DEVELOPMENT AND IMPACT ASSESSMENT OF IMPROVED BIOMASS COOKSTOVES IN RURAL COMMUNITIES

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by

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But seek ye first the kingdom of God, and his righteousness; and all these things shall be added unto you.

This thesis is dedicated to my teachers

To the teacher who birthed and raised me to become the woman that I am today

To the teacher who taught with patience in high school

To the teacher who inspired me to pursue a subject in a male-dominated stream,

To the teacher who pushed me to get out of my comfort zone

To the teacher who made me value my own analysis and opinion

To the teacher who allowed me enough freedom to learn from my mistakes, and grow

Your lessons extend far beyond the classroom. Thank you for being my mentors, guides, and sources of inspiration. This thesis is a testament to your profound impact on my life.

CERTIFICATE

This is to certify that the thesis entitled " Development And Impact Assessment Of Improved Biomass Cookstoves In Rural Communities", being submitted by **Ms. Imlisongla Aier** to the **Indian Institute of Technology Delhi** for the award of **"Doctor of Philosophy"** is a record of bonafide research work carried out by her. She has worked under our guidance and supervision and has fulfilled the requirements for the submission of this thesis. To the best of our knowledge, the results contained in this thesis have not been submitted in part or full to any other university or institute for the award of any degree or diploma.

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(Ms Imlisongla Aier)

ABSTRACT

Cooking with traditional cookstoves using biomass fuel is a popular practice in rural parts of most low-income countries. To overcome the barriers and challenges associated with the implementation, uptake, and continued use of improved cookstoves, a comprehensive strategy that considers factors relating to the user's socio-economic, cultural, and cookstove design specifications is necessary. The study was conducted in the region Gaindi Khata hamlet in Haridwar, Uttarakhand where improved cookstoves had previously been introduced to homes. Here, the popular designs of biomass traditional cookstoves used in the village, such as forced draft and natural draft, were selected to conduct cooking tests and determine which cookstove among them performed the best. The testing protocols for testing of cookstoves, namely ISO 19867-1:2018(E) (International Organization for Standardization), BIS (Bureau of Indian Standards), and CCT (Controlled Cooking Test) testing methodologies, were followed for the cookstove performance test. The Weighted Sum Method (WSM), a multi-criteria decision analysis, was used to determine the optimal cookstove in this study based on the cookstove performance criteria such as cooking time, specific fuel consumption, CO (Carbon monoxide) and $PM_{2.5}$ (Particulate matter) emissions, capital cost, and cost of fuel saving. During rice cooking, the highest levels of $PM_{2.5}$ emissions were found in cookstoves in ND (Natural Draft) and TCS (Traditional Cookstoves), and the highest CO emissions in TCS and ND. In contrast, it was found that during the roti cooking test, the FD (Forced Draft) cookstove produced the maximum emissions of CO and $PM_{2.5}$, followed by the TEG (Thermoelectric Generator) cookstove. According to the laboratory cookstove test results for thermal efficiency, cookstoves of the FD type had the maximum efficiency, followed by those of the TEG, TCS, and ND types. The WSM analysis indicated the FD cookstove to be the most ideal for preparing rice, and the TCS cookstove as ideal for cooking roti. Since the tests were carried out under simulated conditions to estimate the performance and concentrations of emissions in the user

kitchen, the study sheds light on the appropriate cookstove to be implemented for the targeted communities. To analyze why improved cookstoves were not adopted by households in rural communities, a longitudinal survey was conducted after two years. Applying the Behaviour-Change Wheel (BCW) helped to identify interventions that might help overcome the behavioral obstacles to adoption, and the Capability, Opportunity, Motivation-Behaviour (COM-B) framework was adopted to explain the factors why. Physical barriers to continuous usage were their short lifespans without maintenance, their narrow fuelwood inlets, the presence of only one hob, and their suitability for only low- or slow-temperature heating. The unawareness of the users of the health advantages of improved cookstoves over traditional cookstoves, as well as certain user-experience hurdles, were identified as barriers to use. This emphasized the need for incorporating users in the co-design process for the upgraded cookstove.

In the fourth objective, development of a household-scale improved cookstove with an output power rating of 3 kW was carried out using an iterative design method. Three prototype cookstoves were tested namely SC1, TS10, and TS5 cookstoves were developed and tested under both natural and forced draft conditions. Cookstove SC1 was provided with a straight combustion chamber, while TS10 and TS5 cookstoves were provided with a throat section of radius 10 cm and 5 cm at a height of 0.5 of the total cookstove height. According to laboratory testing, the cookstoves with the highest thermal efficiency were those with forced draft, achieving 32–36%, 25–28%, and 20–13% for models SC1, TS10, and TS5, respectively. Heat transfer studies confirmed that the cookstove SC1 had the maximum heat gained by the cooking pot, followed by TS10 and TS5. Furthermore, the cookstove SC1's enhanced heat transmission efficiency suggested a larger surface area exposed to combustion gases from the cooking pot. Cookstoves with forced draft settings produce lower emissions, according to emission analysis. Under natural draft conditions, SC1, TS10, and TS5 operated at CO, 7.09, 8.12, 129.79, 113.24, and 171.20 mg/MJd; under forced draft conditions, CO, 6.32, 6.05, and 6.88 g/MJd, and $PM_{2.5}$, 69.80, 110.32, and 84.37 mg/MJd, were recorded. According to the study's findings, designing cookstoves with an iterative method can produce highly efficient appliances with minimal CO and $PM_{2.5}$ emissions while also considering user feedback.

सार

बायोमास ईंधन का उपयोग करके पारंपरिक कुकस्टोव के साथ खाना बनाना अधिकांश कम आय वाले देशों के ग्रामीण हिस्सों में एक लोकप्रिय प्रथा है। बेहतर चूल्हे के कार्यान्वयन, तेज और निरंतर उपयोग से जुड़ी बाधाओं और चुनौतियों को दूर करने के लिए, एक व्यापक रणनीति आवश्यक है जो उपयोगकर्ता के सामाजिक-आर्थिक, सांस्कृतिक और कुकस्टोव डिजाइन विनिर्देशों से संबंधित कारकों पर विचार करती है। यह अध्ययन उत्तराखंड के हरिद्वार में गैंडी खाता बस्ती में आयोजित किया गया था, जहां पहले घरों में बेहतर चूल्हे पेश किए गए थे। यहां गांव में इस्तेमाल किए जाने वाले बायोमास पारंपरिक कुकस्टोव के लोकप्रिय डिजाइन, जैसे कि जबरन मसौदा, और प्राकृतिक ड्राफ्ट को खाना पकाने के परीक्षण करने और यह निर्धारित करने के लिए चुना गया था कि उनमें से किस कुकस्टोव ने सबसे अच्छा प्रदर्शन किया है। कुकस्टोव प्रदर्शन परीक्षण के लिए बीआईएस और सीसीटी परीक्षण पद्धतियों का पालन किया गया था। भारित राशि विधि (डब्ल्यूएसएम), एक बहु-मानदंड निर्णय विश्लेषण, का उपयोग इस अध्ययन में इष्टतम कुकस्टोव को निर्धारित करने के लिए किया गया था, जो खाना पकाने के समय, विशिष्ट ईंधन की खपत, सीओ और पीएम 2.5 उत्सर्जन, पूंजीगत लागत और ईंधन की बचत की लागत जैसे कुकस्टोव प्रदर्शन मानदंडों पर आधारित था। चावल पकाने के दौरान एनडी और टीसीएस में कुकस्टोव में पीएम 2.5 उत्सर्जन का उच्चतम स्तर पाया गया, टीसीएस और एनडी में उच्चतम सीओ उत्सर्जन। इसके विपरीत, यह पाया गया कि रोटी खाना पकाने के परीक्षण के दौरान, एफडी कुकस्टोव ने सीओ और पीएम 2.5 का अधिकतम उत्सर्जन किया, इसके बाद टीईजी कुकस्टोव का स्थान रहा। थर्मल दक्षता के लिए बीआईएस परीक्षण के परिणामों के अनुसार, एफडी प्रकार के चूल्हे की अधिकतम दक्षता थी, इसके बाद टीईजी, टीसीएस और एनडी प्रकार के थे। डब्ल्यूएसएम विश्लेषण ने संकेत दिया कि चावल तैयार करने के लिए एफडी कुकस्टोव सबसे आदर्श है और टीसीएस कुकस्टोव रोटी पकाने के लिए आदर्श है। चूंकि परीक्षण उपयोगकर्ता रसोई में उत्सर्जन के प्रदर्शन और सांद्रता का अनुमान लगाने के लिए नकली परिस्थितियों में किए गए थे, इसलिए अध्ययन लक्षित समुदायों के लिए लागू किए जाने वाले उपयुक्त कुकस्टोव पर प्रकाश डालता है। यह विश्लेषण करने के लिए कि ग्रामीण समुदायों में परिवारों द्वारा बेहतर कुकस्टोव क्यों नहीं अपनाए गए, दो साल बाद एक अनुदैर्ध्य सर्वेक्षण किया गया था। व्यवहार-परिवर्तन चक्र (BCW) को लागू करने से उन हस्तक्षेपों की पहचान करने में मदद मिली जो अपनाने के लिए व्यवहार संबंधी बाधाओं को दूर करने में मदद कर सकते हैं, और कारकों को समझाने के लिए क्षमता,

अवसर, प्रेरणा-व्यवहार (COM-B) ढांचे को अपनाया गया था। निरंतर उपयोग के लिए भौतिक बाधाएं रखरखाव के बिना उनके छोटे जीवनकाल थे, उनके संकीर्ण ईंधन लकड़ी के इनलेट, केवल एक हॉब की उपस्थिति, और केवल कम या धीमी गति से तापमान हीटिंग के लिए उनकी उपयुक्तता। पारंपरिक चूल्हे की तुलना में बेहतर चूल्हे के स्वास्थ्य लाभों के बारे में उपयोगकर्ताओं की अनभिज्ञता, साथ ही साथ कुछ उपयोगकर्ता-अनुभव बाधाओं को उपयोग करने में बाधाओं के रूप में पहचाना गया था। इसने उन्नत कुकस्टोव के लिए सह-डिजाइन प्रक्रिया में उपयोगकर्ताओं को शामिल करने की आवश्यकता पर जोर दिया।

चौथे उद्देश्य में, 3 किलोवाट की आउटपुट पावर रेटिंग के साथ घरेलू स्तर पर बेहतर कुकस्टोव का विकास एक पुनरावृत्ति डिजाइन विधि का उपयोग करके किया गया था। तीन प्रोटोटाइप कुकस्टोव का परीक्षण किया गया था, अर्थात् एससी 1, टीएस 10, और टीएस 5 कुकस्टोव को प्राकृतिक और मजबूर ड्राफ्ट स्थिति दोनों के तहत विकसित और परीक्षण किया गया था। प्रयोगशाला परीक्षण के अनुसार, उच्चतम तापीय दक्षता वाले कुकस्टोव मजबूर ड्राफ्ट वाले थे, क्रमशः मॉडल SC1, TS10 और TS5 के लिए 32-36%, 25-28% और 20-13% प्राप्त करते थे। हीट ट्रांसफर अध्ययनों ने पुष्टि की कि कुकस्टोव SC1 में खाना पकाने के बर्तन द्वारा प्राप्त अधिकतम गर्मी थी, इसके बाद TS10 और TS5 थे। इसके अलावा, कुकस्टोव SC1 की बढ़ी हुई गर्मी संचरण दक्षता ने खाना पकाने के बर्तन से दहन गैसों के संपर्क में आने वाले एक बड़े सतह क्षेत्र का सुझाव दिया। उत्सर्जन विश्लेषण के अनुसार, मजबूर ड्राफ्ट सेटिंग्स वाले कुकस्टोव कम उत्सर्जन का उत्पादन करते हैं। प्राकृतिक ड्राफ्ट शर्तों के तहत, SC1, TS10, और TS5 CO, 7.09, 8.12, 129.79, 113.24, और 171.20 mg/MJDd पर संचालित होते हैं; मजबूर ड्राफ्ट शर्तों के तहत, सीओ, 6.32, 6.05, और 6.88 ग्राम / एमजेडी, और पीएम 2.5, 69.80, 110.32, और 84.37 मिलीग्राम / एमजेडी दर्ज किए गए थे। अध्ययन के निष्कर्षों के मुताबिक, एक पुनरावृत्ति विधि के साथ कुकस्टोव डिजाइन करने से उपयोगकर्ता प्रतिक्रिया पर विचार करते हुए न्यूनतम सीओ और पीएम 2.5 उत्सर्जन के साथ अत्यधिक कुशल उपकरणों का उत्पादन किया जा सकता है।

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LIST OF SYMBOLS

Symbols / Syntax	**Description**
%	Percentage
η	Thermal efficiency of the cookstove
γ	Latent heat of vapourised water
Δt_c	Time to boil pot
$	United States dollar
ρ_a	Air density
ρ_b	Biomass bulk density
μ	Superficial velocity
ρ	Density of flue gas
ΔT_{cond}	Difference in temperature
ΔT_{conv}	Difference in temperature
ξ^0	Exergy input
φ_{dry}	Ratio of specific chemical exergy to net calorific value of dried fuelwood

LIST OF UNITS

Units	Description
W	watt
g/MJ_d	gram per megajoule of energy delivered
mg/MJ_d	milligram per megajoule of energy delivered
cm	centimeter
cm^3	cubic centimeter
h	hour
^oC	degree centigrade
kJ	kilojoule
kJ/kg	kilojoule per kilogram
kg	kilogram
kW	kilowatt
min	minute
s	second
g	gram
mm	millimeter
$Lmin^{-1}$	litre per minute
ppm	Parts per million
ml	milliliter
Kg/h	mass flow rate
kg/m^2s	kilogram per square meter second
W/m^2K	watt per square meter kelvin
$J\ kg^{-1}\ K^{-1}$	joule per kilogram kelvin

W.m/K	watt meter per kelvin

LIST OF ABBREVIATIONS

Abbreviations	Description
IEA	International Energy Agency
PICs	Products Of Incomplete Combustion
TCS	Traditional Cookstoves
IAP	Indoor Air Pollution
GHGs	Greenhouse Gas Emissions
BC	Black Carbon
ICS	Improved Cookstoves
LPG	Liquefied Petroleum Gas
CEEW	Council on Energy, Environment and Water
IRES	Indian Residential Energy Survey
NBCP	National Biomass Cookstove Program
NBCI	National Biomass Cookstove Initiative
UCA	Unnat Chulha Abhiyan
TLUD	Top-Lit Updraft Gasifier
TEG	Thermoelectric Generators
WBT	Water Boiling Test
O_2	Oxygen
N_2	Nitrogen
H_2O	Water
m_{air}	Mass of air
m_{fuel}	Mass of fuel
CO	Carbon Monoxide

ISO	International Organization for Standardization
IWA	International workshop agreement
$PM_{2.5}$	Particulate Matter of 2.5 mm or smaller in diameter
TCS	Traditional Cookstove
SUMs	Stove Use Monitor
FD	Forced Draft
ND	Natural Draft
SFC	Specific Fuel Consumption
TE	Thermal Efficiency
ACS	Advanced Cookstove
C	Carbon
H	Hydrogen
N	Nitrogen
S	Sulphur
NH	National highway
IIT	Indian Institute of Technology Delhi
BIS	Bureau of Indian Standards
CCT	Controlled cooking test
WSM	Weighted sum method
X_{fuel}	Mass of solid fuel consumed
H_{fuel}	Calorific value of wood
X_k	Mass of kerosene used for ignition
H_k	Calorific value of kerosene
H_{out}	Heat output from stove
H_{in}	Heat input to stove

n	No of vessel used
W	Mass of vessel with lid
$C_{p,v}$	Specific heat of the material of the vessel
w	Mass of water in vessel
t_1	Initial temperature of water
t_2	Final temperature of water
t_3	Final temperature of water in last vessel
C_w	Specific heat of water
P_o	Power output rating (kw) of cookstove
X_{fuel}	Mass of solid fuel consumed
H_{fuel}	Net calorific value of wood
X_k	Mass of kerosene used for ignition
Q1	Useful energy delivered
Q_u	Useful energy delivered
C_p	Heat capacity of water
$m_{w,f}$	Final mass of water
P_c	Cooking power
m_{char}	Char mass product
C	Mass of the remaining char
E_{char}	Char energy productivity
$Q_{net.char}$	Calorific value of remaining char, kj/kg
$t_{c,I}$	Time when boiling initially started
$t_{c,f}$	Time when boiling ends
ASTM	American Society for Testing and Materials
EFs	Emission factors

f_i	Initial weight of fuels
f_f	Final weight of fuels
f_d	Equivalent dry wood consumed
W_f	Weight of cooked food
x_i	Value of x in the sample
$\bar{x}$	Mean value of x in the sample
y_i	Value of y in the sample
$\bar{y}$	Mean value of y in the sample
WSM	Weighted Sum Mean
COM-B	Capability, opportunity, motivation, behaviour
BCW	Behaviour change wheel
USD	United States Dollar
SDG	Sustainable development goals
UN	United Nations
USB	Universal Serial Bus
ESMAP	Environmental & Social Sensitivity Mapping
COVID19	Coronavirus Disease of 2019
SA	Stoichiometric air
FCR	Fuel consumption rate
Q_{out}	Power output
Q	Fuelwood volumetric flow rate of air
Re	Reynolds number
v	Viscosity of the fluid
d	Diameter of cookstove
v_{fan}	Volumetric flow of blower fan

N_p	Primary air holes
N_s	Secondary air holes
A_p	Primary air holes
A_s	Secondary air holes
v_p	Primary air holes
v_f	Secondary air holes
D_p	Diameter of primary holes
A_p	Area of primary holes
T_f	Flame temperature
m_g	Air flux
T_{fb}	Temperature of the fuel bed
T_i	Ignition temperature
$Q_{conduction}$	Conduction heat transfer
k	Thermal conductivity,
A_{cond}	Area of cross-section
L_{cond}	Area of cross-section
$Q_{convection}$	Convection heat transfer
h	Coefficient of convection
A_{conv}	Surface area exposed
T_{rad2}	Inner surface temperatures
T_{rad1}	Outer surface temperatures
$Q_{radiation}$	Heat transfer from blackbody radiation
Ex_{in}	Thermal exergy input
T_a	Surrounding temperature
T_{fb}	Temperature of the fuelwood being burned in the combustion chamber

NCV	Net calorific value
w_m	Moisture percentage of fuelwood
h_{fg}	Enthalpy of water vaporization
h	Mass fractions of H
n	Mass fractions of N
o	Mass fractions of O
c	Mass fractions of C
t_{v1}	Vessel's initial temperatures
t_{v2}	Vessel's final temperatures
Ex_o	Exergy production from the cookstove
HH	Household
GIS	Geographical Information System