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Climate change mitigation potential of rural households in Chattogram District of Bangladesh

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A holistic analysis of climate change mitigation potential at the household level has not yet been conducted in Bangladesh. We aimed to quantify the climate change mitigation potential of carbon storage in homegarden trees and wooden furniture across households of different income levels in Anowara Upazila, Chattogram, Bangladesh. We also quantified the substitution potential of wooden furniture and use of renewable energy sources. Following simple random techniques, we surveyed a total of 217 homegardens and their respective households from the three villages of Boirag Union, with a sampling intensity of 5%. Furniture manufacturers were also surveyed to determine the typical amount of wood and types of tree species used for furniture. We found that homegarden trees stored on average 42 Mg CO_2 per hectare, and most carbon was found in *Albizia lebbeck*, *Tectona grandis*, *Acacia auriculiformis*, and *Swietenia macrophylla*. Carbon storage and substitution benefits of wooden furniture were significantly ($p < 0.05$) higher in the upper-middle (2.07 and 2.32 Mg CO_2 household^{-1} year^{-1}) than in the lower-middle (1.2 and 1.34 Mg CO_2 household^{-1} year^{-1}) income group. Households in the upper-middle income group generated higher emissions from combusting fossil fuels (electricity and LPG) than those in the lower-middle income group. These emissions could be avoided by using improved cooking stoves and biogas obtained from kitchen waste, poultry waste, and cowdung. The emission reduction potential of using biogas was significantly ($p < 0.05$) higher in the upper-middle (2.43 Mg CO_2 household^{-1} year^{-1}) than in lower-middle group (1.87 Mg CO_2 household^{-1} year^{-1}). The research findings suggest that implementing sustainable management and low carbon practices in households can significantly contribute to climate change mitigation by intervening policy mechanisms, while offering carbon farming techniques as well as a carbon market.

Keywords Carbon storage, Displacement factors, Fossil counterparts, Homegarden trees, Wooden furniture, Substitution potential

Climate change is a global issue primarily driven by burning fossil fuels, which releases greenhouse gases (GHGs) into the Earth's atmosphere[1]. The combustion of fossil fuels generates approximately 21.3 billion tonnes of carbon dioxide (CO_2) annually, with natural processes absorbing only about half, resulting in a net increase of 10.65 billion tonnes of atmospheric CO_2 each year[2–4]. In Bangladesh, CO_2 emissions in 2021 totaled 106.87 megatonnes (Mt), with 0.623 tonne CO_2 per capita marking increases of 167.5% and 124%, respectively, compared to 2005[5]. While global emissions from fossil fuel use continue to rise, it is also important to recognize the role that terrestrial ecosystems, particularly forests, play in mitigating climate change. However, the integrated role of forests and forest biomass (wood, biomass fuels) that could play in mitigating CO_2 emissions is seldom studied in Bangladesh.

Tropical forests covering around 60% of global forested areas, sequester about 2.3 gigatons (Gt) of CO_2[6], playing a crucial role in the global carbon cycle[7]. However, deforestation and degradation of vegetation reduce carbon storage in these tropical forests[8,9]. As tropical forests are declining, small-scale forests, such as homegardens and urban vegetation, become increasingly important for carbon storage[10]. Homegarden systems have been found to store carbon between 80.81 and 112.30 Mg C ha^{-1} in various locations in Ethiopia[11] and an average of 13 Mg C ha^{-1} of above-ground biomass carbon in Srilanka[12]. In Bangladesh, homegardens in hilly,

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coastal, and plain land areas store between 4.57 and 36.35, 46.11, and 53.53 Mg C ha^{-1}, respectively[13–15]. Despite the substantial carbon storage potential of homegardens in Bangladesh, their full potential in climate change mitigation has yet to be comprehensively studied.

Forest-based climate change mitigation also includes the use of harvested wood products (HWPs) and biomass fuels (e.g., fuelwood) that reduce CO_2 emissions by substituting fossil fuel-intensive materials (e.g., steel, plastic, and concrete), and fossil fuels (e.g., liquefied petroleum gas (LPG), oil, and gas) while storing wood carbon[16–22]. However, the potential of HWPs and biomass fuels in climate change mitigation depends on product pairs (e.g., steel vs. wooden furniture or bioenergy vs. LPG), embodied carbon in the substituted materials, variety of wood products (e.g., furniture, construction), and functional unit used[23–28].

In Bangladesh, homegardens provide approximately 70–80% of all wood, bamboo, and fuelwood used[29]. A large share of HWPs is used in construction, particularly in engineered wood products (e.g., beam, column, centering, etc.) and more than 72% of houses are built with wood[30]. Additionally, sawn wood is widely used in furniture manufacturing. With population growth and improved living standards, the demand for wood and the wood industry in Bangladesh is rapidly increasing. The furniture industry is growing at a pace of 19% annually and accounts for about 0.29% of the nation's GDP[31]. In 2016–17, Bangladesh's furniture sector generated a total value-added of 0.86 billion US dollars[30].

In Bangladesh, the use of biomass fuels in traditional cooking stoves (TCS) at the household level remains a major source of emissions[32]. In comparison, improved cooking stoves (ICS) are more efficient, reducing fuel consumption by 27% and CO_2 emissions by 25%[33]. In developing countries, household biogas systems, which utilize kitchen waste and manure, may offer a viable alternative for lighting and cooking, replacing solid biomass fuels[34–36]. In Bangladesh, biogas technologies have already been adopted and have been found they be technologically and economically viable at the rural scale[37,38]. For instance, a "union-based biogas plant model" for electricity generation is introduced[39]. Different government and non-government organizations have already established around 76,771 biogas plants till 2020[40], and they are mainly cowdung and poultry waste-based[37]. Being an agrarian country, Bangladesh has the potential for biogas-based power generation from a large number of livestock (24, 25, and 312 million cattle, goat, and poultry, respectively), and the total electricity potential from biogas was 7.30 GWh in 2014-15[41].

Homegardens are a multifunctional land use system, with a potential carbon reservoir and supply of wood and biomass fuels that support rural household livelihoods. Recognizing carbon storage in homegarden trees and wood, and biomass-based energy systems, it opens new opportunities for generating carbon credits via Clean Development Mechanism (CDM) and Reducing Emissions from Deforestation and Forest Degradation (REDD+) processes, which rural households can use as livelihood strategy. However, the role of wood in climate change mitigation, both emission avoidance and storing carbon, has been overlooked in the policy of Bangladesh, including the climate change strategy and action plan[42], possibly due to limited research and documentation. The lack of appropriate data and estimation of carbon storage, particularly in tropical and small-scale forests[43,44]. complicates the successful application of REDD + and CDM. Under CDM, the substitution of wood may work indirectly, with renewable energy systems, through voluntary carbon marketing, for which, there is a need of carbon accounting models in HWPs and recognizing the lifecycle carbon benefits of wooden furniture. Integrating the CDM and REDD + into national policy in a country like Bangladesh enhances the utilization of global mitigation funds and promotes GHG emission reductions in accordance with nationally determined contribution (NDC) and sustainable development goals (SDGs). This is important to assess the carbon benefits of homegarden trees, wood, and substitution in an integrated manner to enable its inclusion into the national accounting system for NDC, which may strengthen the country's climate commitment under the UNFCCC on one hand and on the other hand rural livelihood through sustainable land use planning.

In Bangladesh, earlier household-level studies on homegardens in Bangladesh have primarily focused on socio-economic benefits such as supplying food, timber, fuelwood, and other non-timber forest products[45]. Other research investigated the utilization, conservation, and management of homestead biodiversity and factors (e.g., tree diameter, basal area etc.) affecting the carbon stock in homestead landscape[13,15,46]. Nevertheless, none of them estimated carbon storage and substitution benefits of HWPs nor did they evaluate their potential role in climate change mitigation. For instance, Baul et al. (2024)[24] evaluated avoided emissions of substitution impacts of HWPs but did not take carbon storage of trees and HWPs into account. Furthermore, given the ecological diversity of landscapes, it is necessary to assess the potential carbon storage of various land types at the regional level[47]. To estimate household-level mitigation strategy, there is need of a holistic analysis of carbon storage in homegardens and HWPs as well as potential impacts of HWPs and biomass fuels (e.g., fuelwood, kitchen waste) in avoiding fossil emissions.

To address the research gap, we aimed to estimate the climate change mitigation potential of carbon storage in homegarden trees and wooden furniture across households with varying income levels in Anowara Upazila (sub-district), Bangladesh. Additionally, we quantified the substitution potential of wooden furniture and renewable energy sources. This study can provide useful documentation on effective and community-focused climate action as well as the carbon accounting model of wooden furniture, which will produce new knowledge base in climate change mitigation studies and guiding climate policy intervention.

Materials and methods

Study site

We conducted this study in the households of Boirag Union (lowest administrative unit) of Anowara Upazila (sub-district) under Chattogram District (Fig. 1). Anowara Upazila covers an area of 164.13 sq. km and lies between 22°07' and 22°16' North Latitudes and 91°49' and 91°58' East Longitudes[48]. Patiya Upazila bounds it on the north, Banskhali Upazila on the south, Chandnaish Upazila on the east, and Chittagong Bandar Thana (police station), and the Bay of Bengal on the west. The land is mostly plain, and a small portion of land consists

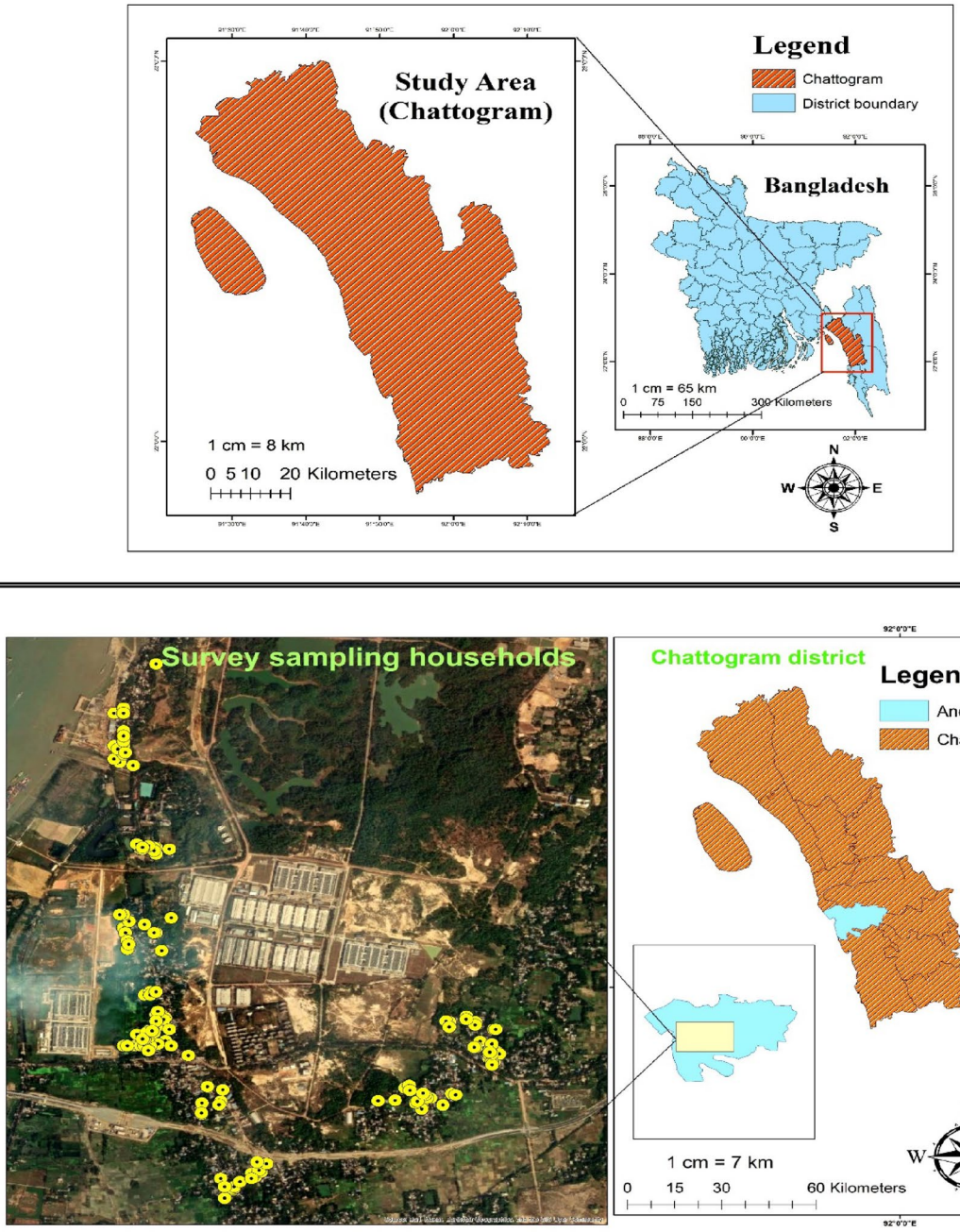

Fig. 1. Maps of Bangladesh and Chattogram district (upper panel), Anowara Upazila and Boirag Union with sampling points (lower panel). The maps are created using ArcGIS 10.8 and Google Earth Pro.

of hills, which are mostly under the Korean Export Processing Zone (KEPZ). The annual average temperature varies from a maximum of 36.3 °C to a minimum of 11.2 °C, and the average rainfall is 2799 mm. The soil of Anowara is brown, very strongly acidic, and mainly loamy soil[49].

Anowara Upazila has 11 Unions, and we selected Boirag Union purposively for the study. This Union is situated near the bank of the Karnaphuli River and connects the Chattogram Metropolitan City (CMC) area through the Bangabandhu Sheikh Mujibur Rahman Tunnel. It holds commercial significance due to its proximity to the CMC and several industrial establishments, including Karnaphuli Fertilizer Company Limited (KAFCO), Bangladesh Marine Academy (BMA), Chittagong Urea Fertilizer Limited (CUFL), and KEPZ. There are 30,545 population, with literacy rates of male 68% and females 57.1% in Boirag Union[50]. The total households and land area are 5662 and 16.24 km^2, respectively[50], and the adjacent areas to the households are occupied with vegetation, which is called homegardens.

Boirag Union in Anowara Upazila was chosen for study because of its economic and environmental importance in Chattogram district. Due to the many commercial establishments mentioned above, the area has

transformed into a semi-urban area from the rural area, eroding the green spaces, for example, homegardens[51]. In addition, this area is located close to the coastal area and has geographical susceptibility to climate change, including coastal flooding, landslides, and the dependence of its population on climate-sensitive livelihoods, for example, fishing, farming, homegardening, and aquaculture. With this vulnerability and limited green spaces in addition to infrastructural challenges, this is crucial to understand how limited resources like homegardens and renewable resources (wood, energy fuels) around them help locals mitigate climate change. However, research on homegarden and wood-based climate change mitigation in this region is scarce. By a quantitative investigation of the homegarden trees and renewable resources of the households in Boirag union, the study can provide useful insights into the potential role of homegarden trees, wood, and energy fuels (e.g., biogas) in climate change mitigation at the household level that can be expanded in other susceptible coastal regions of Bangladesh. Moreover, the findings of this study will be the baseline in this transitional period when the area has transformed from a rural to a semi-urban area.

Field data collection

Sampling of homegardens for carbon storage in trees

Out of 4277 households, a total of 217 samples were surveyed from the three villages of Boirag Union (Fig. 1) using simple random techniques, with a sampling intensity of 5%, as accepted by the UN[52]. For sampling, three (from nearby coastal, roadside, and inland) out of six villages from this Union were selected based on their location, and samples were randomly selected from the lists of the households of these three villages gathered from Union parishad office. Every household was presumed to own a homegarden, whether it was small or large. Local guides were engaged to assist in acclimatizing to the surroundings and in completing field (households and respective homegardens) surveys. Homegardens were separated into quadrats (5 m x 5 m) based on size and orientation from the dwelling. The survey included measurement of the area (ha), height (m), and diameter at breast height (DBH) (cm) of all woody plants (DBH ≥ 5 cm) except seedlings in homegardens along with their identification during May-September 2022. Most common woody species and their uses and management were also explored. A rangefinder (Laser inc technology, Trupulse 200B, USA) was used for measuring the height of trees, while a diameter tape was used to measure DBH. The coordinates of sampled households were recorded by GPS (Garmin GPS 78 S, Taiwan).

Household and furniture manufacturer surveys for carbon storage and substitution potential of wooden furniture and renewable energy fuels

The household survey consisted of a questionnaire designed to collect data on various aspects, including family income, quantities of wooden furniture (in number), fossil fuel-intensive furniture (in number), and fuelwood (in kg). Spot measurement and direct observation were used to randomly verify the respondents' data about the overestimation of fuelwood consumed. Related to biogas generated from kitchen waste, poultry waste, and cowdung, we recorded the quantities of kitchen waste (kg) and the number of poultry birds and cattle per household. Regarding fossil fuels, respondents were asked to provide their actual invoices for monthly consumption of electricity and the quantity of liquefied petroleum gas (LPG) cylinders used, from which the amounts of fossil fuels were quantified for each household. Data were gathered on an annual basis.

For validation and reliability, the questionnaire for the household survey was validated by six key persons such as Union Chairman, Councillor, an NGO official, a school teacher, two elderly man and women, who provided feedback on the questions. Following their comments, the questionnaire was then edited and reorganized for clarity so that household members could easily understand what was asked. New questions were also added according to their suggestions, for example, to know the exact amount of electricity used in a household invoice of monthly consumption of electricity. Moreover, they suggested replacing the monthly amount of poultry waste generated with the number of poultry birds to investigate the biogas potential of waste.

Five furniture manufacturers were also surveyed to determine the typical amount of wood and types of tree species needed to meet the common demand for sampled furniture. To ensure accuracy, the survey excluded any wood waste generated during the manufacturing process, focusing only on the solid wood volume present in household wooden furniture.

Data analyses

Estimation of carbon storage in live tree biomass ($C_{storage}$)

Carbon storage in living tree biomass (C storage) encompasses both above-ground biomass (AGB) and below-ground biomass (BGB) carbon. AGB was estimated by converting tree data into biomass using allometric equations for tropical tree species, *Cocos nucifera*, *Areca catechu*, *Musa sapientum*, and *Bambusa* sp., respectively (Eqs. 1–5; Table A.1). BGB refers to carbon in living plant tissues located below the earth's surface (fine and coarse roots). It was calculated by multiplying AGB by a factor of 0.15, since the root system generally constitutes about 15% of the tree's above-ground weight[53]. Total tree biomass (TB) was obtained by summing AGB and BGB, and $C_{storage}$ was then calculated (Eq. 6; Table A.1) and finally expressed in Mg CO_2 ha^{-1} as 50% carbon of dry mass was considered[54]. Homegarden area and $C_{storage}$ per hectare were correlated but there was no causal effect of area on biomass carbon of homegarden trees (Figure A.1). For estimating biomass, wood density (g cm^{-3}) data were sourced from Bangladesh Forest Research Institute (BFRI)[55]. Moreover, $C_{storage}$ for common and dominant tree species was calculated and expressed in kg CO_2 per individual tree. Tree density (TD) and basal area (BA) of trees were also calculated on a per-hectare basis (Eqs. 7–9; Table A.1).

Estimation of carbon storage (C_{wood}) and substitution (C_{sub}) benefits of existing wooden furniture

The amount of carbon stored (C_{wood}) in each piece of wooden furniture and substitution benefits of wood (C_{sub}) were estimated and expressed per household per year (Mg CO_2 HH^{-1} $year^{-1}$) (Eqs. 10 and 11; Table A1). To

estimate the substitution benefits of wood, a displacement factor (DF) of 1 (t C t C^{-1}, i.e., a ton of fossil carbon emission avoided per ton of carbon used in wood product) was used for wooden furniture[56–58]. The wood use efficiency from sawmilling to furniture manufacture is high (36% residues of its mass)[24]. Moreover, it was assumed that wooden furniture replaces fossil counterparts, such as furniture made from steel and plastic, which have high emissions. In Bangladesh, the energy used in sawmilling is mainly sourced from fossil fuels; however, process emissions related to the use of fossil fuels were not considered in this assessment. Since harvesting wood from public forests is banned in Bangladesh, the sources of wood are limited to social forestry programs, homegardens, roadside plantations, and private forests, all of which are replanted after harvesting[59]. The volume of wood used in furniture was calculated using the typical dimensions used by furniture manufacturers and the number of items in a household, and expressed in m^3 HH^{-1} for each type of furniture. The average wood density of 585 kg m^{-3} of most common tree species used in furniture making was used to estimate the carbon content in the furniture.

The household questionnaire survey recorded the quantities of fossil fuel-intensive furniture items, including plastic chairs, tables, wardrobes, and steel almirahs. It was presumed that an equivalent number of fossil fuel-intensive furniture items could be replaced with wooden furniture of similar dimensions. The substitution of fossil fuel-intensive furniture with wooden furniture is expected to generate C_{sub}. The potential of wooden furniture for C_{sub} and C_{wood} was quantified using Eqs. 10 and 11 (Table A1).

Estimation of substitution benefits of the use of renewable energy

We estimated the emissions from burning fossil fuels and fuelwood in traditional cooking stoves (TCS). The units recorded during the questionnaire survey were kilowatt-hours (kWh) for electricity, liters (l) for LPG, and kilograms (kg) for fuelwood. To facilitate estimation, we converted these units into a single unit of (kWh) for LPG and electricity, using the energy content of the corresponding fuels from the literature (Table A2). The moisture content of fuelwood was assumed to be 15–30%[60]. Household-level monthly CO_2 emissions from using LPG, electricity, and burning fuelwood in TCS were calculated based on monthly fuel consumption (Eq. 12; Table A1) and their respective emission factors (Table A2). The results were presented in Mg CO_2 per household per year (Mg CO_2 HH^{-1} $year^{-1}$).

Regarding estimating the substitution potential of biogas and fuelwood, we assumed that surveyed households using fuelwood in TCS and LPG would switch to ICS and biogas, respectively. The substitution potential of biogas, generated from kitchen waste, cowdung, and poultry waste, and the use of fuelwood in ICS, was estimated by assuming it would replace fossil fuels and fuelwood used in TCS. After determining the quantities of cowdung and poultry waste (Eqs. 13 and 14; Table A1), we estimated the substitution potential of biogas for fuelwood by calculating the difference in emissions (Eqs. 15–17; Table A1 and Table A2) and presented the results in (Mg CO_2 HH^{-1} $year^{-1}$). For example, after estimating the monthly biogas production from cowdung or kitchen waste, the monthly amount of fuelwood used was converted into its biogas equivalent. The net emission reduction from biogas usage was calculated by comparing the emissions from using fuelwood in TCS with those associated with biogas (Eq. 18; Table A1). We calculated the emission reduction of fuelwood use, considering a 25% CO_2 reduction with ICS compared to TCS, following Baul et al. (2022b)[32] (Eq. 19; Table A1).

Income stratification of the households

In accordance with the Asian Development Bank paper's income classification, households were categorized into four distinct income groups based on the income status of the sampled households. The floating class encompassed those households with daily earnings between US$ 2 and US$ 4, the lower middle-class between US$ 4 and US$ 10, the upper middle-class between US$ 10 and US$ 20, and the higher middle-class between US$ 20 and US$ 100[61]. In this study, we surveyed 217 sampled households, of which 169 were in the lower-middle (LM) and 48 in the upper-middle (UM) income groups.

Statistical analyses and modelling work

The data analyzed included mean values for $C_{storage}$, tree density, and basal area (BA) on a hectare basis, and wood volume in wooden furniture, $C_{wood,}$ and C_{sub} on a household basis. A Kolmogorov–Smirnov (K–S) test was conducted to assess the normality of the data for tree height and DBH, which revealed that the data were not normally distributed. As a result, a non-parametric Kruskal-wallis test was used to determine whether there were any statistically significant differences ($p \leq 0.05$) between the two income groups for mean values of $C_{storage}$, density, BA, and wood volume in wooden furniture, C_{wood} and C_{sub}. Additionally, the Kruskal-wallis test was also applied to compare LM (lower-middle) and UM (upper-middle) income groups for household level emissions from burning fuelwood, using LPG and electricity, as well as the net emission reduction potentials of biogas from waste and improved cooking stoves (ICS).

Furthermore, the relationship between $C_{storage}$ (Mg CO_2 ha^{-1}) and tree density (tree no ha^{-1}) and BA (m^2 ha^{-1}) was modelled by using Spearman's rank correlation. All these statistical analyses were performed by using Statistical Package for the Social Sciences (SPSS) version 26.

Results

Carbon storage in live tree biomass ($C_{storage}$) in homegardens

In rural homegardens, mean $C_{storage}$, tree density, and basal area per hectare were higher in lower-middle compared to the upper-middle households, however, there was no significant difference between the income groups (Table 1). $C_{storage}$ was positively associated with tree density and BA (Figure A2). We found a total number of 37 tree species of which frequent species were *Mangifera indica*, *Cocos nucifera*, *Artocarpus heterophyllus*, *Areca catechu*, *Albizia lebbeck*, *Psidium guajava*, *Ziziphus mauritiana*, *Moringa oleifera*, *Acacia auriculiformis*, *Spondias pinnata*, *Annona squamosal*, *Lannea coromandelica*, *Swietenia macrophylla*, *Tectona grandis* (Table A3). As an

Variables (mean values)	LM	UM	Total mean
$C_{storage}$ ($Mg\ CO_2\ ha^{-1}$)	42.20 ± 2.48[a]	37.69 ± 3.48[a]	39.95 ± 2.98
Tree density (Tree no ha^{-1})	164.03 ± 9.75[a]	152.76 ± 11.29[a]	161.53 ± 7.99
Basal area ($m^2\ ha^{-1}$)	5.83 ± 0.34[a]	5.16 ± 0.54[a]	5.68 ± 0.29

Table 1. Mean values of carbon storages in live tree biomass ($C_{storage}$), tree density, and basal area in homegardens of lower-middle (LM) and upper-middle (UM) income groups in Anowara Upazila, Chattogram. ± represents the standard error of the mean. The same letters (a, a) within a row indicate insignificant differences at $p \leq 0.05$ between the income groups.

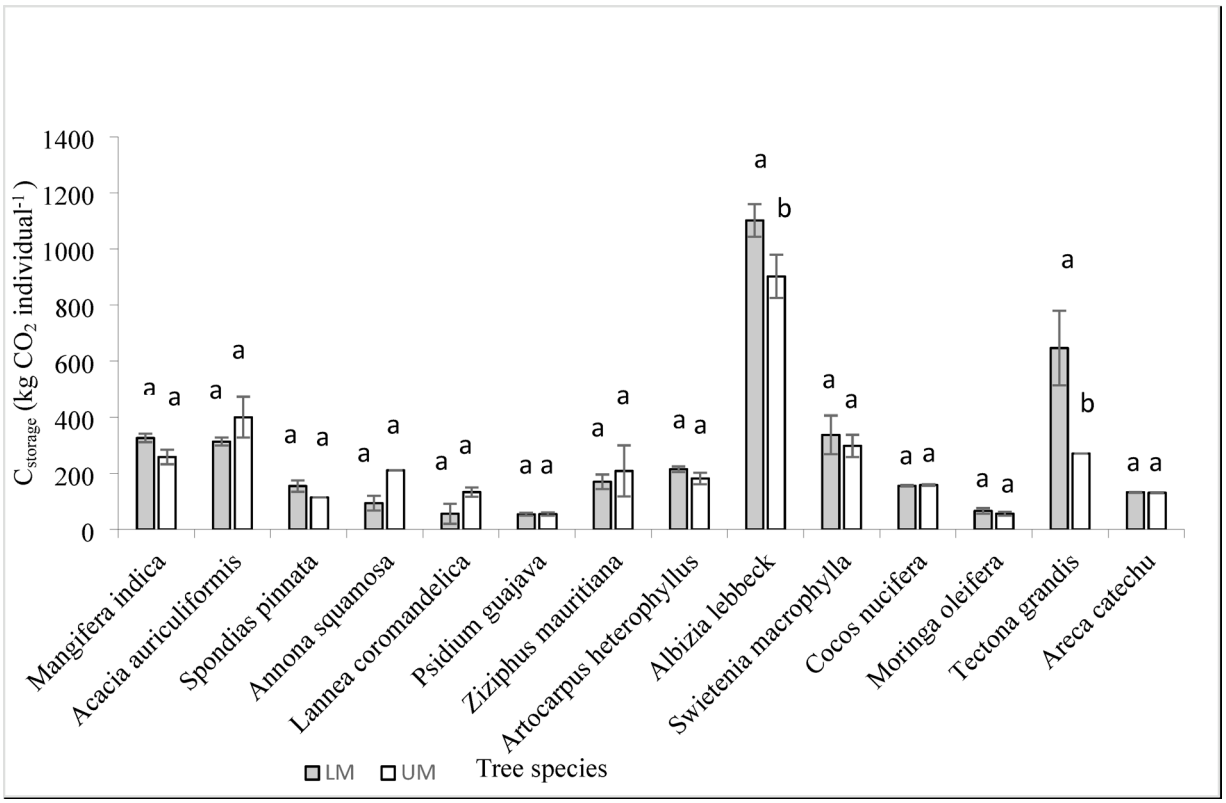

Fig. 2. Carbon storage in live tree biomass ($C_{storage}$) (kg CO_2 individual tree^{-1}) of dominant species in homegardens of lower-middle (LM) and upper-middle (UM) income groups in Anowara Upazila, Chattogram. Bars represent the standard error of the mean. Different letters (a, b) indicate significant difference at $p \leq 0.05$ between the income groups.

individual tree species, $C_{storage}$ was found the most in *Albizia lebbeck*, *Tectona grandis*, *Acacia auriculiformis*, and *Swietenia macrophylla* (Fig. 2).

Carbon storage (C_{wood}) and substitution benefits (C_{sub}) of existing wooden furniture

The survey revealed that tree species commonly used in furniture manufacturing included *Acacia auriculiformis*, *Tectona grandis*, *Samanea saman*, *Gmelina arborea*. A maximum volume of wood was used in making a bed, followed by sofa, showcase, and wardrobe (Fig. 3). Households in the upper-middle income group used significantly ($p < 0.05$) higher volume of wood than those in the lower-middle group (Fig. 3), thus resulting in significantly ($p < 0.05$) higher C_{wood} and C_{sub} of wooden furniture in utilization (Fig. 4).

Carbon storage (C_{wood}) and substitution (C_{sub}) potential of wooden furniture in replacing existing fossil fuel-intensive furniture

Households in the lower-middle income group used a higher number of fossil fuel-intensive (steel, plastic) furniture than upper-middle income households, thus would result in higher C_{wood} and C_{sub} potentials if they are substituted with wooden furniture (Table 2). The carbon reduction (wood carbon and substitution) potential of wood per household was higher in upper-middle than in lower-middle income group (Table 2).

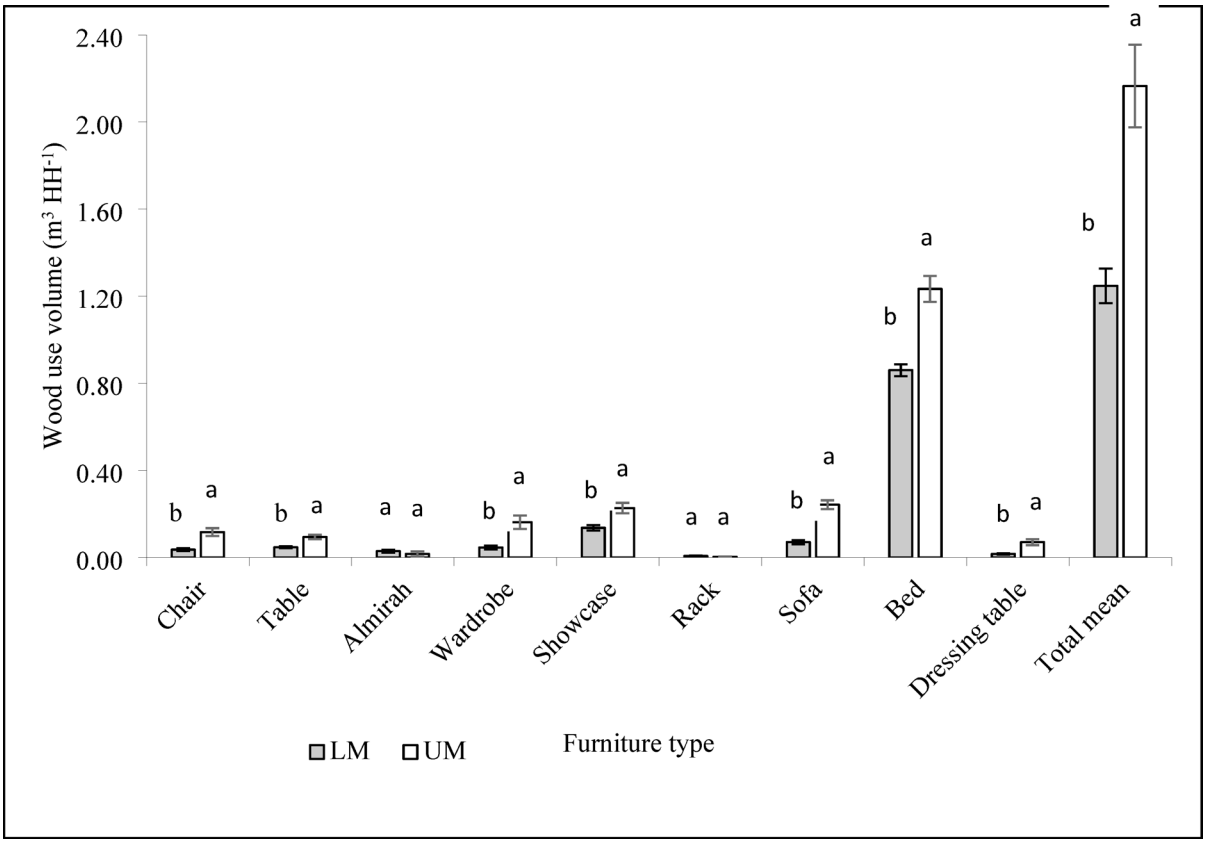

Fig. 3. Mean wood use volume (m^3 HH^{-1}) in the households (HH) of lower-middle (LM) and upper-middle (UM) income groups, Boirag Union, Anowara Upazila, Chattogram. Bars represent the standard error of the mean. Different letters indicate a significant difference at $p \leq 0.05$ between the income groups for different furniture types.

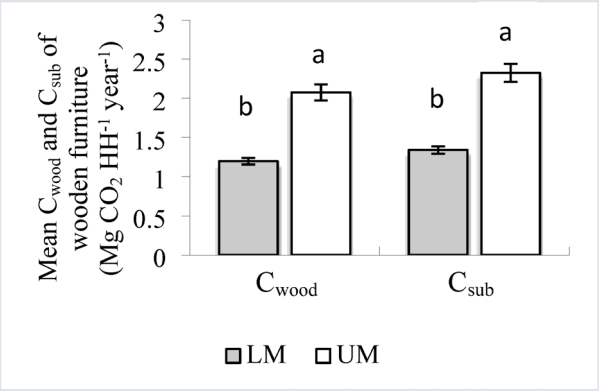

Fig. 4. Carbon storage (C_{wood}) and substitution benefits (C_{sub}) of existing wooden furniture in utilization in households (HH) of lower-middle (LM) and upper-middle (UM) income groups of Anowara Upazila, Chattogram. Bars represent the standard error of the mean. Different alphabets (a, b) indicate the significant difference between LM and UP for C_{wood} and C_{sub}.

Emissions from energy fuels and substitution potential of biogas and improved cooking stoves (ICS)

In general, household level emissions from burning fuelwood were the highest, followed by emissions from using electricity and LPG (Table 3a). Regarding the income level, the fossil fuel related emissions were higher in upper-middle compared to lower-middle income households. However, emissions from burning fuelwood were higher in lower-middle income household than upper-middle group, with no significant difference between them. In terms of emission reduction potentials, biogas derived from kitchen waste had the highest net reduction,

Income group	Lower-middle household			Upper-middle household		
Furniture type	fossil fuel-intensive furniture (Total no.)	C_{wood} potential of wooden furniture	C_{sub} potential of wooden furniture	fossil fuel-intensive furniture (Total no.)	C_{wood} potential of wooden furniture	C_{sub} potential of wooden furniture
Plastic chair	578	21.56	24.18	149	5.56	6.23
Plastic table	79	3.93	4.40	26	1.29	1.45
Steel almirah	151	37.56	42.07	68	16.91	18.95
Plastic wardrobe	17	5.07	5.68	4	1.19	1.33
Mean carbon reduction (Mg CO_2 HH^{-1})		0.4 ± 0.02	0.45 ± 0.02		0.52 ± 0.04	0.58 ± 0.04

Table 2. Status of existing fossil fuel-intensive furniture used in households (HH) and carbon storage (C_{wood}) and substitution (C_{sub}) potential (Mg CO_2) of wooden furniture in replacing existing fossil fuel-intensive furniture in the households of lower-middle and upper-middle income groups of Boirag Union, Anowara Upazila, Chattogram. ± represents the standard error of the mean.

a) Income groups/variables	Mean emissions (Mg CO_2 HH^{-1} $year^{-1}$)			
	Fuelwood	LPG	Electricity	Mean of total
Lower-middle	1.56 ± 0.08[a]	0.39 ± 0.02[a]	0.93 ± 0.05[b]	2.88 ± 0.1[a]
Upper-middle	1.32 ± 0.17[a]	0.48 ± 0.04[a]	1.2 ± 0.1[a]	3.01 ± 0.2[a]
Mean of Total	1.50 ± 0.08	0.42 ± 0.02	0.99 ± 0.05	2.91 ± 0.09

Net emission reduction potentials of biogas and ICS in replacing traditional burning of fuelwood (Mg CO_2 HH^{-1} $year^{-1}$)					
b) Income groups/variables	Reduction potential of biogas from kitchen waste	Reduction potential of biogas from cowdung	Reduction potential of biogas from poultry waste	Reduction potential of ICS	Mean of total
Lower-middle	0.91 ± 0.03[b]	0.56 ± 0.12[a]	0.01 ± 0.00[a]	0.39 ± 0.02[a]	1.87 ± 0.12[b]
Upper-middle	1.14 ± 0.07[a]	0.92 ± 0.37[a]	0.03 ± 0.02[a]	0.33 ± 0.04[a]	2.43 ± 0.42[a]
Mean of total	0.96 ± 0.03	0.64 ± 0.12	0.02 ± 0.00	0.37 ± 0.02	2.0 ± 0.13

Table 3. Household (HH) level emissions from burning fuelwood, using LPG and electricity and net emission reduction potentials of biogas from waste and improved cooking stoves (ICS) in lower-middle (LM) and upper-middle (UM) income groups of Anowara Upazila, Chattogram. ± represents the standard error of the mean. Different letters within a column indicate a significant difference at $p \leq 0.05$ between the income groups for the variables.

followed by biogas from cowdung, use of ICS, and biogas from poultry waste. This emission reduction potential of using biogas was significantly ($p < 0.05$) higher in upper-middle than in lower-middle households (Table 3b).

Total carbon benefits

In terms of total carbon emission removal and reduction, realized substitution benefits of existing wooden furniture (C_{sub}) was the highest, followed by carbon storage in homegarden trees ($C_{storage}$) and in wooden furniture (C_{wood}) in the sampled households of the study area (Table 4). Related to the potential to substitute existing fossil counterparts, the carbon emission reduction potential of biogas was the highest (Table 4).

Discussion

Carbon storage in homegarden live trees

Mean live biomass carbon estimated (42 Mg CO_2 ha^{-1}) in homegarden trees of this study area was lower than that found in the hill (133 Mg CO_2 ha^{-1}) and coastal (168 Mg CO_2 ha^{-1}) homegardens in Bangladesh[13,14]. This may be ascribed by the lower tree density and basal area have led to the lower biomass carbon in our study in comparison to the findings of the aforementioned earlier studies. We also found live tree biomass carbon was positively associated with tree density and basal areas (Figure A.2), however, lower tree density and basal area, and thus lower biomass carbon could be attributed to the transformation of rural areas to semi-urban areas which resulted in cutting of trees for economic zone (e.g., export processing zone, fertilizer industries, tunnel) and associated constructions. In addition, homegarden fragmentation reduced their size (e.g., mean areas of 0.03 and 0.04 hectares in lower-middle and upper-middle homegardens, respectively, in this study), contributing to lower tree biomass carbon stocks. Home gardeners tended to lower tree size through pruning and thinning to allow lateral growth of trees in their limited fields, as well as to meet the demand for timber for consumption and household revenue. We did not find any significant difference in tree biomass carbon between income groups, which may be explained by the fact that there is no effect of homegarden size on live biomass carbon estimated (Figure A1). This can be postulated that small-scale homegardens can contribute significantly to carbon storage by maintaining higher density and DBH than unmanaged forests. In total, 37 tree species were identified in the

Climate change mitigation	CO_2 removal and reduction pathways	Total carbon benefits (Mg CO_2)
Carbon removal	$C_{storage}$ (Carbon storage in homegarden trees)	323.76
Carbon removal	C_{wood} (Carbon storage in existing wooden furniture)	301.08
Carbon reduction	C_{sub} (Realized substitution benefits of existing wooden furniture in utilization)	337.88
Carbon removal and reduction potential	C_{wood} (Carbon storage potential in wooden furniture in replacing existing fossil fuel-intensive furniture)	93.10
	C_{sub} (Substitution potential of wooden furniture in replacing existing fossil fuel-intensive furniture)	104.28
	Emission reduction potential of biogas (annual)	322.28
	Emission reduction potential of ICS (annual)	69.79

Table 4. Total carbon stored in homegarden tree biomass ($C_{storage}$), in wood (C_{wood}) and substitution benefits (C_{sub}) of existing wooden furniture in utilization, and potentials of C_{wood}, C_{sub}, biogas, and improved cooking stoves (ICS) in replacing fuelwood used in traditional cooking stove (TCS) and fossil fuel-intensive materials in sampled households of Anowara Upazila, Chattogram.

sampled households, closely resembling the 43 species found in Hathazari of Chattogram district, Bangladesh[46]. Among these species, *Mangifera indica*, *Acacia auriculiformis*, *Artocarpus heterophyllus*, *Swietenia macrophylla*, *Albizia lebbeck*, *Tectona grandis*, contributed the highest CO_2 accumulation in individual trees across both income groups. Jaman et al. (2016)[15] also reported the most contribution of these species on live biomass carbon storage in homegardens of Bangladesh.

Carbon storage and substitution benefits of wooden furniture

In general, a rural household was able to store and avoid 1.3 Mg CO_2 and 2.2 Mg CO_2 annually by choosing wooden furniture over fossil fuel-intensive alternatives. Annual carbon storage and realized substitution benefits of existing wooden furniture were 75% and 73% greater in higher-income households than in lower-income households, respectively. This was explained by the fact that households with higher incomes used 73% more wood than those with lower incomes. This might be because these households were more financially stable and environmentally conscious, which led them to use more wooden furniture. On the other hand, lower-income households may be less likely to use wooden furniture due to the lower cost of steel and plastic furniture. Previous studies[24,62] in Bangladesh also reported that wooden furniture served as an effective substitute for fossil fuel-intensive options due to its user- and environment-friendly properties. A study by Yadav et al. (2014)[63] in India found that increasing the share of wood use (currently at 65%) by 5% in place of metal and plastic could avoid CO_2 emissions by approximately 624,000 Mg. Using wooden furniture as long-lived products retain carbon longer in wood before released into the atmosphere while generating substitution benefits.

In estimating the substitution benefits of wooden furniture used in households, we used a displacement factor of 1 t C t C^{-1}, which is close to that (average 1.2 t C t C^{-1}) found in[57] based on the literature review. In earlier studies, displacement factors used for wooden furniture were 1 t C t C^{-1} in Bangladesh[24] and 0.9 t C t C^{-1} in Finland[64]. Country-level displacement factors may be lower than those of product-level factors, such as 0.5 found for Canada[27]. However, a comprehensive picture of the potential for wood use to mitigate climate change cannot be obtained by relying solely on displacement factors for specific products. Because the benefits of material substitution decrease as forest carbon sinks are reduced[64,65]. In our case, harvesting wood from homegardens to substitute for steel and plastic furniture may diminish forest carbon sink. Further, in Bangladesh, the process emissions generated in producing wood products are mainly from fossil fuels, which are the main source of generating power. Consequently, this study's displacement factor might have exaggerated the potential to mitigate climate change. Future research could concentrate on local displacement factor calculation for furniture in order to estimate more accurate substitution benefits because the feedstock is locally manufactured and traded in Bangladesh. Using a life cycle assessment technique for the furniture industry, this entails creating country-specific displacement factors for different furniture products (such as chairs, tables, and cabinets).

Substitution potential of biogas and improved cooking stoves (ICS)

We found that the emission reduction potential was 31% higher in higher-income households than in lower-income households, as the former generated more kitchen waste and cowdung. The use of biogas to reduce fossil CO_2 emissions at the household level was highlighted by Roubík et al. (2020)[66]. The household's economic situation, such as income, influences these CO_2 reduction potentials[67]. In the households of this study, fossil fuel-generated (electricity and LPG) emissions (1.35 Mg CO_2 household^{-1} year^{-1}) were two times higher than those generated in the households in northern Chittagong, Bangladesh (0.68–0.7 Mg CO_2 household^{-1} year^{-1})[23,68]. This may be due to the higher amount of fuel required in TCS than in technologically improved stoves (ICS). Using biogas and biomass fuels in ICS for cooking could reduce the CO_2 emissions from burning fuelwood and fossil fuels in TCS. Excessive fuel use in TCS contributes to deforestation and higher emissions than ICS[69,70]. ICS is a feasible option in rural Bangladesh since it is well-disseminated and found cheaper[33,68]. With installation costs ranging from only 115 to 250 US dollars in Bangladesh for 100 to 300 cubic feet of gas production per day[71], biogas systems also seemed like technically and financially feasible options, particularly small household-based fixed dome models[38,71]. Furthermore, Infrastructure Development Company Limited (IDCOL), a government company, has promoted and subsidized the use of biogas-to-electricity, which has driven the success of these renewable energy programs, achieving energy access and economic stability for rural households[71]. A study

in Pakistan by Yousaf et al. (2021)[72] stated that LPG could be replaced with ICS for cooking. In Vietnam, after adopting biogas technology, greenhouse gas emissions drop significantly to 4.52 Mg CO_2 e per household per day[73].

Total carbon benefits

Total carbon storage in the sampled homegardens of the study area and wooden furniture in the corresponding households were 324 and 301 Mg CO_2, respectively. Moreover, the realized substitution benefits of existing wooden furniture in utilization were accounted as 338 Mg CO_2. As a comparison, in Bangladesh, the energy sector and Agriculture, Forestry, and Other Land Use (AFOLU) sector contributed 54% (115 Mt CO_2 eq) and 34% (72 Mt CO_2 eq), respectively, to the total GHG emissions (213.19 Mt CO_2 eq) in 2019[74] for which homegarden trees and wooden furniture and energy technologies can play a pivotal role. In the NDC 2021 target, the energy and AFOLU sectors would reduce GHG emissions 95.4 and 2.3%, respectively, compared to the business as usual (BAU) in 2030[75]. The NDC offers a framework for government-backed initiatives in which households contribute to building a more sustainable future by engaging in activities. For households, this NDC commitment has several scopes, such as using energy-efficient practices, ICS, and renewable energy technologies like biogas plants using organic waste to reduce emissions from burning fuelwood and fossil fuels. Besides, in attaining sustainable development goals (SDGs), carbon storage in homegardens and wooden furniture can contribute to climate change mitigation (SDG 13) and substitution benefits of wooden furniture and renewable energy (biogas and ICS) offers pathways for affordable, sustainable, and clean energy for cooking (SDG 7) and sustainable and responsible consumption of the resources (SDG 12). In addition, sustainable management of homegardens for storing carbon will help to protect and restore terrestrial ecosystems (SDG 15) while fostering economic benefits at the rural household level to reduce poverty (SDG 1).

Limitations of the study

This study is only based on one case study conducted in a Union, which might not present the actual scenarios of rural homegardens, use of wooden furniture, renewable energy fuels, and fossil fuel-intensive furniture and fossil fuels in the entire rural areas of Chattogram. This kind of study needs to increase the sample size, covering a large geographical area. Furthermore, to understand the feasibility of the mitigation technology, a monetary evaluation involving costs and economic and environmental benefits is needed, which requires a rigorous study.

Concluding remarks

The research findings suggest that implementing sustainable practices in households can significantly contribute to climate change mitigation. This study will establish a carbon accounting procedure for the total climate impacts of forest biomass at the household level while reducing the gap between documentation and generation of estimated carbon benefits from homegardens and wooden furniture and fuels. The country's climate commitment under the UNFCCC will be strengthened if the carbon benefits of wood, homegarden trees, and wood substitution are included in the national accounting system for NDCs. This could be encouraged by efficient, community-focused climate action that prioritizes both individual and national-level contributions. Millions of homegardeners can contribute substantially to attaining SDGs by conserving and enhancing carbon stocks in their gardens through REDD + and by creating carbon markets for indirect benefits of using wooden furniture and renewable energy technologies under CDM while improving livelihoods by receiving credit from the national climate trust fund. Besides, these insights can help the government to develop tailored policies that promote climate-smart forestry practices.

To advance a forest-based bioeconomy, national planning should emphasize the sustainable management of homegarden trees and the utilization of forest biomass for furniture production and energy, while ensuring that the climate benefits of forest biomass are fully recognized. Given the various income levels, investigating consumer education campaigns and awareness about long-term climate benefits of wood, along with their willingness to use wooden furniture and recycled wooden products is required. Such an effort could increase the adoption of wooden furniture and solidify its role as a sustainable and eco-friendly solution across all economic groups. The findings of the study will be applicable to countries with similar demographic, environmental, and natural attributes.

Data availability

Data related to this study is available within the manuscript.

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Author contributions

Md. Zeesun-Ul Haque and Thuhidul Islam: Data Collection, Curation, and Analysis; Tarit Kumar Baul and Md. Zeesun-Ul Haque: Conceptualization, Methodology; Tarit Kumar Baul: Project administration, Supervision; Tarit Kumar Baul, Md. Zeesun-Ul Haque and Thuhidul Islam: Investigation; Tarit Kumar Baul, Mohammed Jashimuddin, Antti Kilpeläinen, Ashraful Alam: Resources, Validation, Visualization; Md. Zeesun-Ul Haque and Tarit Kumar Baul: Writing- Original draft preparation; Antti Kilpeläinen, Tarit Kumar Baul, Ashraful Alam, Mohammed Jashimuddin, and Shiba Kar: Writing- Reviewing and Editing.

Declarations

Competing interests
The authors declare no competing interests.

Ethics approval and consent to participate
The survey protocol received approval from the academic and research committee of the Institute of Forestry and Environmental Sciences (IFES) at the University of Chittagong, Bangladesh. This study which involves primary survey in 217 households and five furniture manufacturers, has been conducted in strict adherence to the guidelines set forth by the IFES. Compliance with all academic, ethical, and procedural standards outlined in the programme guidelines of IFES have been ensured. Respondents were aged 18 and above, and confidentiality and anonymity of their participations in this study were maintained. Verbal informed consent was obtained prior to the interview from the respondents of the surveys. Respondents were informed about the purpose of the study, the procedures involved, and their rights to withdraw at any time without any consequences.

Consent for publication
Verbal informed consent was obtained prior to the interview from the respondents of the surveys to publish the data collected. This report adhered to the STROBE declaration about the reporting of cross-sectional studies, in compliance with the Declaration of Helsinki for research involving human subjects.

Additional information
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