ABSTRACT

This study presents the design, fabrication, and performance evaluation of a novel Dual Fuel cookstove that integrates in-situ biochar production through slow pyrolysis with conventional solid fuel combustion as well as volatile gas combustion. The first cookstove prototype was evaluated using Water Boiling Test (WBT) protocols, achieved a thermal efficiency of 18–21% and a biochar yield of 34.5% and 37.5%, establishing a baseline for further optimization. The thermogravimetric analysis (TGA) of locally abundant biomass feedstocks — pine needles and bamboo — confirmed that operating temperatures within the stove corresponded to optimal conditions for pyrolysis and effective biochar production, while biomass resource assessment supported the feasibility of sustainable feedstock availability. A significant increase in the composition of carbon mass fraction was observed from 45.11 % in raw biomass to 79.4-87.24 % in the biochar. The carbon composition had increased as the reaction time increased.

Dual Fuel cookstove was developed in accordance with BIS cookstove design protocols and subjected to comprehensive performance and emission testing through controlled laboratory experiments (WBT, ISO and BIS protocols) and Controlled Cooking Tests (CCT). Results demonstrated thermal efficiency achieved while using PJ biochar as fuel, the thermal efficiency were reported in the range of 24-37% when using wood as fuel and when using biochar as fuel the thermal efficiency range reported were 31-43% for testing protocols ISO, WBT and BIS. The results demonstrated higher thermal efficiency as compared to comparative biomass cookstoves as reported in the literature. Reduced pollutant emissions for CO and particulate matter (PM), while using PJ wood as fuel was 3.78±0.13 g/MJ_d and 30.42±1.67 mg/MJ_d, respectively. PJ biochar as fuel, the CO and $PM_{2.5}$ emission was 2.35±0.18 g/MJ_d and 28.5±1.45 mg/MJ_d, respectively while conducting WBT protocols. It was found that the CO emission factor of the Dual Fuel stove as2.44±0.25 g/ MJ_d and $PM_{2.5}$ as 27.4±3.69 mg/MJ_d while using PJ wood, and 2.08±0.4 g/MJ_d and 24.18 ± 2.02 mg/MJ_d while using PJ biochar as fuel during

ISO test. Biochar produced was characterized for its material properties, confirming significant enhancement in physicochemical properties post-pyrolysis. Controlled Cooking Test was conducted in a simulated kitchen like those of rural households by preparing rice and roti to determine specific fuel consumption (SFC, g/kg) compared across different types of cookstoves. Traditional and conventional cookstoves such as TCS, TEG, ND, and FD show very high SFC values (ranging from ~997 to 1626 g/kg), indicating lower fuel efficiency and large variability in performance while Dual Fuel cookstove using PJ wood and PJ biochar was found 222±71 and 192±45 g/kg. CO emission levels reported for PJ wood was 33.13±3.05 mg/m^3 and while using PJ biochar for cooking was reported as 28.64±3.57 mg/m^3. Similarly for $PM_{2.5}$ emission levels, PJ wood reported 1137±73.48 $\mu g/m^3$ and during cooking by PJ biochar was reported as 908±65.32 $\mu g/m^3$.

Field trials conducted in households validated real-world performance, showing reduced fuel consumption and lower smoke emissions compared to traditional stoves. User feedback informed ergonomic refinements — including pot-stove gap reduction, pyrolysis chamber redesign, and fuel inlet modification — leading to a subsequently patented optimized design. Energy balance assessment of the final design showed approximately 40% of input fuel energy delivered as useful heat and ~12.85% retained in the biochar product. Steady-state thermal simulation of the optimized stove was validated against experimental temperature profiles, confirming model reliability and supporting the robustness of the design.

The study demonstrates the potential of the developed cookstove technology to advance clean cooking, improve indoor air quality, enhance energy access, and enable productive biochar utilization, providing a strong foundation for further scale-up and deployment.