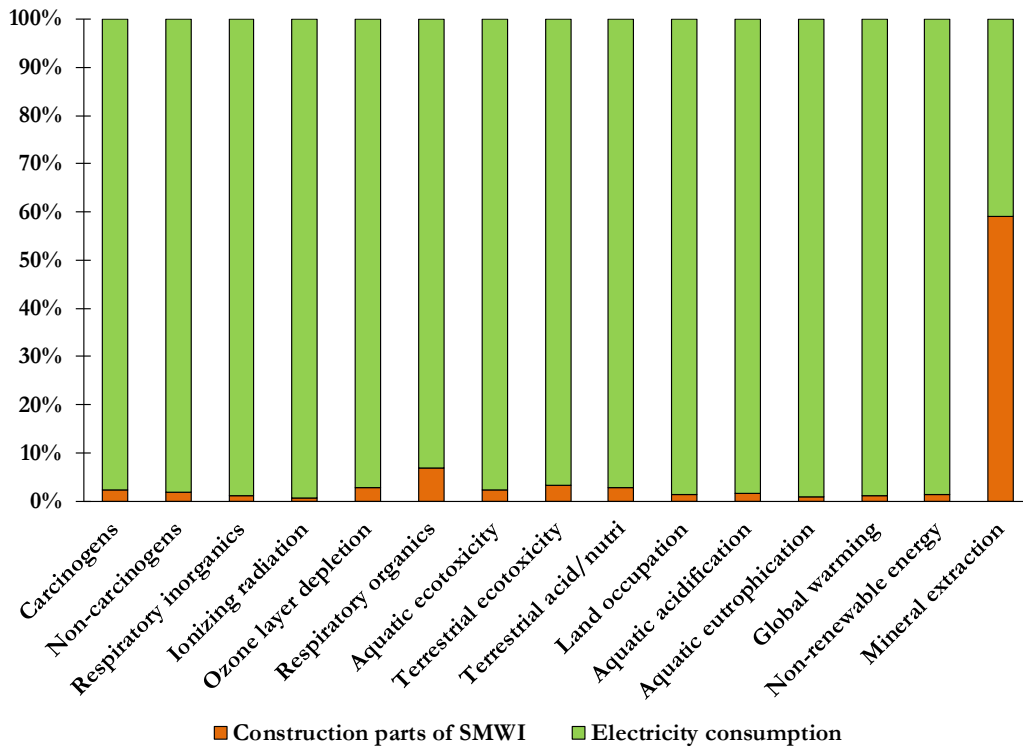
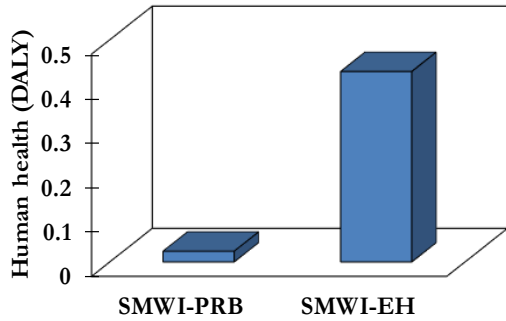


Fig. 4.18 Characterized data on SMWI-EH (Impact category)

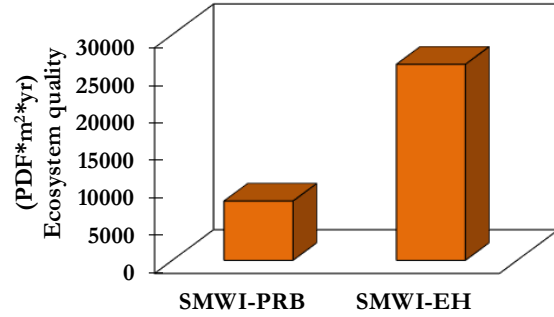
IMPACT 2002+ method has been adopted in the present study to compare the environmental impacts caused by SMWI-PRB and SMWI-EH during both the stages of their fabrication and power consumption. The results indicated that the environmental impacts of SMWI-PRB are significantly lower than SMWI-EH in all the categories. As the environmental impacts for SMWI-EH are assessed considering cradle-to-gate LCA, the electricity generation, its transfer, and consumption are considered for the study. The environmental impact of electricity is higher when compared to LPG consumption in PRB<sub>LPG</sub> though electricity is high-grade energy since the impact during the production of electricity has a huge impact.

**Figs. 4.19, 4.20, 4.21 and 4.22** represent the comparative assessment of the impact caused by SMWI-PRB and SMWI-EH based on the damage category in the IMPACT 2002+ LCA method. It is found that SMWI-PRB has a lower environmental impact than SMWI-EH in all categories. It must be noted that, though electricity is high-grade energy, its environmental impact is higher when compared to LPG consumption in PRB<sub>LPG</sub>. This is because, the impact on the environment is considered from cradle to gate i.e., from the electricity generation stage to the consumption stage via transmission stage. Another observation from the LCA analysis highlights that the environmental impacts from the construction of SMWI are very less compared to the impacts from the energy consumption of the heating devices, which highlights the importance of employing an efficient heating device to curb the overall environmental impact caused by SMWI.

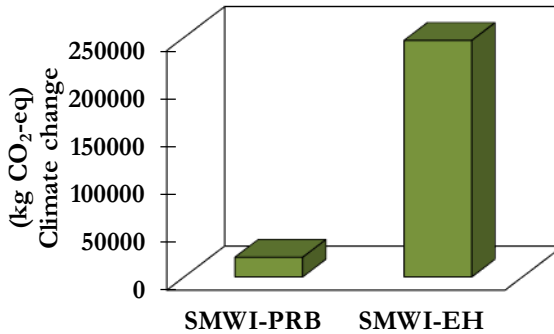
Also, the impact of LPG consumption in PRB<sub>LPG</sub> is found to be less than electricity consumption in Electric heater in all considered categories. For a considered SMWI life of 10 years and 100 kg daily incineration, the impact from the LPG consumption in PRB<sub>LPG</sub> accounts for about 82%, 91%, 85%, and 97% in Human health, Ecosystem quality, Climate change, and Resource utilization damage categories, respectively. In the Primary energy utilization and Climate change category, SMWI-PRB accounts for about 1608895 MJ of energy utilization and 20481.16 kg CO<sub>2</sub>-eq, respectively, whereas in the case of SMWI-EH, the same are 3520570.17 MJ and 246784.07 kg CO<sub>2</sub>-eq, respectively. It is found that SMWI-PRB showed a reduction in the impact of about 94%, 70%, 92% and 54% in Human health, Ecosystem quality, Climate change, and Resource utilization damage categories, respectively. Thus, from the IMPACT 2002+ LCA analysis, it is understood that SMWI-PRB is environmentally superior to SMWI-EH, as the impact of SMWI-PRB in all four damage categories is less compared to SMWI-EH.



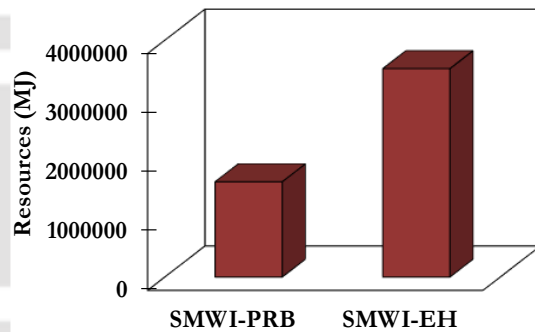
**Fig. 4.19** Impact of SMWI-PRB and SMWI-EH on Human health



**Fig. 4.20** Impact of SMWI-PRB and SMWI-EH on Ecosystem quality



**Fig. 4.21** Impact of SMWI-PRB and SMWI-EH on Climate change



**Fig. 4.22** Primary energy required for SMWI-PRB and SMWI-EH

#### 4.4 Summary

On conducting the LCA of biogas plant construction, it is observed that the digestate leakage has an impact only on the Marine eutrophication category. Through sensitivity analyses, it is identified that the system is susceptible to biogas and digestate leakages. This suggests that reducing biogas and digestate leakages with proper plant maintenance, cleaning of the sludge, and regular check of the plant's working will reduce the plant's environmental impacts. Also, proper implementation of the government programs to promote the generation and utilization of biogas in rural and semi-rural areas of the country, such as MNRE, BPGTP and NNBOMP will ensure the adaptation and wide application of biogas plants all over the country.

- Like all other studies of LCA, the present study also has certain limitations because of the technology considered, geographical location, time and availability of the raw material, LCIA method, type of plant and burners and so on.

- Since most of the material is available at the local market, there may be variations in the environmental impacts of transport related data, if the material is gathered from the far places.
- The vehicle pollution standards considered for the study are Bharat Stage V standards and there would be variation for the later period, hence the study cannot be generalized.

On conducting LCA for fabrication and recycling phase of PRB<sub>LPG</sub> based CB<sub>LPG</sub> based domestic cook-stoves, it is observed that the impact of PRB<sub>LPG</sub> based cook-stove is lesser when compared to CB<sub>LPG</sub> based cook-stoves. Through the assessment results obtained, it can be concluded that PRB<sub>LPG</sub> cook-stove is a better sustainable product than CB<sub>LPG</sub> cook-stove, in terms of both making and recycling, and operation. PRB<sub>LPG</sub> cook-stove can be adopted as a potential replacement for existing CB<sub>LPG</sub> cook-stove as it is better product in terms of environmental sustainability for 1-3 kW LPG power output of domestic cooking applications.

- There is a negative impact value of PRB<sub>LPG</sub> based cook-stove on Ionizing radiation impact of midpoint characterization factors due to the use of refractory aluminium in the fabrication of the burner.
- The cook-stoves fabrication and environmental impact may vary depending on the distance of the availability of the product's raw material.
- Environmental impact of the labour factor could not be considered for the impact assessment as the metabolism rate of each human would be different and it cannot be generalized.

Also, an LCA study has been performed to investigate the approximate environmental impact caused by SMWI-PRB with a capacity of 20 kg/hr. A comparative assessment has been presented to find out the best option among PRB<sub>LPG</sub> and Electric heater as a heating device in the secondary chamber of the SMWI. Results indicated that PRB<sub>LPG</sub> is a better choice when compared to an Electric heater as an auxiliary heating device in the secondary chamber of SMWI. The reduction in the impact on Primary energy utilization damage category is nearly 54% compared to Electric heater. It is also found that more than 82% of the total environmental impacts are due to the operation of heating devices, and this highlights the importance of employing an efficient heating device to curb the overall environmental impact caused by SMWI. Thus, from the present work, it can be concluded that the PRB<sub>LPG</sub> will be a better choice as an auxiliary heating device in SMWI.

In the present work, the LCA approach is limited to the construction of SMWI and the operation of the auxiliary heating devices.

- The efficiency of EH is considered as 95% since there is not much wastage of electricity, which may not be the same in actual conditions.
- The LCA approach is limited to the construction of SMWI and the operation of the auxiliary heating devices.



## Chapter 5

# Techno-economic Assessment of Porous Radiant Burner-based cook-stoves

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The present chapter describes the Techno-economic Assessment (TEA) of applications of Porous Radiant Burner (PRB), emphasizing domestic and commercial cooking applications. Porous Radiant Burner (PRB)-based LPG cook-stoves operating in domestic households and eateries and restaurants have been assessed for their economic performance and viability. In this chapter, the conceptual design for the functioning of the LPG-based cook-stoves has been discussed. Process flow study has been performed primarily to understand the technological process involved in the PRB and also to estimate the cost of manufacturing. The cost estimation has been made by gathering the materials required to match the conceptual design and the direct and indirect costs have been calculated. The Prime Cost has been calculated by taking the direct labor, direct material, and other direct expenses involved in the manufacturing of the product. And also, the factory and the work costs have been calculated taking other fixed costs and variable costs into consideration. The cost-benefit analysis has been done through Net Present Value (NPV), and Internal Rate of Return (IRR) for the manufacturing unit with a capacity of 250 units per day. The Pay Back Period (PBP) for both the consumers and manufacturing unit has been estimated. Also, sensitivity analyses has been performed considering the production capacity of 50, 250, and 500 cook-stoves per day to compare the accuracy and the viability of PRB-based cook-stoves.

### 5.1 Need for conducting TEA on PRB-based cook-stoves

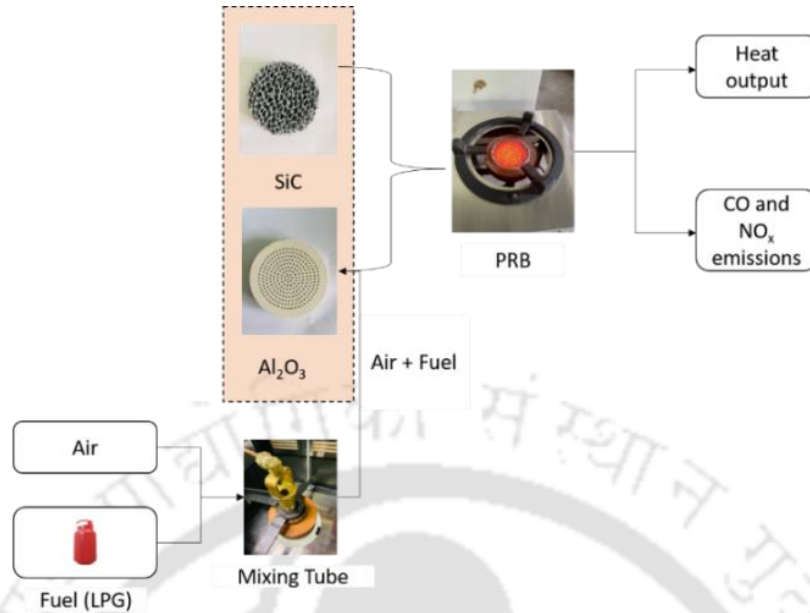
Testing the environmental sustainability of a product alone is not sufficient for it to be considered a sustainable product. A product has to be tested for its economic and social sustainability too, when it is an energy-efficient and environment-friendly product which can be done by a Techno-economic assessment (TEA) test. TEA tests the economic feasibility of a technology or a product and is significant especially when the viability of a new product or a technology has to be estimated and when there is no ready information available on the industries of a similar technology or product. However, there is no study performed on the TEA of PRB except for the studies conducted

on the PRB-based stove operated with waste cooking oil and LCA and TEA of LPG operated PRB cook-stove for 5-10 kW (Kaushik and Muthukumar, 2018, 2020). The results indicated that PRB is economically feasible when operated with waste cooking oil; and also environmentally and economically feasible even with 5-10 kW LPG. These economic assessments performed for the technology of PRB were focused on the performance of the PRB when used with different fuels. But, no TEA of PRB was performed to assess the economic feasibility of PRB-based cook-stoves working with 1-3 kW and 5-7 kW; when the industry has to be set up for the mass production of PRB-based cook-stoves. Studies are to be conducted to verify PRB's financial viability, and also the returns the consumers are going to get on their investment in PRB-based 1-3 kW and 5-7 kW cook-stoves. And so, there is a need to conduct an economic assessment before commercializing the present technology and to minimize the cost wherever possible and reduce the financial risks (Abdelhady, 2021). In the present study, TEA of mass production PRB-based cook-stoves of 1-3 kW and 5-7 kW is performed. The present TEA not only estimates the returns and cost of production of PRB-based cook-stoves, but it also takes into consideration the socio-TEA of consumers focusing on their returns, savings, and PBP for the investment made by the consumer on the PRB-based cook-stove.

## 5.2 Process flow of the cook-stoves

Designing the concept and procedural flow are developed into the Process Flow Diagram (PFD). A PFD is a diagrammatic representation of the process, which is normally drawn in a stylized pictorial form using international standards symbols (Shah et al., 2016).

**Fig. 5.1** shows the PFD of the PRB-based cook-stove. The operational procedure of the PRB-based cook-stove as evident from **Fig. 5.1** is that the air and fuel mixture is given as input into the mixing tube, which passes to the preheating zone of the PRB. The preheating zone of PRB is made up of Alumina ( $\text{Al}_2\text{O}_3$ ). The combustion takes place in the combustion zone of PRB which is made up of Silicon Carbide (SiC). When the combustion is in progress, heat is given as output along with  $\text{CO}_2$ , CO, and  $\text{NO}_x$  emissions.



**Fig. 5.1** Process Flow Diagram of PRB-based cook-stove

### 5.3 Cost estimation and calculation of PRB-based cook-stoves

In the present study, TEA is conducted to estimate the prime cost, works cost, administration cost, production cost and the cost of sale incurred for a plant that manufactures 250 PRBs of 1-3 kW and 5-7 kW on daily basis.

#### 5.3.1 Direct Costs

In the present study, the direct costs are calculated by considering raw materials required to manufacture 250 units of PRBs of 1-3 kW and 5-7 kW capacity for each day. The materials required for the manufacturing of the PRB are SiC, Al<sub>2</sub>O<sub>3</sub>, Refractory Alumina casing, Steel frame, etc. Also, the direct costs incurred for PRB-based cook-stove manufacturing includes fitting accessories and the transport to carry the raw material to the manufacturing unit. The manufacturing costs of PRB are represented by  $MC_{PRB}$ .

Man-power engaged for the making of PRB is also considered as the direct cost incurred for the making of PRB-based cook-stove, which is indicated as  $MP_{PRB}$ . As the cook-stove manufacturing is not a complicated process and does not require high-end machinery, the man-power requirement is only limited to five staff levels and the direct costs incurred for the man-power are their wages. The prime costs are represented as  $PrC_{PRB}$ ,

Where

$$PrC_{PRB} = MC_{PRB} + MP_{PRB} \quad (5.1)$$

### 5.3.2 Factory Costs

Factory costs of the PRB-based cook-stove ( $FC_{PRB}$ ) are indirect costs that include rent of the unit, insurance charges, factory vehicle, expenses incurred for the cleaning and maintenance of the unit.

### 5.3.3 Administrative Costs

The administrative costs for the manufacturing unit of the PRB-based cook-stove ( $AC_{PRB}$ ) are majorly for advertising.

### 5.3.4 Production Costs

The production cost is the total cost of all the direct and indirect costs. Production costs of the PRB-based cook-stove ( $PC_{PRB}$ ) are given by

$$PC_{PRB} = PrC_{PRB} + FC_{PRB} + AC_{PRB} \quad (5.2)$$

### 5.3.5 Sales Price

The sales price of PRB-based cook-stove ( $SP_{PRB}$ ) will analyze the ability of the manufacturing unit to design, procure, source, and manufacture the cook-stoves at an affordable and reasonable price for the end-user. The sales price is given by

$$SP_{PRB} = PC_{PRB} + profit \quad (5.3)$$

where  $SP_{PRB}$  is the selling price of PRB

Considering a 50% profit margin, the sales price of PRB-based cook-stove cost is proposed.

## 5.4 Economic Analysis of PRB-based cook-stoves

NPV, IRR, and PBP analysis methods have been considered to test the economic viability of manufacturing PRB-based cook-stoves of 1-3 kW and 5-7 kW capacity that are operated with LPG fuel input. These analyses are used to make a decision on investing in a process or product or service if viable or rejecting the investment in it (Ben-Horin and Kroll, 2017).

### 5.4.1 Net Present Value (NPV)

Net cashflows of PRB ( $NCF_{PRB}$ ) are estimated for six years and using the trial-and-error method discounting factor to compute present values of estimated cash flows of PRB are determined. To find Net present value of PRB, Initial investment is to be deducted from the present value of cash flows at 50% (The discounting factor derived from trial-and-error method). Then, the initial investment made for the manufacturing of 250 PRB-based cook-stoves is deducted from  $DCF_{PRB}$  to obtain  $NPV_{PRB}$  value.  $NPV_{PRB}$  is given by

$$NPV_{PRB} = \sum_{i=1}^6 (NCF_{PRB} * DCF_{PRB}) - Initial\ investment \quad (5.4)$$

Where

$NCF_{PRB}$  = Net cashflows estimated for manufacturing PRB;

$DCF_{PRB}$  = Discounting factor i.e., 50% in this case

From the computation it is evident that the maximum positive  $NPV_{PRB}$  is obtained at  $DCF_{PRB}$  of 50% for both 1-3 kW and 5-7 kW capacity PRB cook-stoves with the cash flows of 82321601 INR for 1-3 kW and 10171168 INR for 5-7 kW, respectively.

### 5.4.2 Internal Rate of Return (IRR)

Internal Rate of Return is a financial analysis metric that is used to estimate the profitability of the investments made in a project. IRR of the PRB-based cook-stoves ( $IRR_{PRB}$ ) present is calculated using the forward method after calculating  $NPV_{PRB}$ . The value of  $IRR_{PRB}$  is obtained by,

$IRR_{PRB} =$

Lower discount rate +  $\frac{NPV\ at\ Lower\ discount\ rate}{NPV\ at\ Lower\ discount\ rate - NPV\ at\ higher\ discount\ rate} * (Higher\ discount\ rate - Lower\ discount\ rate)$

From trail-and-error method adopted for computing NPV it is observed that the maximum positive Net present value of PRB is observed at 50% (Lower discounting factor) and minimum negative

net present value is observed at 60% (Highest discounting factor), thus the NPV at 50% and 60% are used in computation of IRR for PRB.

The value of  $IRR_{PRB}$  obtained is 52.1 % for 1-3 kW cook-stoves and 51.4 % for 5-7 kW cook-stoves. It may be noted that for any initial startup, an IRR of 15% and above is considered as highly beneficial in investing in that project.

### 5.5 Benefit to the consumer

In the present study, the benefit to the consumer of adapting to PRB-based cook-stoves is obtained by estimating the returns a consumer will get by investing in the PRB-based cook-stove. The returns are estimated by calculating the payback period of the investment on the PRB-based cook-stove ( $PBP_{PRB}$ ). Also, the cumulative returns are estimated at the end of the life of the stove. In the present study, 10 years of life period is considered.  $PBP_{PRB}$  is obtained by,

$$PBP_{PRB} = (\text{No. of years before the investment recovery}) + (\text{Cost that is not recovered at the start of the year}) / \text{Cashflow during the year}$$

### 5.6 Results of the Assessment

#### 5.6.1 Consumption by PRB-based cook-stoves

The consumption of LPG of a PRB-based cook-stove is compared with that of a CB-based cook-stove of the same capacity through the field study.

**Table 5.1** LPG consumption for PRB-based and CB-based domestic cook-stoves

Factors	Units
Total LPG cylinders consumed annually with CB-based cook-stove	10
Consumption of LPG in kg annually with CB-based cook-stove	142
Total cylinders annually consumed with PRB-based cook-stove	6
Consumption of LPG in kg annually with PRB-based cook-stove	85.2
Fuel saved in kg annually with PRB-based cook-stove	56.8
Total cylinders saved annually with PRB-based cook-stove	4
Cost spent on LPG cylinders annually with CB-based cook-stove in INR	10000
Cost spent on LPG cylinders annually with PRB-based cook-stove in INR	6000
Total cost saved annually with PRB-based cook-stove in INR	4000

The study for 1-3 kW cook-stoves is conducted with respect to the domestic households. Whereas the study for 5-7 kW cook-stoves is conducted in small-scale eateries, medium-scale eateries and large-scale eateries. The capacity of the LPG cylinders considered is 14.2 and 19 kg for 1-3 kW domestic cook-stoves and 5-7 kW commercial cook-stoves, respectively. The operation of the cook-stoves for 1-3 kW is considered annually (daily operation) and for 5-7 kW is considered for 6 days a week. **Table 5.1** shows the details of the consumption of LPG cylinders for the cook-stoves of 1-3 kW capacity with CB and PRB.

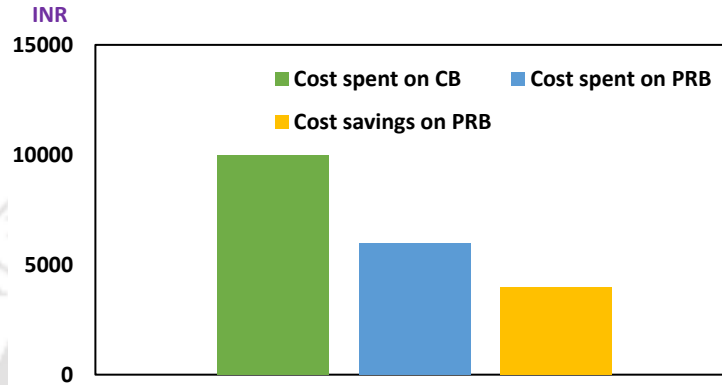
**Table 5.2** shows the details of the consumption of LPG cylinders for commercial cook-stoves of 5-7 kW capacity with CB and PRB. The values in **Tables 5.1** and **5.2** show that 1-3 kW cook-stoves with PRB save up to 40% and 5-7 kW cook-stoves with PRB save up to 30% respectively, on LPG when compared to those cook-stoves with CB of the same capacity.

**Table 5.2** LPG consumption for PRB-based and CB-based commercial cook-stoves

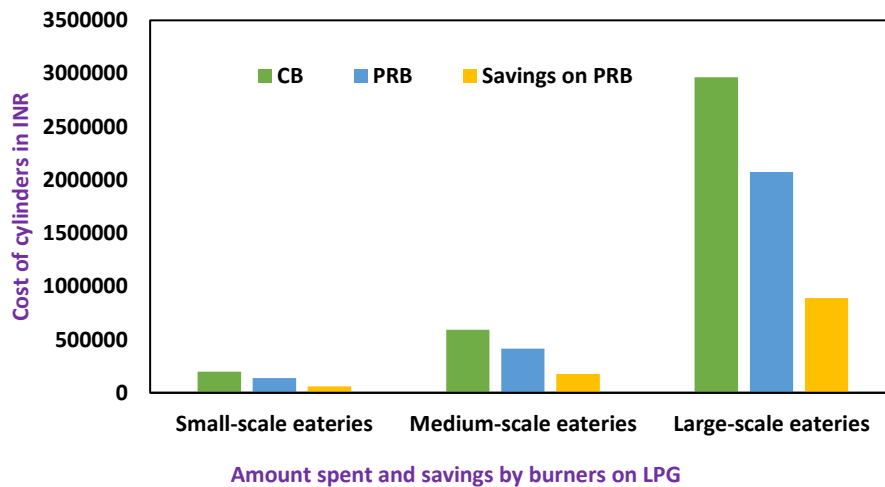
Factors	Small-scale eateries	Medium-scale eateries	Large-scale eateries
Consumption of LPG cylinders with CB-based cook-stove	2 for a week	1 each day	5 each day
Total cylinders in a year with CB-based cook-stove (312 days)	104	312	1560
Consumption of LPG in kg with CB-based cook-stove (312 days)	1976	5928	29640
Total cylinders in a year with PRB-based cook-stove (312 days)	73	218	1092
Consumption of LPG in kg with PRB-based cook-stove (312 days)	1387	4142	20748
Fuel saved in kg in a year with PRB-based cook-stove (312 days)	589	1786	8892
Total cylinders saved in a year with PRB-based cook-stove (312 days)	31	94	468

### 5.6.2 Cost savings on LPG by PRB-based cook-stoves

Cost savings play a major role in deciding the economic feasibility of a product or a service. The cost savings on the LPG fuel by 1-3 kW domestic LPG cook-stoves is shown in **Fig. 5.2**; whereas the cost savings of the small-scale, medium-scale and large-scale eateries when adapted to PRB-based cook-stoves of 5-7 kW is shown in **Fig. 5.3**.



**Fig. 5.2** Annual cost spent on LPG by 1-3 kW cook-stoves and savings of PRB



**Fig. 5.3** Annual cost spent on LPG by 5-7 kW cook-stoves and savings of PRB

It is evident from **Fig. 5.2** that the total fuel cost spent by the households on domestic cook-stoves which operate on 14 kg LPG cylinders annually in India is approximately 10000 INR while using CB-based cook-stoves. By adapting to PRB-based cook-stoves the cost can be reduced to 6000 INR per annum with 40% reduction in fuel consumption and henceforth, cost savings.

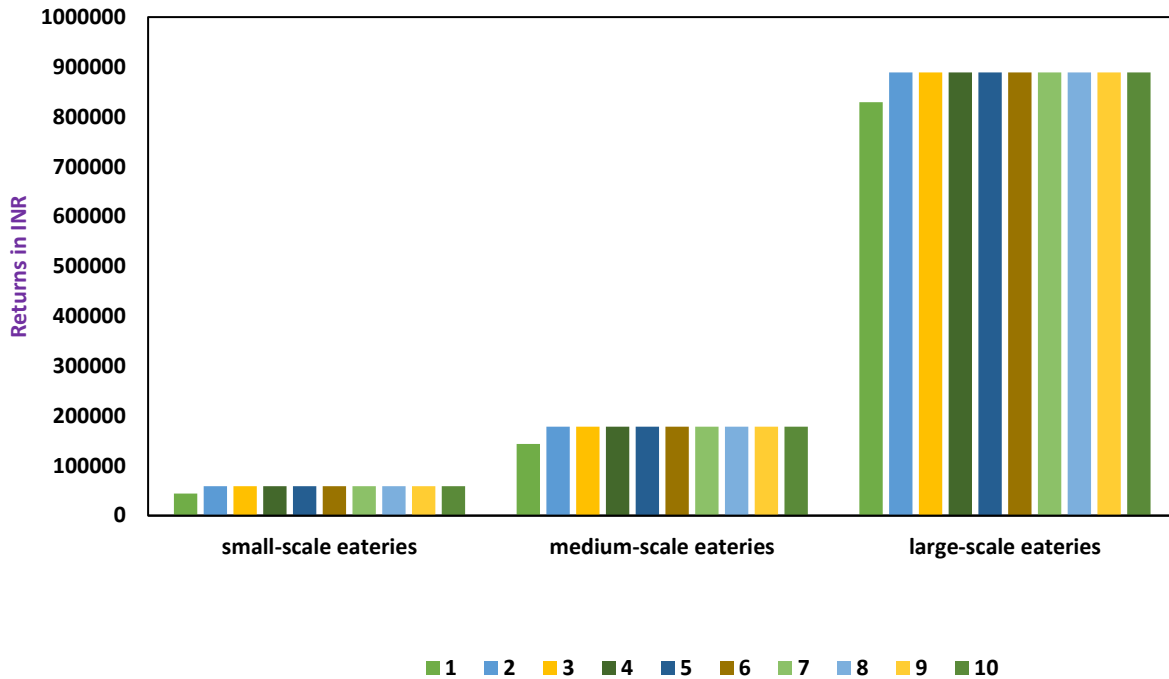
It is understood from **Fig. 5.3** that the total fuel cost spent by the small-scale eateries on LPG annually in India is approximately 197600 INR while using CB-based cook-stoves. The fuel cost for medium-scale and large-scale eateries on LPG is approximately 592800 INR and 2964000 INR, respectively for CB-based cook-stoves of 5-7 kW. Whereas for PRB-based cook-stoves, the annual cost spent on LPG by the small-scale, medium-scale and large-scale eateries is approximately 138700 INR, 414200 INR and 2074800 INR, respectively. This indicates that there is a 30% saving on the fuel cost spent on 19 kg LPG cylinders (assuming each LPG cylinder costs 1900 INR) when PRB-based cook-stoves are used (Kaushik and Muthukumar, 2020).

### ***5.6.3 Returns at the end of life of PRB-based cook-stove***

The returns obtained on the investment of any product or service give assurance to the end-user or the consumer that the investment in the product or process is optimal or not. The cost of the PRB-based cook-stoves of 1-3 kW and 5-7 kW operating on LPG is estimated approximately to be 4400 INR and 5000 INR respectively, after performing the assessment. For PRB-based cook-stoves of 5-7 kW, a small-scale eatery will operate with 3 cook-stoves and the cost incurred will be 15000 INR. Whereas for the medium-scale and large-scale eateries, the requirement of the cook-stoves will be 7 and 12, respectively. Hence the cost incurred for the medium-scale and large-scale eateries on the cook-stoves will be 35000 INR and 60000 INR, respectively. This cost is  $SP_{PRB}$ , obtained considering a 50% profit margin on  $PC_{PRB}$  for the cook-stoves.

With this cost incurred on PRB-based cook-stoves, the end-users maximum PBP of the PRB-based cook-stove ( $PBP_{PRB}$ ) is estimated as 1.1 year for 1-3 kW domestic cook-stoves and for 5-7 kW commercial cook-stoves used in small scale eateries, the PBP is 0.25 year. For the medium-scale and large-scale eateries the PBP is 0.2 years and 0.07 years which is a remarkable  $PBP_{PRB}$ . Hence, it assures that PRB-based cook-stoves of both 1-3 kW and 5-7 kW capacities that operate on LPG fuel are commercially feasible and beneficial products. Also, the cumulative returns for the consumer at the end of the life of a PRB-based cook-stove who invest on 5-7 kW cook-stoves is 574000 INR for small-scale eateries, 1751000 INR for medium-scale eateries and 8832000 INR for large-scale eateries in total for 10 years life of the cook-stoves based on the fuel-savings as compared to CB.

The returns estimated for small, medium and large-scale eateries at the end of each year is represented in **Fig. 5.4**. It is evident that the investment in a 5-7 kW PRB-based cook-stoves made by the consumer will be gained back in less than twelve weeks for a small-scale eateries; and for medium-scale and large-scale eateries, the investment will be gained back in less than nine weeks and four weeks, respectively.



**Fig. 5.4** Returns on the investment of 5-7 kW cook-stoves by small, medium and large-scale eateries

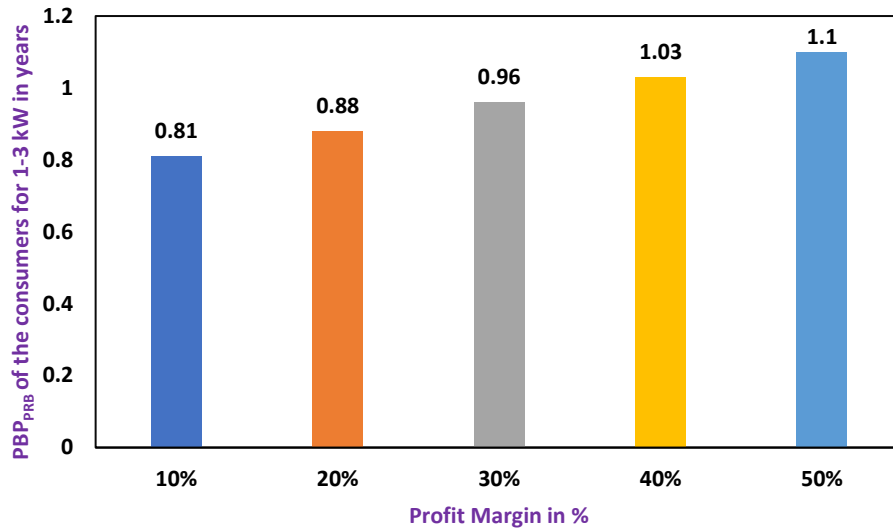
## 5.7 Sensitivity Analyses

A sensitivity analysis is performed to analyze the economic feasibility of PRB taking into consideration the possibilities of profit margins of the manufacturing units,  $PBP_{PRB}$  of the end-user at different costs that are incurred for the purchase of the 1-3 kW and 5 -7 kW PRB-based cook-stoves for domestic cooking and commercial cooking, respectively.

### 5.7.1 Profit margin of the manufacturing unit

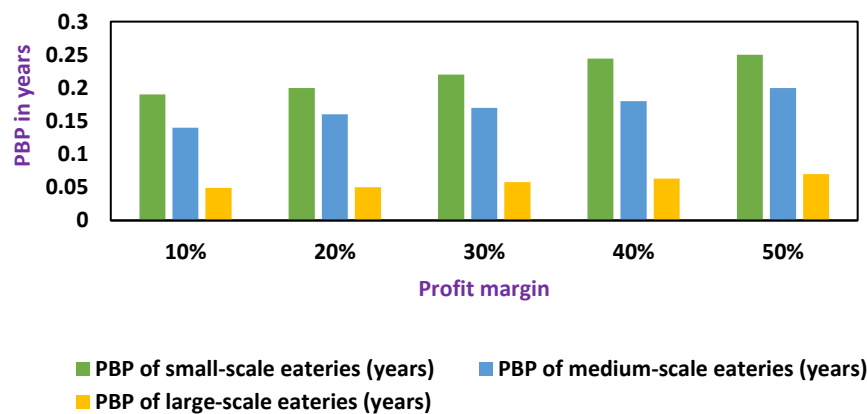
The sensitivity analysis is done for the estimation of different  $PBP_{PRB}$  of the consumers at different profit margins of the manufacturing unit. The different profit margins considered for the sensitivity

analysis are 10%, 20%, 30%, 40% and 50%. The respective  $PBP_{PRB}$  obtained for the profit margins are shown in **Fig. 5.5** for 1-3 kW cook-stoves and in **Fig. 5.6** for 5-7 kW cook-stoves.



**Fig. 5.5**  $PBP_{PRB}$  of 1-3 kW PRB-based cook-stoves at different profit margins of manufacturing unit

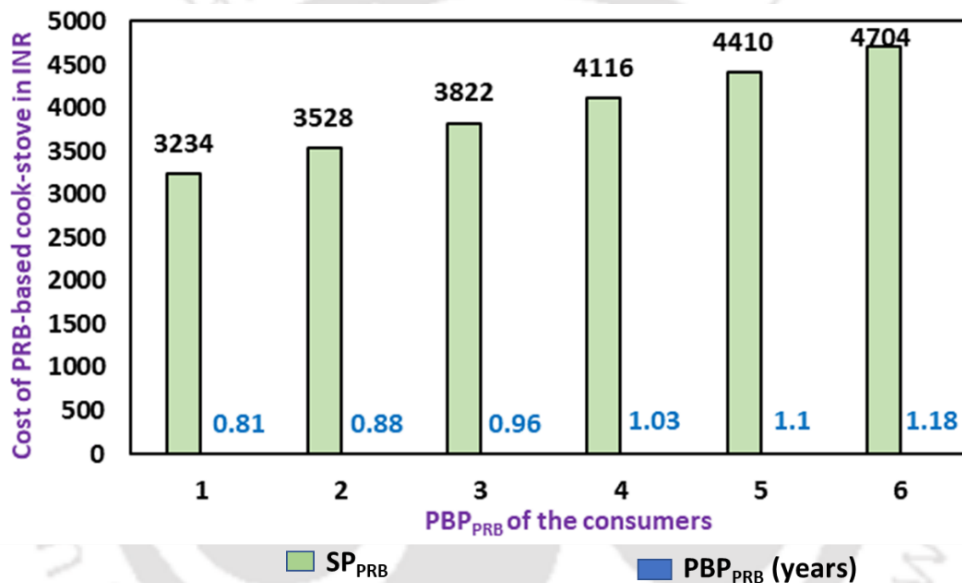
From **Fig. 5.5**, it can be understood that the  $PBP_{PRB}$  is in co-relation with the profit percentage of the manufacturing unit. The  $PBP_{PRB}$  of 1-3 kW PRB-based cook-stove is less than 1.1 years even for up to a profit margin of 50%. The  $PBP_{PRB}$  of 5-7 kW for the eateries at different profit margins of the manufacturing unit is represented in **Fig. 5.6**. However, for 5-7 kW PRB-based cook-stoves, at small-scale eateries there is a requirement of 3 cook-stoves and for medium and large-scale eateries, there is a requirement of 7 and 12 cook-stoves, respectively.



**Fig. 5.6**  $PBP_{PRB}$  of 5-7 kW PRB-based cook-stoves at different profit margins of manufacturing unit

### 5.7.2 Cost of the cook-stoves

Sensitivity analysis is done to identify different  $PBP_{PRB}$  for the end-user at different costs of the cook-stoves of 1-3 kW and 5-7 kW capacities. As the  $PBP_{PRB}$  plays a key role in determining the economic viability of a product, this data can help in fixing the  $SP_{PRB}$ , so that it will be beneficial for both the consumer and the manufacturing unit. **Fig 5.7** shows the details of different  $PBP_{PRB}$  at different  $SP_{PRB}$  for 1-3 kW domestic cook-stoves and **Fig. 5.8** shows the details of different  $PBP_{PRB}$  at 5-7 kW commercial cook-stoves for small, medium and large-scale eateries at different  $SP_{PRB}$ .



**Fig. 5.7**  $PBP_{PRB}$  of 1-3 kW PRB-based cook-stoves at different  $SP_{PRB}$

A product is considered to be economically feasible for the consumer or the end-user if the  $PBP$  of that product is less than two years. Figs. 5.7 and 5.8 show that even when the  $SP_{PRB}$  of the stove is raised by half of its original  $SP_{PRB}$ , the  $PBP_{PRB}$  is much lesser which makes the PRB-based cook-stoves of 1-3 kW and 5-7 kW economically feasible for the end-user.

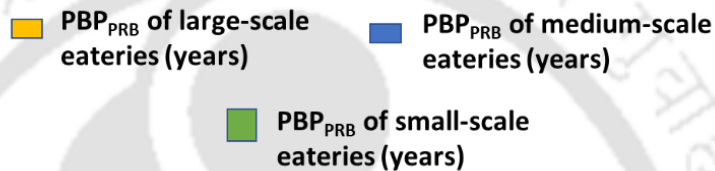
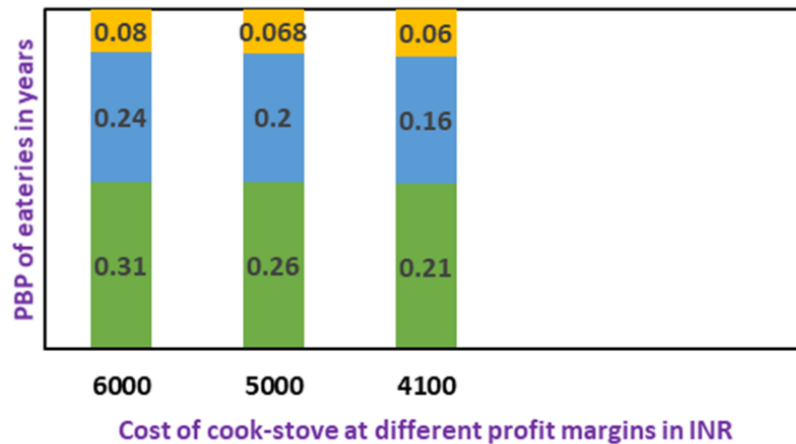
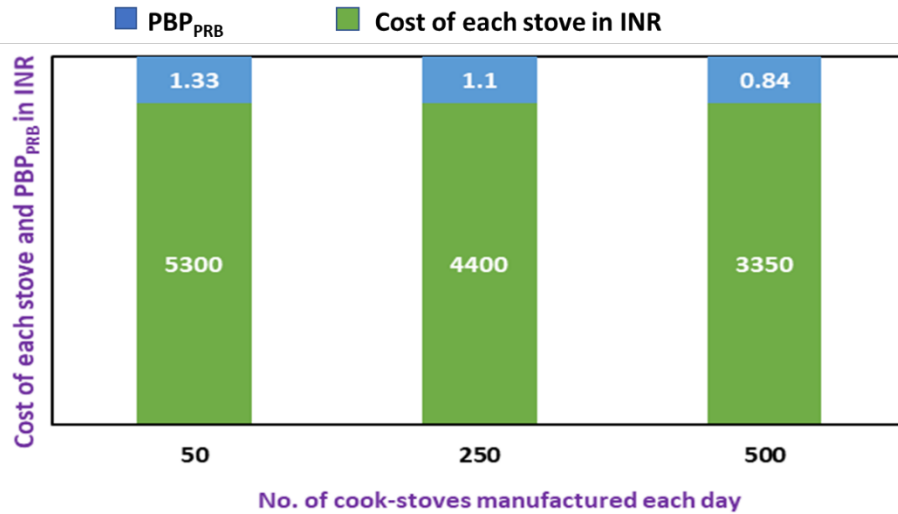


Fig. 5.8 PBP<sub>PRB</sub> of 5-7 kW PRB-based cook-stoves at different SP<sub>PRB</sub>

### 5.7.3 Effect of manufacturing capacity on the PBP<sub>PRB</sub> of the consumers

Sensitivity analysis is conducted to calculate the PBP<sub>PRB</sub> for the end-user when the manufacturing unit's capacity is varied. For a manufacturing unit that has the capacity of manufacturing 50 units of PRB-based cook-stove, the SP<sub>PRB</sub> of each cook-stove even with a 50% margin is estimated to be 5300 INR for 1-3 kW capacity and 6000 INR for 5-7 kW capacity. Whereas for the manufacturing units that have the capacities of manufacturing 250 and 500 units of PRB-based cook-stoves, the SP<sub>PRB</sub> of each cook-stove is estimated to be 4400 INR and 3350 INR for 1-3 kW and 5000 INR and 4100 INR for 5-7 kW, respectively. At these SP<sub>PRB</sub>, the PBP<sub>PRB</sub> at different plant unit capacities is calculated. Fig. 5.9 shows the PBP<sub>PRB</sub> of the consumers at different manufacturing capacities of the plant and the respective SP<sub>PRB</sub> of the plants with different manufacturing capacities for 1-3 kW domestic cook-stoves.



**Fig. 5.9** PBP<sub>PRB</sub> and SP<sub>PRB</sub> of 1-3 kW PRB-based cook-stoves for different plant capacities

**Table 5.3** PBP<sub>PRB</sub> and SP<sub>PRB</sub> of 5-7 kW PRB-based cook-stoves for different plant capacities

Plant capacity (No. of units manufactured per day)	SP <sub>PRB</sub> (INR)	PBP <sub>PRB</sub> of small-scale eateries (years)	PBP <sub>PRB</sub> of medium-scale eateries (years)	PBP <sub>PRB</sub> of large-scale eateries (years)
50	6000	0.31	0.24	0.08
250	5000	0.26	0.2	0.068
500	4100	0.21	0.16	0.06

From **Fig. 5.9** and **Table 5.3**, it can be understood that both the SP<sub>PRB</sub> and PBP<sub>PRB</sub> for the end-user will be reduced if the manufacturing plant increases the capacity of its production. The PBP<sub>PRB</sub> for the end-user if the plant manufactures 500 units per day is estimated to be 0.84 years for 1-3 kW domestic stoves and 0.21, 0.16, and 0.06 years respectively for small, medium and large-scale eateries for 5-7 kW for commercial cook-stoves. Whereas the PBP<sub>PRB</sub>, when the plant manufactures 50 units and 250 units are estimated to be 1.33 and 1.1 years for 1-3 kW domestic cook-stoves and 0.31, 0.24 and 0.08 years for small, medium and large-scale eateries respectively, for 50 units capacity for 5-7 kW cook-stoves. For 250 units capacity of 5-7 kW cook-stoves, the PBP<sub>PRB</sub> for small, medium and large-scale eateries is 0.26, 0.2 and 0.068 years respectively. Thus, it can be concluded that a plant with a higher manufacturing capacity proves beneficial for the end-users as it results in lower SP<sub>PRB</sub> and PBP<sub>PRB</sub>.

## 5.8 Summary

After conducting the TEA of PRB-based cook-stoves of 1-3 kW and 5-7 kW capacities operating with LPG fuel, the results indicate that PRB-based cook-stoves are economically feasible products. The PFD of a PRB-based cook-stove is also not a complicated process and PRB is assembled with easily available materials. Also, as the assembly does not require any complicated procedures and heavy machinery, the direct costs incurred for the material procurement and the manpower is also minimal. With the present TEA, PRB-based cook-stoves are considered highly efficient and economically feasible products as they provide high IRR along with huge savings on fuel, with short  $PBP_{PRB}$  and high returns.

- Only the PBP is calculated to test the economic sustainability of PRB, which will ignore the shadow prices.
- External environmental factors like market demand have not been calculated.
- Socio-economic factors of the customers/consumers are not considered and the respective price subsidies are not considered for fixing up the cost and manufacturing costs only are taken into consideration.

## Chapter 6

# Proposed Organizational Design for Mass Production of Porous Radiant Burner-based Cook-stoves

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In the present chapter, a business model has been proposed for an entity to start the manufacturing of PRB cook-stoves. A business model portrays the value a product proposes to the end user. Environmental assessment and cost-benefit analysis have also been considered for proposing the business model. Assessing the business model, an organogram is proposed with more of a mechanistic structure as well as a slight tinge of organic structure; thereby work-flow has been analyzed. A user study has been conducted for the production department based on the workflow analysis for various roles and positions and based on this, competency indicators have been proposed for various positions of the production department.

### 6.1 Need for the business model for PRB-based cook-stoves manufacturing

As natural resources are depleting at a faster rate across the globe, sustainability has gained the utmost attention in recent times. Also, environmental pollution is piling up with consumerism and use of advanced technology. With the introduction of agendas like Millennium Development Goals (MDGs) and Sustainable Development Goals (SDGs), the entire world is moving towards realizing a sustainable world. In this era of sustainability, the main focus is to bring sustainable products to public usage through emerging technologies and technological innovations. Considering the three pillars of sustainability viz., environmental, economic and social sustainability, a sustainability product called Porous Radiant Burner (PRB) suitable for Indian cooking conditions has been developed (Kaushik and Muthukumar, 2020). When brought into the market, sustainable products like PRB promote the core values of all the stakeholders of the business. The main aim of any product should be to generate value for society and provide utility to the customer or consumer (Meier et al., 2010). Any product purchased by a consumer or customer is not bought for the product, but for what the product is meant for, and PRB is no exception to this. Moreover, PRB has a sustainable advantage as the existing competitors cannot imitate the technology (Kuncoro and Suriani, 2018). Though PRB has a competitive advantage technology-wise, the transfer of

technology into the market and the commercialization of the product remains a tedious exertion (Bröring et al., 2020). This can be achieved by developing an appropriate business model.

Hence in this chapter, a business model has been developed to extend the value of PRB from environmental and economic values to social and sustainable values. After the business model has been developed, an organogram is designed, and accordingly, a competency mapping structure is proposed for the production department. The competency indicators were developed after conducting an expert study for different levels of the production department and summarized in this chapter to act as a reference for any organization to start with PRB cook-stove manufacturing.

## **6.2 Business Model for value proposition**

The business model in the present study is developed by taking the business canvas model into reference (Parry, 2014). The business model canvas majorly comprises of three sections viz., the value the entity provides to its customers, the procurement of the necessities to provide those values and the customer base and how to reach it. In the present study, along with these three sections, two more sections have been added of which one represents the environmental and societal benefits the PRB cook-stoves provide and the other represents the economic benefits PRB cook-stoves provide to the consumers and manufacturers.

## **6.3 Organogram / Organizational Design**

In the present study, organizational design is proposed taking various aspects of the business model into consideration to provide the best output in the due course of the manufacturing of PRB cook-stoves. In the organogram, both the line and staff functions have been analyzed thoroughly and represented.

## **6.4 Value chain analysis and Competency Mapping**

In the present study value chain is analyzed for the work procedure of manufacturing PRB cook-stoves. After the analysis is done, the focus was given to the production department and competency indicators have been developed after consulting with the respective expert's at different levels of the department. After conducting the literature survey, all the skills have been analyzed and categorized into four broad skill sets at different levels of the organizations.

The different skill set types indicate interpersonal skills, conceptual skills, diagnostic skills, and technical skills (Griffin & Moorhead, 2010). Depending on these broad skill set types, sub-skill sets have been categorized for various positions in the organization and categorized accordingly, for the production department. After the categorization of the skill-set, questionnaires have been framed to understand the PRB cook-stoves production department's working procedure. Telephonic interviews have been conducted and depending on the results, competency indicators have been developed for mapping.

Competency, similar to the business model does not have a specified definition. According to Holtkamp, Jokinen, and Pawlowski (2015), competence is the collection of skills, abilities, and attitudes to provide a solution to a problem in a context. Competencies are related to human resource management and education at the individual level (Delamare et al., 2007). Whereas competencies are focused from the resource-based view, at the enterprise perspective (Wernerfelt, 1984). In the present study, competencies of the production department have been considered for various positions and roles of the production department and they have been considered at the individual level to start with. However, few competencies at the enterprise level have already been considered while designing the business model.

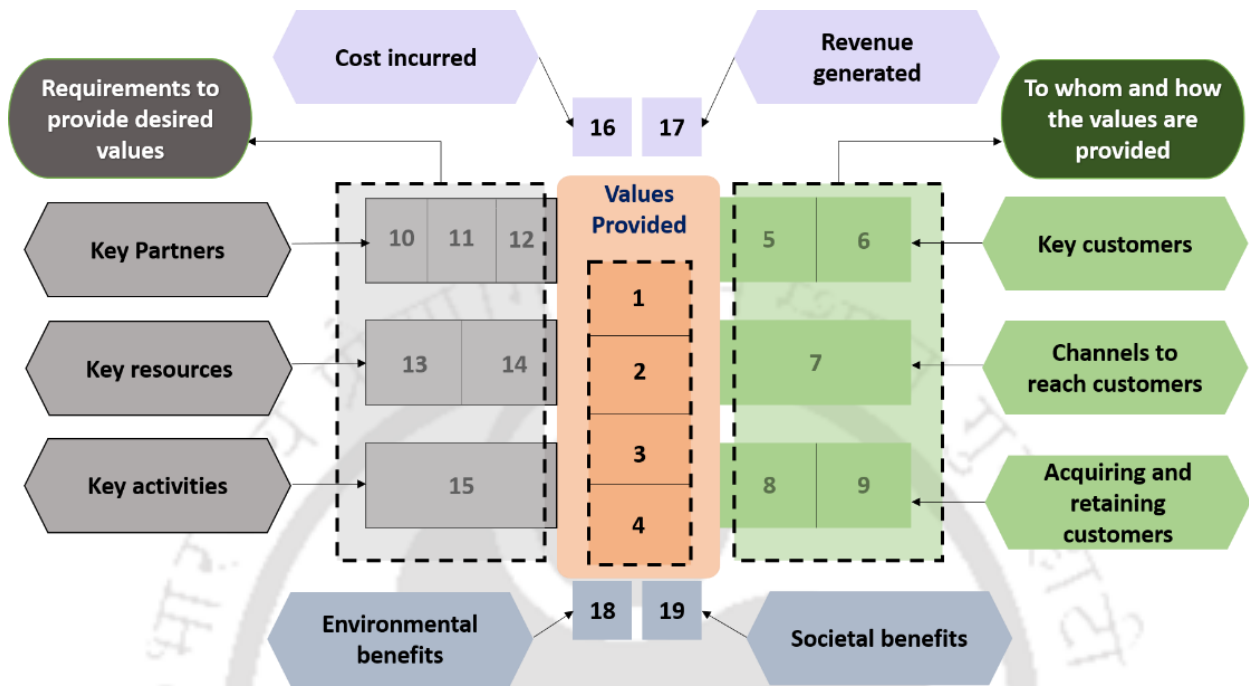
## **6.5 Results of Proposition**

### ***6.5.1 Proposed Business Model***

The resultant business model is indicated as a butterfly model in which the central block and first four sections represent the values provided by the PRB cook-stoves to the respective consumers. The same is represented in **Fig. 6.1**. The right block i.e., sections 5 to 9 represent the customer base as such to whom the values are provided, how they are provided and the means or channels to reach them. Whereas the left block from sections 10 to 15 represents the requirements or the inputs needed to provide the desired values to the targeted consumer base.

The top block of the business model which is represented by sections 16 and 17 indicates the costs incurred for the manufacturing of the PRB cook-stoves and the revenue generated by them through the fuel savings. This has been analyzed by conducting a Techno-economic Analysis of PRB cook-stoves and the results indicated high returns and huge savings on the fuel. The bottom and last two blocks of the business model viz., 18 and 19 represent the environmental and social benefits the

PRB cook-stoves provide, which have been analyzed by conducting a Life Cycle Assessment of the PRB cook-stoves of various fuel input capacities.

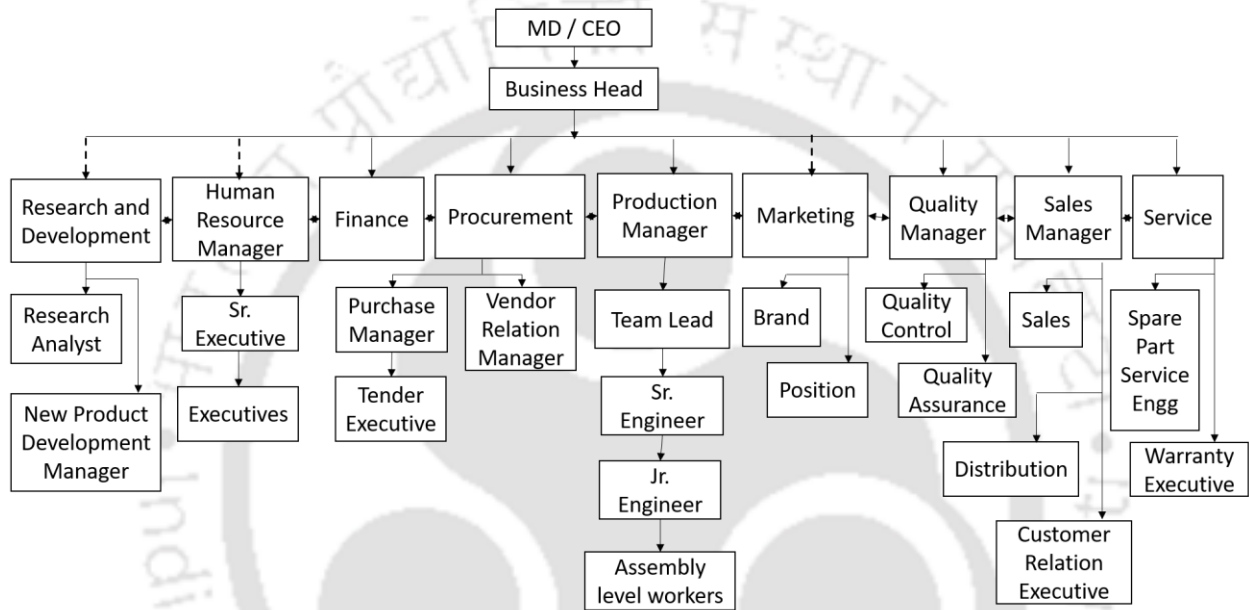


**Fig. 6.1** Proposed business model for an entity to mass produce PRB cook-stoves

1. To provide PRB based cook-stove that contributes up to 42% on LPG saving
2. To provide PRB based cook-stoves to promote clean cooking
3. To provide PRB based cook-stove for lesser CO and NOx emissions
4. To provide PRB based cook-stoves for higher efficiency and lesser cooking-time
5. Small-scale, medium-scale, and large-scale eateries
6. LPG-consuming households involved in everyday cooking
7. Retailers and Retail Stores
8. Providing awareness to retailers through training and demonstrations
9. Application of advertising and marketing strategies
10. SiC (Silicon Carbide providers)
11. Al<sub>2</sub>O<sub>3</sub> (Alumina) providers
12. Casting cement providers
13. Human personnel for assembling the product and sales force to take it to market
14. Capital for the purchase of raw-material
15. Technical skills of the personnel to assemble PRB cook-stoves and the training associated with it
16. For the setup of the plant, maintenance and operational activities (TEA is already conducted)
17. Per unit sale (TEA conducted)
18. Lesser emissions of CO and NOx; savings on non-renewable sources of energy (here LPG fuel) for up to 42%
19. Pollution-free kitchens; cost savings on fuel (LPG cylinders), Pay Back Period of less than a year; additional savings on LPG cylinders for the rest of the life period of cook-stove; healthier households

### 6.5.2 Proposed Organizational Design

The inputs from the business model have been taken and after analyzing them, an organogram is proposed with various functional departments to ensure smooth mass production of PRB cook-stoves. **Fig. 6.2** Represents the organizational design depicting various departments required for the mass production of PRB cook-stoves. However, the structure of an organization is not limited to an organogram.



**Fig. 6.2** Proposed organogram for the mass production of PRB cook-stoves

The departments represented by the dotted line in Fig 6.2 are the staff function departments and the departments represented by the continuous line are the lines function departments. By categorizing the organizational departments into line and staff organizations, the division of labor would become easy and accordingly tasks can be carried out without any hindrance. The heads or managers of line departments have direct executive powers as well as responsibility and authority to see that the right decisions are made at the right time and place (Economics, 2013). Whereas the staff heads or managers, provide advisory and support services to the line managers. The organizational design proposed here is a mechanistic organizational structure with centralized authority rather than an organic structure. Since, PRB technology is a new concept and the major aim is to provide benefits to the general public in the Indian context, cost-cutting strategies have

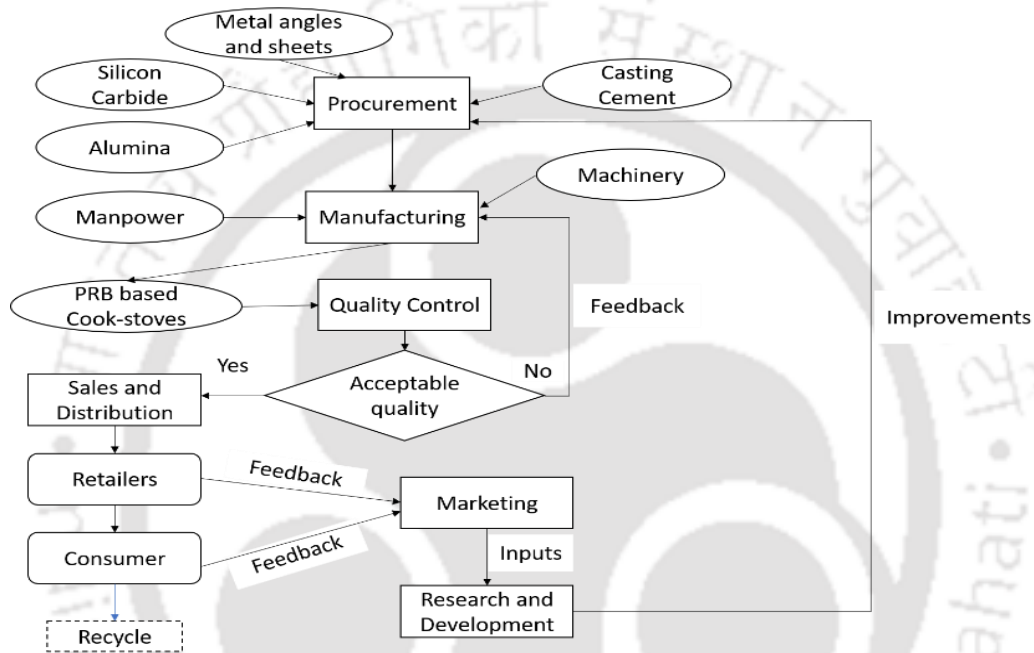
to be adopted to bring in a quality product at an affordable price. The departments have been categorized by taking operative tasks into consideration to produce the end product of the PRB cook-stove. Quality Assurance mentioned in the organogram focuses on how the process of manufacturing PRB-based cook-stoves will be performed. Quality control focuses on supervising or inspecting the PRB-based cook-stoves to ensure that they are fabricated as per the required specifications. Since, the organization is still in the entrepreneurial phase of the organizational life cycle, a mechanistic organogram has been proposed as a vertical hierarchy will be more prompt rather than a horizontal hierarchy during this phase. Also, in the vertical hierarchy, the span of control will be clearly defined and departmental technologies will be clearly demarked to provide efficient and effective work output. However, the proposed organizational design is not strictly limited to mechanistic structure and slight features of the organic structure are also adopted to provide a flexible horizontal hierarchy. This has been proposed since creative departments like Research and Development are involved; also slight collaboration is required between departments like procurement, quality, production, sales and distribution, and so on. Hence, an organogram with more a mechanistic structure and slight organic structure is proposed for an entity for the mass production of PRB cook-stoves.

### ***6.5.3 Value chain and Competency Indicators***

Investigating the organizational design and various operations, the analysis resulted in the value chain represented in **Fig 6.3**. The operational procedure to mass produce PRB cook-stoves and bring them to the market can be understood from the same.

The procurement department will procure from the vendors, the raw material required for the fabrication of the PRB cook-stoves. The raw material after tested for quality assurance is sent to the production department. With the machinery and manpower sources, it is converted into the end product, which is in turn sent to the quality department for quality testing. Once the product passes the quality testing, it is sent to the sales and distribution department from where it is distributed in the market and brought into public usage. Periodic feedback is collected at regular intervals at each department to provide quality assurance and improvise product quality. This will ensure high-quality products of PRB cook-stoves with the least wastage of material and other resources.

After analysing the value chain, the focus is given to the production department and experts at each position of that department have been identified, who have expertise and knowledge in similar technologies and products. Experts are identified from five levels of production department viz., Managerial level, Team Lead level, Senior Engineer level, Junior Engineer level and Assembly worker level.



**Fig. 6.3** Value Chain of PRB cook-stoves

Skills have been identified accordingly and skill-set has been considered for these respective levels. Based on the categorization of the skill-set, a questionnaire has been framed for each level and depending on their expertise, the competency indicators have been proposed. **Table 6.1** represents the competency indicators for the Product Managers of the proposed entity.

**Table 6.1** Competency indicators for Product Manager

Skill	Indicators
	Parts of PRB and cook-stove
	Dimensions of the parts of the PRB and cook-stove
	Assembly procedure of the cook-stove
	Performance parameters of PRB
	Performance testing as per BIS standards of cook-stoves

Product Knowledge       Company Knowledge	Various vessel sizes for specific cook-stove designs
	Vessel type safety measures with respect to product manufacturing
	Characteristics of the fuel used for particular PRB
	Knowledge of ceramic manufacturing
	Theoretical knowledge of heat transfer and combustion
	Type of business the company is in
	Vision and Mission
	The products and processes manufactured by it
	Objectives
	Goals and future scope
	Market dynamics
	Competitors
Optimization Techniques	Arrangement of PRB parts
	Operating conditions of PRB
	Geometrical dimensions and configurations of PRB cook-stove
	Optimization of material
	Operating parameters of fuel flow rate and pressure
	Design specifications of the cook-stove
Suitable power rating (heat) for each kind of vessel used with the cook-stove	
Problem Identification	Aesthetics
	Material
	Breakage of all ceramic parts including Porous Zone, Combustion Zone and burner casing
Leadership Skills	Staff meeting planning and arrangements
	Capability to get the assembly work done as per desired targets and standards
	Firm decision-making capability
	Ability to identify training needs required for subordinates and make necessary arrangements for their training
	Motivating subordinates
Team Management Skills	Ability to delegate generalized and specialized work related to PRB cook-stoves among subordinates
	Ability to group people as per their knowledge on the parts of PRB and cook-stove and the related material
	Ability to get feedback about the work procedure and the complications in the assembly of cook-stoves
	Ability to identify deviations from targeted outcomes related to PRB
	Ability to take corrective measures in case of deviations in producing PRB cook-stoves

Communication Skills	Ability to listen keenly (Bottom-up)
	Ability to communicate orally avoiding jargon to subordinates (Top-down)
	Ability to understand as well as write e-mails clearly up to the point (Top-down and Bottom-up)
	Ability to understand and clearly communicate with clients both orally and in writing
	Ability to make presentations to clients as well as team members
	Non-verbal (Top-down and Bottom-up)
Analytical Skills	Visual observation capability for ceramic breakage
	Ability to avoid repetition of mistakes
	Ability to analyse the deviations from the prescribed standards without major loss
	Ability to analyse the exact production quantity

Under the problem identification competency, in the words of one of the experts, “better aesthetics without compromising on the safety and performance of the burner is of utmost importance.” Also, the expert stressed that firm decision-making is required and punctuality is mandatory to be a good leader. According to another expert, understanding of vision and mission of the company is mandatory, without which the managers will be working vaguely.

For the next hierarchy in the production department, experts in the Team Lead level have been identified and competency indicators have been framed as per their feedback to the respective questionnaire.

**Table 6.2** Competency indicators for Team Lead

Skill	Implications
Product Knowledge	Parts of PRB and cook-stove
	Dimensions of the parts of the PRB and cook-stove
	Assembly procedure of the cook-stove
	Performance parameters of PRB
	Functions of fitting elements
	Types of fuels used with PRB cook-stoves
	Performance testing as per BIS standards of cook-stoves
	About various related vessel sizes for specific cook-stove designs
	Properties of refractories and ceramics
	Working of combustion devices
	Operating procedure of the cook-stove

Technical Knowledge	Heat transfer
	Behavior of Ceramics
Leadership Skills	Ability to conduct group meetings with subordinates
	Materializing tasks
	Ability to analyze and distribute tasks among subordinates that are given by the superiors
	Motivating subordinates
Team Management Skills	Ability to coordinate and synthesize work among subordinates
	Ability to classify work
	Ability to provide support and necessary training as and when required
	Ability to resolve conflicts among team members
	Ability to analyze the root cause of the issues and resolve them
	Ability to encourage workmen participation to enhance product quality
Communication Skills	Ability to listen keenly (Bottom-up)
	Ability to communicate orally avoiding jargon to subordinates (Top-down)
	Ability to understand as well as write e-mails clearly up to the point (Top-down and Bottom-up)
	Non-verbal (Top-down and Bottom-up)

A similar expert study is conducted for the next positions in the hierarchy of the production department i.e., for the Senior and Junior Engineers Levels. **Tables 6.3** and **6.4** respectively indicate the competencies required for these positions.

**Table 6.3** Competency indicators for Senior Engineer Level

Skill	Implications
Product Knowledge	Parts of PRB and cook-stove
	Assembly procedure of the cook-stove
	Dimensions of the parts of the PRB and cook-stove
	About alternative materials of PRB
Technical Knowledge	Heat transfer
	Thermal characterization techniques of PRB
	Casting knowledge
	About metal joining techniques
Team Player Skills	Ability to work with subordinates in assembling PRB cook-stoves
	Ability to rectify bottlenecks in assembling cook-stoves
	Ability to listen keenly (Bottom-up)
	Ability to communicate orally avoiding jargon to subordinates (Top-down)

Communication Skills	Ability to understand as well as write e-mails clearly up to the point (Top-down and Bottom-up)
	Non-verbal (Top-down and Bottom-up)
Product Assembly Skills	Ability to provide design specifications of the PRB cook-stove that is to be assembled

It is evident from **Tables 6.3** and **6.4** that all the competencies required by the Senior and Junior Level Engineers are the same except the technical knowledge as the Junior Engineer also requires the knowledge of the load withstanding capacity of the frame and the knowledge of fuel and temperature pressures required for the effective functioning of PRB cook-stoves.

**Table 6.4** Competency indicators for Junior Engineer Level

Skill	Implications
Product Knowledge	About alternative materials of PRB
	Parts of PRB and cook-stove
	Assembly procedure of the cook-stove
	Dimensions of the parts of the PRB and cook-stove
Technical Knowledge	Heat transfer
	Thermal characterization techniques of PRB
	About load withstanding capacity of the frame
	About fuel pressure and temperatures of PRB
Team Player Skills	Ability to work with subordinates and peers in assembling PRB cook-stoves
	Ability to rectify bottlenecks in assembling cook-stoves while in team
Communication Skills	Ability to listen keenly (Bottom-up)
	Ability to communicate orally avoiding jargon to subordinates (Top-down)
	Ability to understand as well as write e-mails clearly up to the point (Top-down and Bottom-up)
	Non-verbal (Top-down and Bottom-up)
Product Assembly Skills	Ability to provide design specifications of the PRB cook-stove that is to be assembled

The last set of experts interviewed in the hierarchy of the production department are the Assembly Level workers. **Table 6.5** represents the competency indicators of the Assembly Level workers.

**Table 6.5** Competency indicators for Assembly Level Workers

<b>Skill</b>	<b>Implications</b>
Product Knowledge	Parts of PRB and cook-stove
Technical Knowledge	Welding and sheet metal works
Communication Skills	Ability to listen keenly to what is communicated by superiors (Top-down)
	Ability to communicate clearly to superiors orally regarding the procedural issues and related work processes (Bottom-up)
	Ability to communicate non-verbally (Top-down and Bottom-up)
Product Assembly Skills	Ability to assemble the PRB cook-stove as per the prescribed design specifications

With the obtained competency indicators of the different hierarchical levels of the production department of an entity engaged in the PRB cook-stove manufacturing, smooth workflow can be ensured.

## **6.6 Summary**

Considering the multilateral benefits of PRB cook-stoves, a business model has been proposed so that an entity can start with the mass production of PRB cook-stoves. The business model proposed includes the key resources section which would act as a reference for vendor management. Previous studies conducted on PRB cook-stoves like Life Cycle Assessment and Techno-economic Assessment have also been included in the business model to provide a clear indication of the environmental, economic, and social benefits PRB cook-stoves provide. Through the proposed business model, an organogram that is majorly mechanistic and slightly organic is proposed for an entity engaged in the commercialization of PRB cook-stoves. Value chain analysis has been done for the same to understand the workflow. Focus is given to the production department and competency indicators have been identified for different hierarchal positions of the production department. The study will be useful for any entity to start up with the mass production of PRB cook-stoves but, competencies for other departments have not been indicated.

- Competency indicators and skills of departments other than production have not been taken up because of the limitation on the volume of the study.

- As the study is only the proposition of the model and value chain for PRB cook-stoves commercialization, the market conditions, in reality, may vary.
- There could be changes in the competency indicators as and when the changes in the market conditions, job roles, and job positions take place.
- The business model and competency indicators only act as references in the procedure of recruitment, appraisal, and training for the PRB cook-stove manufacturing and are not absolute.



## Chapter 7

### Conclusion and Future Scope

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This chapter summarizes the results obtained while performing the environmental, economic and social sustainability tests of Porous Radiant Burner (PRB), when applied for cooking and industrial applications. The first test performed was environmental assessment test when PRB was integrated with biogas-based cook-stoves and LPG based cook-stoves. Also, the environmental assessment of PRB's performance was assessed when it was integrated as a heating device with the Medical Waste Incinerator. Both the tests proved that PRB is environmentally sustainable than its counterparts in both the cooking and industrial applications. After the environmental assessment of PRB is done, it is tested for its economic sustainability and social sustainability by conducting a Techno-economic Assessment. This assessment was conducted for PRB-based cook-stoves that are operated with LPG fuel. Cook-stoves of 1-3 kW and 5-7 kW have been tested for their economic viability and the assessment proved that PRB is economically more sustainable and viable than the cook-stoves of the same capacity when integrated with Conventional Burners (CB). The last section of the chapter is the result of application of business model to make the PRB widely available for the public use. Along with the concluding results, the future scope is also presented in the current chapter.

#### 7.1 Life Cycle Assessment of PRB

The results of LCA tests of PRB when used for cooking and industrial applications are as below:

##### 7.1.1 PRB based cook-stoves used with biogas

- On comparing the construction and operation of the biogas system, results show that the environmental impacts namely, Climate change, Water depletion and Photochemical oxidant formation of household biogas technology i.e. Deenbandhu type biogas plant with Biogas Operated Conventional Burner (BGS<sub>CB</sub>) or Biogas Operated Porous Radiant Burner (BGS<sub>PRB</sub>), operating under Indian conditions, are mainly attributed to the system's operational phase.

- In the operational phase of the plant, there is a major impact on Climate change and Photochemical oxidant formation factors because of the biogas leakage.
- Results indicate an overall low contribution to the environmental effects from BGS<sub>PRB</sub> than BGS<sub>CB</sub>. Low contribution in the case of BGS<sub>PRB</sub> is mainly attributed to its construction and efficient burning of biogas.
- The application of BGS<sub>PRB</sub> can vastly reduce environmental impact and improve the biogas system's environmental profile.

### **7.1.2 PRB based cook-stoves used with LPG**

- On conducting LCA for fabrication and recycling phase of LPG operated Porous Radiant Burner (PRB<sub>LPG</sub>) based cook-stove and LPG operated Conventional Burner (CB<sub>LPG</sub>) based domestic cook-stoves, it is observed that the impact of PRB<sub>LPG</sub> based cook-stove is lesser on all the midpoint impact factors except on Fossil depletion category.
- The endpoint assessment categories show that PRB<sub>LPG</sub> based cook-stove reduces damage to Human health and Resources by 34% and 19% respectively when compared to the damage of CB<sub>LPG</sub> based cook-stove in the course of its making and recycling.
- During the operational phase of PRB<sub>LPG</sub> and CB<sub>LPG</sub> cook-stoves, the impact on the environmental factors is more than because of their fabrication and recycling. It is because of the higher footprint due to the life span of these cook-stoves.
- When PRB<sub>LPG</sub> and CB<sub>LPG</sub> cook-stoves are being operated at 1 kW LPG power output, PRB<sub>LPG</sub> cook-stove resulted in lesser damage on Human health, Ecosystems and Resources by 15%, 15% and 15% than that of CB<sub>LPG</sub> cook-stove.
- While PRB<sub>LPG</sub> and CB<sub>LPG</sub> cook-stoves are being operated at 3 kW LPG power output, PRB<sub>LPG</sub> cook-stove resulted in lesser damage on Human health, Ecosystems and Resources by 15% each than that of CB<sub>LPG</sub> cook-stove.
- Through the assessment results obtained, it can be concluded that PRB<sub>LPG</sub> cook-stove is a better sustainable product than CB<sub>LPG</sub> cook-stove.

### **7.1.3 PRB when integrated with Medical Waste Incinerator**

- On conducting the LCA of PRB and Electric Heater (EH) when integrated with a Medical Waste Incinerator (MWI), the reduction in the impact on Primary energy utilization damage category with PRB is nearly 54% compared to Electric heater.
- More than 82% of the total environmental impacts are due to the operation of heating devices, and this highlights the importance of employing an efficient heating device to curb the overall environmental impact caused by Small Scale Medical Waste Incinerator (SMWI).

### **7.2 Techno-economic Assessment of PRB-based cook-stoves**

After conducting the TEA, the following results are obtained:

- After conducting the TEA of PRB-based cook-stoves of 1-3 kW and 5-7 kW capacities operating with LPG fuel, the results indicate that PRB-based cook-stoves are economically feasible products.
- Since the TEA is done for a manufacturing unit that manufactures 250 PRB-based cook-stoves per day, other costs incurred like the administration costs and factory costs are also very less.
- The sales cost of the PRB-based cook-stove accounted for 4400 INR for 1-3 kW and 5000 INR for 5-7 kW including 50% profit to the manufacturing unit, which indicates very good returns.
- The IRR for the manufacturing unit is 52.1% for 1-3 kW cook-stove and 51.4% for 5-7 kW cook-stove with 50% profit, making PRB-based cook-stove a revolutionary and economically feasible product.

### **7.3 Proposed Organizational Design for mass production of PRB-based cook-stoves**

The Organizational Design for the mass production of PRB-based cook-stoves has resulted in:

- In subsequent to the working principle of the PRB cook-stoves, a business model has been proposed so that an entity can start with the mass production of PRB cook-stoves. Through the PRB cook-stoves, the core values that are to be provided by the entity to the key

customers and channels through which the entity can reach key customers have been proposed in the business model.

- Through the proposed business model, an organogram that is majorly mechanistic and slightly organic is proposed for any entity engaged in the commercialization of PRB cook-stoves. Value chain analysis is done for the same to understand the workflow.
- Focus is given to the production department and competency indicators have been identified for different hierarchal job positions of the production department.
- The study will be useful in recruitment, training, and performance appraisal and can act as references for the respective job positions. The same competency indicators can be further categorized into required and existing competency indicators to identify the exact gap for the futuristic betterment of human resources.

#### **7.4 Future Scope**

After conducting the research to test the sustainability of PRB, this conclusion has been reached that in the future the following studies may be taken up related to the applications of PRB:

##### ***7.4.1 PRB based cook-stoves used with biogas***

- Further research on LCA on PRB can be done for its applicability to other cooking fuels like methanol, ethanol, kerosene etc.
- Studies can be taken up for proposing the policy making which can promote biogas.

##### ***7.4.2 PRB based cook-stoves used with LPG***

- As the environmental sustainability of PRB<sub>LPG</sub> cook-stove is tested, the future studies can be taken up like United Nations Industrial Development Organization (UNIDO) approach and Little Mirrlees (LM) approach to test its economic and social sustainability.
- Applicability of PRB can be taken forward not only in cooking applications with LPG as fuel but also in others like Kerosene, methanol, ethanol etc.,
- Experiments can also be conducted on the application of PRB in the area of ceramic industries, incineration, food-drying industries and so on.

#### ***7.4.3 Medical Waste Incinerator integrated with PRB***

- In future work, the proposed SMWI-PRB will be tested for its performance and emissions. Also, an LCA study will be performed to analyze the environmental impact caused by the incineration of medical waste, bottom and fly ash produced from the incineration process and the entire system including the air pollution control system and cooling system.
- Another future scope is the utilization of end products (Fly ash and bottom ash) in ceramic, glass and construction industries.

#### ***7.4.4 Techno-economic Assessment of PRB-based cook-stoves***

- The analysis can be further extended to other aspects like marketing, advertisement and organizational structure for such sustainable products, apart from the economic feasibility of the product to make it easier for the manufacturing units to adapt themselves for the wide manufacturing of PRB-based cook-stoves.
- Studies can be taken up to design training programmes which will create job opportunities on a wider scale all over the country to promote small-scale industries that will manufacture PRB-based cook-stoves.
- Further studies can be taken up to frame policies to shift from conventional cooking technologies to energy-efficient PRB technologies.

#### ***7.4.5 Proposed Organizational Design for mass production of PRB-based cook-stoves***

- The competency indicators used for the production department can be further categorized into required and existing competency indicators to identify the exact gap for the futuristic betterment of human resources.
- The study conducted on Organizational Design will be useful for any entity to start up with the mass production of PRB cook-stoves as the focus is given to the production department. However, competencies for other departments have not been indicated and each department can be taken up as an individual study in the future.

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## Publications

### *Journals*

**Shaik, S.R.**, Muthukumar P., and Kalita P C. (2022). Life Cycle Assessment of LPG Cook-stove with Porous Radiant Burner and Conventional Burner – A Comparative Study. **Sustainable Energy Technologies and Assessment**, 52, 102255 [IF: 7.63] <https://doi.org/10.1016/j.seta.2022.102255>

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Mahalingam, A. K., **Shaik, S. R.**, Kaushik, L. K., Muthukumar P., and Kalita, P. C. (2022). Design and Lifecycle Assessment of Small-scale medical waste incinerators. **Indian Chemical Engineers Journal** [IF: 1.09] <https://doi.org/10.1080/00194506.2022.2098180>

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Arun Kumar M., **Shaik, S. R.**, Kaushik, L. K., Muthukumar P., Kalita, P. C. (2021). Life Cycle Assessment of Incinerator with Porous Radiant Burner, Conventional Burner and Electrical Heater- A comparative study. - Presented at **International Conference on Recent Technologies and Advanced Materials for Green Energy and Sustainable Environment– RTAMGESE 2021**, held on 12-13 March, 2022. (held at NIT, Trichy in online mode)

**Shaik, S. R.**, Muthukumar P., Kalita, P. C. (2021). Life Cycle Assessment of LPG cook-stove with Porous Radiant Burner and Conventional Burner - A comparative study. - Presented at **1st International Conference on Water, Energy and Environment– WEECON 2021**, held on 23-24 December, 2021. (held by ISET Research India in association with IE Vietnam in online mode)

**Shaik, S.R.**, Muthukumar P., and Kalita, P.C., (2022). Life Cycle Assessment of Biogas Operated Porous Radiant Burner and Conventional Burner for Cooking Applications. - Presented at **second International Conference on Renewable Energy – ICRE 2022**, held on 25-27 February, 2022. (held at University of Rajasthan Jaipur, India in online mode)

**Shaik, S.R.**, Muthukumar P., and Kalita, P.C., (2022). Techno-Economic Assessment of LPG operated Porous Radiant Burner based Cook-stoves for Commercial Cooking Applications. - Presented at **Second International Conference on Sustainable Energy, Environment and Green Technologies - ICSEEGT 2022**, held on 24-25 June 2022 (Awarded the “**best paper**”) doi: 10.1088/1755-1315/1084/1/012014 (held at Poornima college of Engineering, Jaipur, Rajasthan in hybrid mode)

**Shaik, S.R.**, Vaneeth K., Muthukumar P., and Kalita, P.C., (2023). Proposed Organizational Design for an entity to mass produce and commercialize PRB Cook-stoves. - Presented at **International Conference on Contemporary Research in Management - ICCRM 2023**, held on 11-12 January 2023 (held at PSG Institute of Management, Coimbatore, India in hybrid mode)

